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The application of a microprocessor to engine cylinder disablement

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THE APPLICATION OF A MICROPROCESSOR TO
ENGINE CYLINDER DISABLEMENT

by

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A Master's Thesis

Submitted in partial fulfilment of the requirements
for the award of

Master of Philosophy of the Loughborough University
of Technology

10th April 1985

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NOTATION

S.I.	Spark Ignition
C.I.	Compression Ignition
CSO	Cylinder Shut-off
FSO	Fuel Shut-off
VSO	Valve Shut-off
ECM	Electronic Control Module
ECU	Electronic Control Unit
NVH	Noise, Vibration and Harshness
N	Engine Speed rpm.
P	Power kW or bhp.
T	Torque Nm or lbft.
FC	Fuel Consumption Kg/hr or lb/hr.
BSFC	Brake Specific Fuel Consumption g/kWhr or lb/bhphr.
τ	Inlet Manifold Pressure kN/m ² or mmHg.
t	Time sec.
f	Frequency Hz.
A	Correction Factor (Engine Performance)

SUMMARY

The power output of a spark ignition, internal combustion engine is normally controlled by the use of a throttle on the air intake system. As a result, the part-load efficiency of the engine suffers when compared with the compression ignition engine.

A microprocessor development system was adapted for use with the electronic fuel injection of a 6 cylinder, spark ignition engine in order to selectively disable any number of individual cylinders by interrupting the fuel flow from the injectors of those cylinders. The system allows any number and combination of cylinders to be disabled cyclically, with the view of keeping all cylinders hot and minimising engine vibration.

The theory of cylinder disablement, and work published in this field are discussed in this Thesis. Also included are the results of engine testing carried out to determine the economy gains possible with cylinder deactivation, and to investigate the behaviour of a cylinder under disablement, and subsequent reactivation by control of its injector. The relationship between cylinder deactivation sequence and engine vibration, and means of minimising the amplitude of that vibration were also investigated, and the results obtained discussed, together with the results of limited emission and fuel consumption testing of a vehicle fitted with cylinder disablement.

The main conclusions reached at the end of this research were:

- (i) The use of a microprocessor system, in conjunction with electronic fuel injection to disable cylinders by control of their injectors is an effective way of implementing cylinder disablement.
- (ii) Fuel economy gains achieved varied from over 50% at idle to 25 - 45% at light load, steady state conditions, with actual vehicle tests returning almost 40% fuel economy over the European 04 Test driving cycle, accompanied by moderate increases in exhaust pollutants.
- (iii) Engine vibration, resulting from the imbalance of the non-firing cylinders can be reduced to acceptable levels by arranging the disabled cylinders according to their firing order and engine speed, as shown in this Thesis.

Finally, the possibilities of expanding the microprocessor development system used for this research, to incorporate the additional disablement control features, are discussed and recommendations made, based on the results of the research.

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1. INTRODUCTION

INTRODUCTION

The spark ignition engine, as fitted to the vast majority of passenger vehicles today, has enjoyed over eighty years of continuous development. The principle of operation of the engine has not changed in that time, implementing the Otto Cycle to the best of its ability. Advances in the field of materials technology, and a better understanding of the processes taking place inside the combustion chamber, have pushed the power output/ displacement ratio to increasingly higher limits. As a result, today's top F1 racing engines with the aid of forced induction and high octane fuels, can deliver almost 1000 bhp from just 1.5 litres under race qualifying conditions.

With passenger vehicles however, ease of manufacture, cost, fuel economy and reliability are the key factors in the design of an engine for the volume market. In particular, the increasing awareness of the value of the remaining oil reserves of this planet both in economic and social terms, highlighted by the oil price crisis of the early '70s, has urged motor manufacturers to design and produce engines that deliver the required power to give acceptable performance, while at the same time be very efficient in the way they use fuel under all driving conditions.

This drive to make the spark ignition engine more fuel efficient has resulted in major developments in all areas of engine construction and operation, and these can be categorised as follows:

- (i) Improvements in Mechanical Efficiency
 - eg. Low friction lubricants and bearings, lighter internal moving parts, specially coated friction surfaces etc.
- (ii) Improvements in Thermodynamic Efficiency
 - eg. High compression, better combustion chamber design, lean-burn engines etc.
- (iii) Electronic Engine Management Systems
 - eg. Microprocessor based control of all engine systems for precise metering of fuel and ignition, under all conditions.
- (iv) Alternative Fuels
 - eg. LPG, alcohols, NG, LNG, hydrogen.
- (v) Modular Engines
 - eg. Variable displacement engines, Cylinder disablement.

The work described in this Thesis concerns this last means of improving the fuel economy of engines, and in particular, cylinder disablement.

CYLINDER DISABLEMENT

Cylinder disablement, or Cylinder Shut-off (CSO) as is commonly referred to, is a concept that has existed since the early days of the motor car. It is based on the fact that the full power of the engine in a vehicle is needed only on relatively rare occasions such as hill climbing, full throttle accelerations and overtaking. For most of its life the passenger vehicle operates in the part load and idle conditions, particularly so if the engine capacity is large and delivers adequate torque at small throttle openings.

The spark ignition engine has achieved dominance worldwide as a drive unit for passenger cars over the diesel because of its high power to displacement, volume and weight ratios, higher maximum speed, smooth and low-noise operation, and low cost per unit of power output. The thermodynamic efficiencies of both engines at maximum power are comparable, however, the efficiency of the S. I. engine reduces more rapidly at part load and transient conditions(1).*

The reason for this is the method of controlling the power output of the S. I. engine, namely by varying the quantity of air/fuel mixture by means of a throttle. Consequently, at part loads and idle the engine operates with very low inlet manifold pressures incurring high losses and low efficiency associated with the gas cycle. One possible solution is to deactivate some of the cylinders, the number of active cylinders being adapted to the performance requirements of the engine, and thus operating at optimum efficiency.

This concept was utilised as early as 1916 on the Enger Twin-Unit Twelve, an American touring car powered by an overhead-valve V-12 engine(2). A large lever on the steering column operated a system of linkage and cams, blocking open the exhaust valves on one bank and shutting off the fuel supply to the cylinders of that bank. However, the low cost of fuel at that time made the economy gains seem insignificant with this complex system, and the Enger Motor Car Company ceased operations in 1917.

The principle of CSO can be implemented in various ways depending on the configuration of the engine, available space, and the complexity and cost involved. Past and present systems can essentially be split into three main categories:

(i) Power Unit Disablement

* Numbers in parentheses indicate references at end of Thesis.

(ii) Valve Shut-off

(iii) Fuel "

Power unit disablement involves parallel operation of primary and auxiliary power units coupled together. With complete disengagement of the aux. power unit under part load, friction and pumping losses in that unit are avoided. This concept, although taking the principle of CSo to its full extent, has the major disadvantage of complexity, and hence cost of the coupling and synchronization of the two engines and transmission control.

The disablement of inlet and/or exhaust valves constitutes a more realistic approach to CSo. This is generally accomplished by electromechanically, or hydraulically isolating the valves from the camshaft while in the 'closed' position. This restricts the pumping work to the active cylinders, while at the same time it results in the general dethrottling of the engine at part load and hence better efficiency.

Fuel shut-off represents the simplest method of CSo, involving purely engine-based measures of stopping fuel to the deactivated cylinders and specific adaptation of engine controls. It is performed with electronic fuel injection systems via a corresponding control of the injectors, and with mechanical systems through additional valves between fuel pump and injectors.

In the cases of both valve and fuel shut-off the effective dethrottling of the engine is achieved through separate control of the main, or additional throttles by mechanical means, such as a camplate on the throttle linkage, or electrically by the use of a stepper motor. In all cases a microprocessor is used to control the cylinder deactivation sequences and to intervene in the engine controls so as to provide smooth delivery of power under all conditions.

2. LITERATURE SURVEY

CYLINDER DISABLEMENT SYSTEMS

Over the last decade there has been a revived interest in the subject of cylinder disablement as a means of increasing the fuel economy of existing S. I. engines. Virtually every major car manufacturer has looked at the possibility of adapting current engines in their model range to run on fewer cylinders by devising additional or, in some cases new engine control systems. In many cases this has been done to the larger capacity engines, where the benefits of CSO are more apparent. The principle has been applied to most engine configurations, from a large V-16 diesel engine of 50 litres displacement from Cummins, which idles on eight cylinders(3), to the small Suzuki SSC three-cylinder two-stroke unit of 0.539 litres, which operates on two cylinders at light load conditions(4).

When cylinders are deactivated on a S. I. engine it is desirable to retain even spacing between firing intervals, in order to maintain a smooth delivery of torque over the complete cycle of the engine. Figure 1 shows the positions of deactivated cylinders on various engine configurations, based on the firing order of those engines. Cylinder disablement therefore, is favoured with multi-cylinder engines, particularly those of the V-configuration.

When CSO is accomplished by deactivating the inlet and exhaust valves of an engine the pumping losses incurred are minimised. In each deactivated cylinder the unchanged charge is merely compressed and expanded by the action of the piston, with the only energy consumed directed to normal frictional losses and compression heat lost through the cylinder walls. In addition, cooling of that cylinder is minimised, with shorter subsequent reactivation time and lower emissions of unburned hydrocarbons.

Figure 2 shows a valve disablement mechanism developed by the Eaton Corporation(5) and installed in the GM Cadillac 6.0 litre models in 1981(6). The mechanism consists of a solenoid acting on a blocker plate, and mounted on the rocker arm studs of the over-head valve pushrod engine, with one solenoid acting on both inlet and exhaust valves. In the 'active' mode, shown at left in Fig. 1, the selector body is prevented from moving upward by contact between projection on the body and the blocking plate above it. The rocker arm fulcrum point is held down by the blocking plate and the body, and the valves operate as normal.

On activation of the selector, as shown at the right of Fig. 2, the blocking plate is rotated by the solenoid to align small openings in the plate with corresponding projections on the body. As the rocker arm is raised by the pushrod, its fulcrum point is moved to the tip of the valve stem as the body is no longer restrained by the blocker plate. The rocker arm pivots about the top of the valve stem, and the valve is effectively disabled.

The selector mechanism can only change operating mode during rest periods of both valves. When deactivation occurs therefore, a combustible charge is trapped and ignited but, since the valves are closed, following the power stroke the spent gases are prevented from escaping. For the following few strokes the piston re-compresses the burned gases, creating sharp pressure spikes in the cylinder. Due to blow-by past the piston rings, the (gauge) pressure inside the cylinder eventually reaches an equilibrium situation whereby pressures are positive during the compression and negative during expansion.

This CSo system uses inlet manifold pressure to sense the load requirements of the engine, via a manifold vacuum sensor whose signal, together with other signals relaying engine speed, throttle position, coolant temperature and transmission gear, is fed to an electronic control unit (ECU). The ECU then increases or decreases the number of active cylinders according to power demands, keeping the inlet manifold vacuum to between 2 and 12 ins. Hg. In this way, the V-8 engine can operate on 4, 5, 6, 7, or 8 cylinders, with the system automatically switching to 4-cylinder operation during idle. On the production version of this system however, the engine operated only in the 8, 6, or 4 cylinder mode, to avoid excessive vibration from too uneven firing intervals. In the 4-cylinder mode, the engine behaves like a 90-deg. V-4, with no inherent imbalance. In the 6-cylinder mode however, it operates as a 90-deg. V-6, which has inherent imbalance in the form of a secondary rocking couple. Consequently, the engine mounting system was redesigned to dampen these secondary vibrations effectively.

The above system was fitted by Eaton Corp. in a 1977 Mercury V-8 engined experimental vehicle, with no changes made to the carburetion or E.G.R systems. The vehicle returned fuel economy improvements ranging from 10-15% during light acceleration/Highway cruise to over 40% at idle conditions, with lower levels of HC and CO emissions, but higher levels of NOx. The production version on the Cadillac also claimed similar improvements.

The Mitsubishi Motor Corporation also introduced a vehicle in 1982 which incorporated CSo by valve disablement, applied to their 1.4 litre in-line four cylinder engine in the Mirage model(7). A microprocessor unit controls engine operation between two and four cylinders, according to signals from sensors for inlet manifold pressure, gear in use, coolant temperature, engine speed, and vehicle road speed. Figure 3 shows the principle of operation and an outline of the system.

Small hydraulic cylinders built in the rocker arms actuate small forked plates controlling spring-loaded plungers which act on the valve stem. Under normal operation the plunger is held rigidly by the plate, and the valve can be opened by the action of the rocker arm. When the cylinder is disabled, oil pressure pushes the fork so as to enable the plunger to pass through it. As a result, the valve remains closed while the plunger moves in

the rocker arm. With this system installed, improvements in fuel economy of 25% over the Japanese 10-mode city cycle, and 15% at constant 60 km/h are reported.

Intake and exhaust valve control using an on-board computer was applied to a 5.8 litre Ford V-8 vehicle, whose engine management systems were recalibrated to enable the engine to operate on the most efficient number of cylinders under all conditions(8). Again, the valve disablement system developed was similar to the Eaton system, allowing the engine to work on eight cylinders (hard acceleration), to zero cylinders under deceleration. Emission levels during transition periods between four and eight cylinder operation, under three different load conditions, showed an overall decrease in HC, CO and NOx levels in CSo mode under idle and light load conditions, with NOx increasing slightly under higher loads, as shown in Figure 4. A spike on the HC levels was also recorded as the engine was switched from four to eight cylinders, the severity of which was counteracted by the subsequent lower overall levels.

Research at the Institute of Vocational Training in Japan also showed that significant fuel economy gains are available at part load with valve deactivation, on a 6-cylinder S. I. engine(9). In particular, the power for activating the inlet and exhaust valves, and the pumping power for the inlet were measured and the results related to the decrease in fuel consumption by valve disablement. Simple fuel cut-off was also compared with valve disablement, and was found to be nearly as effective, as shown in Figure 5. It was also reported that idling on three cylinders decreased the level of vibration from the engine, thought to be due to the apparent volume increase of the inlet manifold for the active cylinders, adding to the slight increase in volumetric efficiency by the wider throttle opening required to maintain idle speed in the 3-cylinder mode.

Valve disablement, and also fuel shut-off, were tested on a Mercedes 5.0 litre V-8 engine equipped with electronic fuel injection(10, 11). This application featured a throttle compensation system whereby the relationship between the accelerator pedal angle, indicative of load requirement, and the angle of the throttle valve was governed by an electronic unit controlling a stepper motor. In this way, the throttle valve angle was adapted to the engine conditions, using engine speed as a parameter, as shown in Figure 6. The ECU also received signals from a number of sensors monitoring such engine parameters as speed, temperature and gear selected, activating the optimum number of cylinders between eight, six and four. Fuel consumption tests at idle, constant speed and urban driving, with both valve and fuel shut-off, resulted in the economy gains shown in Figure 7. In addition, reductions of approximately 30% in fuel consumption were achieved over the European 04 City Cycle.

The multi-displacement concept can be applied using valve disablement, or fuel cut-off. Due to the complexity, and the relatively small additional economy gains available by the former, the Ford Motor Co. chose the latter method in applying CSO to their 2.8 litre V-6 engine(12). The engine, equipped with Bosch L-Jetronic fuel injection, supplemented by Ford's own EEC IV engine management system, was essentially divided into two banks, each constituting a separate engine. The right bank, engine 1, operated full time, while the left bank, engine 2, came into operation at higher load demands.

Two separate inlet manifolds were used, each with its own intake on a twin-throttle body. It is here that this application of CSO is of importance, for the two throttle valves are controlled by a common camplate which is connected to the accelerator pedal. In this way the delivery of power from each engine is controlled automatically to provide smooth transition between three and six cylinder operation. Figure 8 shows the installation of the camplate.

As the accelerator pedal is depressed the camplate rotates, it opens the full-time engine 1 throttle up to an angle of 43 deg., corresponding to a camplate angle of 37 deg. At this point the engine 1 throttle begins to close as engine 2 throttle begins to open. At 67 deg. camplate rotation the two throttles are fully synchronized, and the engine behaves as a six-cylinder. This throttle valve relationship is illustrated in Figure 9.

The intake system for each engine was designed for optimum performance in the operating range of that engine. The engine management system controls all engine functions, including fuel injection to each cylinder, engine changeover and idle speed. With this system, separate ignition characteristics are provided for each engine, to ensure operation at peak efficiency. On the three-cylinder mode the throttle valve of the disabled engine is held open by a solenoid, so as to minimise pumping losses. When the throttle is closed and the vehicle decelerating, fuel cut-off takes place until engine speed drops to 1100 rpm, when engine 1 is switched on and the engine idles on three-cylinders. The idle speed in this case is slightly higher than normal, at 900 rpm.

It is reported that, despite the sophisticated control of this engine, it is essentially a three-cylinder engine under CSO mode. The effect on torque output, shown in Figure 10, caused certain excitations on the driveline of the test vehicle, calling for further research in the NVH aspect of the installation. However, fuel consumption gains experienced with this system, coupled with reasonable emission levels over the Euro 04 Cycle-shown in Figures 11 and 12 respectively, make this CSO system a future production possibility.

Another major motor manufacturer to use fuel cut-off for cylinder disablement is Alfa Romeo, with their 2.0 litre fuel injected engine(13, 14). In disablement mode, periodic switching occurs every 200 crankshaft revolutions between paired cylinders 1,4 and 2,3. This gives an even 360 deg. rotation between firing strokes, on the 4-cylinder engine. CSo is controlled by Alfa's Electronic Control Module (ECM), which also controls ignition timing. An outline of the system is shown in Figure 13.

Inputs to the EMC are from sensors for engine speed, throttle valve angle, and water, oil and air temperature. Four cylinder operation is maintained above 3,800 rpm and/or throttle angles beyond 40 deg. Engines equipped with this dual-mode system were fitted on a number of taxi cars, which reported fuel economy gains between 16% and 18%, compared with the standard-engined vehicles.

When cylinders are deactivated for a long period of time, the subsequent cooling, and possible oil accumulation in the combustion chamber tends to make reactivation of those cylinders a relatively slow process, with detrimental effects on both driveability and emissions in the form of unburned hydrocarbons. One way of minimising this effect is by cycling of the disabled cylinders, as in the dual-mode system described above. The BMW Motor Company however devised a system whereby the exhaust gases from the active cylinders are directed to the inlets of the disabled ones, in their 323i 6-cylinder engine fitted with CSo(15, 16).

The inlet manifolds of the front and rear 3-cylinder groups of the in-line engine are split, with separate throttles. Fuel injection and ignition is controlled separately by the BMW Motronic computer for each group of cylinders. In addition, the synchronisation of the two throttles is also automatic, for smooth power delivery under CSo. When three cylinders are disabled, exhaust gases bypass the throttle in the internally split manifold, and are used to fill the inactive cylinders. Apart from outside air, exhaust gases are particularly suitable for this purpose since, with increased throughput, their low density also reduces the pumping work of the disabled cylinders. Figure 14 shows the principle of this system. Fuel savings of up to 25% in the European 04 City Cycle test are reported with this system, with the vehicle operating on the three-cylinder mode for 85% of the time, under normal driving.

The same principle of exhaust gas recirculation, combined with cylinder disablement was one of the features shown in the Toyota FX-1 concept vehicle in 1984. A twin-turbocharged 24-valve six cylinder engine was equipped with the Company's Modulated Displacement System (MDS), which redirected exhaust gases to the three inactive cylinders, under fuel cut-off CSo. With this engine, Figure 15, fuel gains of more than 10% were obtained over the Japan 10 Mode emission test procedure.

The principle of dividing a large capacity engine into two smaller capacity ones, both operating at higher, and hence more efficient, loads than normal was also adopted by Porsche in their experimental V-8 engine(17). The 4.6 litre engine was split into two V-4 engines with separate inlet and exhaust systems, with cylinders 1-4-6-7 operating all the time, Figure 16.

This arrangement offers the advantage of each crank pin carrying one working and one non working cylinder, under CSo. This, while it provides for even firing intervals it also ensures even heat distribution along the engine under disablement mode. The fuel injection system is Bosch L-Jetronic utilizing twin airflow meters, one for each separate inlet manifold, with its own throttle. The synchronization of the twin throttles was accomplished by a camplate system, similar to that used by Ford in the 3 x 6 Engine. For engine 1 to operate efficiently at low engine speeds and engine 2 at the higher speed range of the engine, the two intake manifolds were designed accordingly, with longer inlet tracts for engine 1 resulting in more torque at low rpm. By differentiating valve lift curves, valve sizes and exhaust pipe configuration for each engine, this resulted in an engine that operates at virtually peak efficiency throughout its speed range.

In order for a CSo system to be viable, it has to offer, in addition to worthwhile fuel economy gains, acceptable emission levels for compliance with legislation in the market it is aimed for. In principle, the reduced exhaust gas volume from the engine under disablement, assuming constant exhaust quality, should relate to a corresponding decrease in pollutants. In practise however, increased levels of certain pollutants, such as NOx due to higher load operation and HC during reactivation of cut-off cylinders, have to be dealt with using additional measures. In the Porsche application these measures take the form of separate fuelling and ignition for each engine, and using the air throughput from the deactivated part of the engine to aid oxidisation of CO and the burning of residual HC in the exhaust, similar to an airpump system. For catalyst application the Company devised a twin-catalyst system, shown in Figure 16, each catalyst being fed with the exhaust from one engine. With this arrangement, during four-cylinder operation the exhaust gas from engine 1 is purified twice, with catalyst A in conjunction with the oxygen sensor acting as a 'three-way catalyst'. The system is adjusted so that catalyst A converts mainly NOx emissions, the remaining HC and CO emissions, together with air from engine 2 being post-oxidized in catalyst 2. At the same time, the hot gas from engine 1 preheats oxygen sensor B and catalyst B, prior to activation of sensor B on switching over from four to eight cylinder operation. In this way, a Porsche 928 vehicle fitted with such a system was able to comply with the 1980 Federal Emission Legislation, while returning a 23% fuel economy gain during the CVS City Cycle, with a 15% improvement in the Highway Test.

Finally, cylinder disablement has also been applied to the famous Jaguar V-12 engine, first by the Company and currently by an independent engineering concern(18). Taking advantage of the firing order of the V-12 -see Figure 1, one bank of cylinders is shut-off by deactivating those injectors. At the same time, the add-on control unit opens the throttle of that bank to minimise pumping losses and oil pull-over. Other refinements of this system include the widening of the initial injector pulses on reactivation of the disabled bank of cylinders, in order to give the cooler cylinders a rich mixture start, returning to normal injection timing soon after. The vacuum signal to the automatic gearbox is also regulated under CSo, to provoke early upchange points which would otherwise be occurring on light throttle with 12-cylinder operation.

One disadvantage with this system is the absence of automatic CSo control, the 6 or 12-cylinder running being selected by the driver via a foot switch. However, significant reductions in fuel consumption are reported with constant 6-cylinder operation, as shown in Figure 17.

From the work covered so far, it is clear that considerable gains in fuel economy are offered by the application of CSo on production S. I. engines. The concept of cylinder disablement can be implemented to its full extent by redesigning existing powerplants to operate constantly under higher, and hence more efficient loads. In addition, emission levels can be reduced by refining CSo control, and designing exhaust catalyst systems to take advantage of the increased throughput of air from the deactivated cylinders. Although systems of varying complexity have been devised to minimise the pumping losses of an engine with disabled cylinders, the application of even simple fuel cut-off, where one injector per cylinder is provided, can reduce the fuel consumption at part-load quite effectively.

The research programme covered in this Thesis was initiated by the author while undergoing Industrial Training at JAGUAR CARS Ltd., in the final year of the Automotive Engineering and Design course at L.U.T. During that period it was suggested to the Company that the final year project for the course could take the form of an investigation into cylinder disablement of the Company's 6 cylinder fuel injected engine, as a variation on earlier work on the V-12 engine, as mentioned above. As a result, on completion of the four-year course, it was also decided to continue the research on a part-time basis.

Consequently, and further to previous work covered in the Final Year Project Report by the author(academic year 1980-1981), the following objectives were set for the continuation of the work:

OBJECTIVES OF THIS RESEARCH

At the beginning of the research work, the following objectives were set:

(i) To establish a microprocessor-based system to enable selective cylinder disablement, via fuel shut-off, on an electronically fuel injected six cylinder S. I. engine.

(ii) To carry out tests, using the system, to establish the gains in fuel economy attainable with CSO.

(iii) To investigate the possibility of sequential cyl. disablement as a means of reducing vibration amplitude of the power unit on its mounts.

The investigation was carried out at the Transport Technology Department of Loughborough University of Technology, on an engine supplied by the Emission Control Development Department of JAGUAR CARS Ltd., Browns Lane Plant, Coventry. The research has taken the form of part-time attendance at L.U.T. with some of the work carried out at JAGUAR CARS Ltd., over the period January 1982 to December 1984.

The results of testing during that period, together with conclusions drawn and recommendations concerning further investigation are included in this Thesis. In addition, a paper was written on the subject, titled "The Application of a Microprocessor to Engine Cylinder Disablement" by Dr. G. G. Lucas, J. Hughes and A. Manias for the XX FISITA Congress in Vienna (6-11 May 1984), presented by Mr. Hughes and included in Appendix II.

3. EQUIPMENT AND TEST PROCEDURES

ENGINE

The engine used for this investigation is the Jaguar 6-cylinder XK6 unit, similar to that introduced in the XK120 Model in 1948. Through the years the basic design has remained largely unchanged, the engine used being of the following specification:

Number of cylinders	6 in-line
Bore	92.07 mm
Stroke	106 mm
Cubic capacity	4235 cc
Compression ratio	7.8:1
Ignition timing	14 deg. btdc. at idle
Firing order	1,5,3,6,2,4 No.1 at rear

The engine is of cast iron block construction, with aluminium alloy cylinder head and twin chain-driven overhead camshafts, acting directly on the inlet and exhaust valves. The test engine was fitted with a five-speed manual gearbox, with direct fourth and overdrive top gear ratios. Fuelling was by Bosch L-Jetronic electronic fuel injection, of the moving-flap air meter type, with conventional electronic ignition and throttle edge vacuum advance by Lucas distributor.

The fuel injection system is described in detail in Appendix III.

DYNAMOMETER INSTALLATION

The engine and gearbox were installed on a test bed equipped with an eddy current dynamometer of the following specification:

Dynamometer	'Heenan-Dynomatic' MkII
Maximum Volts	90 V dc.
Maximum Amps	8 A
Maximum bhp	300 at 6000 rpm.

A 'total loss' water cooling system was provided, and a Plint fuel measuring rig used to monitor fuel consumption, as shown in Figure 18. The re-routing of the fuel line from the injection pump to the fuel rail through the cooling water of the test bed was a necessary modification to cure fuel vapour-lock problems encountered during extensive engine testing, caused by high fuel temperatures.

Figure 19 shows the layout of the engine installation on the test bed, including the cylinder disablement control system and equipment for measuring and analysing engine vibration and cylinder pressures, as described below.

CYLINDER DISABLEMENT SYSTEM

The means of deactivating the injectors of individual cylinders took the form of opti-coupled silicon-controlled rectifiers (SCR), connected in series with the injectors. These act as electronic switches between each of the six injectors and the ECU. Figure 20 shows the circuitry involved, with side A being the control side, and side B connected in series with the injector power supply. These switches are convenient to use as they react very quickly allowing rapid switching of the injectors.

Optically Isolated S.C.R :

Diode (side A)	S.C.R (side B)
Max. Current 60 mA	300 mA (rms)
Max. Voltage 6 V	400 V
Isolation Voltage 1500 V	

The operation of the SCR is based on the fact that the only time side B allows current through it- thus activating the injector on signal from the ECU- is when there is a current flowing through side A. Once activated, side B remains conductive as long as there is a current flowing through it. It follows therefore, that by providing a controlled signal to side A, and by having one SCR per injector, cylinder disablement could be effected.

Initially, during the Final Year Project period of this work the control of the SCRs was achieved by a Hewlett Packard 2114B general purpose minicomputer, permitting interfacing with real-time devices. This system is shown in Figure 21, and proved adequate for initial work on CSo. For this investigation however, it was deemed necessary to utilise the flexibility, cost and space advantages offered by a modern microprocessor based controlled system for the disablement of cylinders, also being nearer to the concept of a production unit capable of installation in a vehicle.

The basis of the CSo system became therefore a microprocessor development system, forming part of the OPEN UNIVERSITY "Microprocessor Course for Engineers", a self-teaching course

undertaken in the early part of this research, first to gain knowledge in the field of microprocessor systems and programming in Assembly Language, and second to enable the use of the development board supplied in implementing CSO.

The development board, termed "HEKTOR", is based on the Toshiba TMP8085A new generation 8-bit parallel central processing unit, the product specification of which is detailed in Appendix IV. For programming there is 4K RAM available on the standard board, extended by 0.25 K of RAM with a specially designed and built interface board based on the Am8156 RAM and Input/Output chips (see Appendix IV), enabling HEKTOR to communicate with the SCRs, and hence with the injectors on the engine. A monitor, tape recorder and a printer completed the main CSO control system, as shown in Figure 22.

The interface chip provides three I/O ports A, B and C, of which port A is used for controlling the six SCRs. This control is achieved by the six least-significant bits of an 8-bit binary word output to the SCR. Using parallel connections between I/O port and SCR, word bit 0 represents 'injector-off', and bit 1 'injector-on', for example:

Hex	Binary	Effect
3F	00111111 =	All 6 cylinders active
38	00111000 =	First 3 cylinders 1,2,3 disabled

In this way, consecutive words stored in the computer memory represent cyclic disablement sequences, each sequence output to the SCRs occurring on arrival of an interrupt signal from the engine. This signal is provided by a slotted disk and an opto-switch mounted on the crankshaft damper (see Figure 19), incurring an interrupt once every revolution of the engine crankshaft, with other interrupts provided manually via the keyboard.

Since the Bosch fuel injection allows for one fuel injection per revolution of the engine, with all six injectors firing simultaneously and therefore delivering half the required amount of fuel (see Appendix III), it follows that for the disablement of an injector over the complete thermodynamic cycle of the engine- two revolutions of the crankshaft, a particular CSO sequence must be output twice consecutively. This was a result of obtaining an interrupt signal from the crankshaft, a more convenient place with this engine than the distributor or camshaft drives, either of which would give one interrupt signal per thermodynamic cycle. This was accepted for simplicity of the equipment, and is easily catered for by extra sequences in the memory.

The software for the CSo system was written in 8085 Assembler Language, and it was designed to allow the operator to input disablement sequences in direct binary form as described above, with the last six bits entered representing cylinders 'on' and 'off'. This input is converted to hexadecimal form and stored in memory for later retrieval and output to the SCRs, on command from the system. The process can also be reversed, with the program converting hex. to binary form, and displaying it as such on the monitor for inspection/alteration of the sequences. Although provision was made for an input from the throttle, representing load demand via throttle angle and utilising the A/D converter, limitations in HEKTOR's RAM capacity did not allow this to be implemented. Instead, the selection of CSo sequences was accomplished from the keyboard, by reading the voltage output from a throttle pot indicating throttle position. The cylinder disablement program and flowchart are shown in Figures 23 and 24 respectively, with a detailed description of the software given in Appendix V.

CYLINDER PRESSURE MEASUREMENT

In order to obtain information on the changes in cylinder pressures under different engine operating conditions, a KISTLER quartz type miniature pressure transducer was mounted on the cylinder head, communicating with the combustion chamber of cylinder No. 1 at the rear of the engine.

KISTLER Pressure Transducer

Measuring range	0 to 250 bar
Maximum pressure	350 bar
Sensitivity	14 pC/bar
Operating temperature range	-80 to 350 deg. C

(A complete specification and calibration is given in Appendix VI).

The signal from the pressure transducer was put through a KISTLER Type 5007 charge amplifier, and then passed through a A/D converter and stored in a LSI 11/23 microcomputer, for subsequent transfer to a PDP 11/34 minicomputer for analysis, as shown in Figure 19. This data logging system was set up by a research assistant also working on the project, Mr. J. Hughes, primarily for obtaining data on cylinder pressure waveforms in conjunction with an engine vibration simulation program written to predict engine vibration output, under CSo operation (see FISITA Paper in Appendix II).

The pressure inside the cylinder provided an excellent means of determining the effectiveness of injector deactivation as a way of disabling a cylinder, when observed against time and engine revolutions, and this was achieved by analysing the time-domain pressure characteristics, in a way similar to the vibration analysis method described below.

ENGINE VIBRATION MEASUREMENT

A means of comparing the effects of different disablement sequences on the engine vibration was required, and to this end a D.J.BIRCHALL konic general purpose accelerometer was used, mounted on the side of the cylinder head near the front of the engine and forward of the engine mounts, in a plane giving near maximum vibration amplitudes in yaw and roll, the most important factors in engine vibration isolation.

D.J.BIRCHALL A/20/T Accelerometer

Charge mode	Konic
Charge sensitivity	28 pC/g
Temperature range	-55 to 300 deg. C
Max. continuous sine accel.	1000 g

(The specification and calibration sheets are given in Appendix VII).

The accelerometer signal was amplified with a UNHOLTZ-DICKIE D22 Series Special Vibration Analysis charge amplifier, and then recorded with a SANGAMO 3500 tape recorder on 1 ins. magnetic tape. A calibration signal from a BRÜEL.KJÆR Type 4921 Accelerometer Calibrator was always recorded at the beginning of each session, the complete recording then passed through anti-aliasing filters and a A/D converter for input to the PDP 11/34 minicomputer.

Once in the computer, the vibration data were analysed using an available Frequency Analysis software package called 'DATS'. This package, in addition to offering sophisticated graphics facilities for displaying and plotting the data, it included a 'Auto Spectral Density' module (ASD) which was used for representing the vibration data in terms of amplitude with frequency. Figure 25 outlines the general procedure followed in logging and analysing vibration data. A number of problems were encountered in this area, mainly concerning charge amp drift characteristics causing a distortion of the mean amplitude value which should of course be zero. This necessitated correction of the mean value of the data files before display of the 'raw' vibration signal and subsequent ASD analysis.

TESTING PROCEDURES

Engine Performance

The nominal performance figures for the Jaguar XK4.2 Litre engine are given as:

Maximum Power 153 kW (205 bhp) at 5000 rpm

Maximum Torque 321 Nm (237 lbft) at 3750 rpm

Since cylinder disablement benefits lie within the idle to maximum torque speed range, the engine was tested at idle, 750 rpm, and between 1000 rpm and 4000 rpm. Standard engine testing procedures were followed, measuring the following parameters at constant engine speeds:

-Dynamometer Load W in lbs.

-Inlet Manifold Pressure τ in mmHg.

-Time taken for a given ammount
of fuel to be consumed t in sec.

The above procedure was repeated at 250 rpm increments and values for power, torque, brake mean effective pressure, and brake specific fuel consumption were calculated using the formulae detailed in Appendix I. The results were plotted to produce complete engine performance maps, both under normal 6-cylinder and CSo modes. A program was written to assist with the calculations, Figure 26, and the data for the engine performance maps were generated with a mainframe program developed at Jaguar Cars for the interpolation and cross-plotting of such data.

The road load curves superimposed on the maps represent the vehicle power requirements at steady speeds, and were obtained from the Road Load Data shown in Figure 27, for the Jaguar model fitted with this engine. From this information the load curves shown in Figure 28 were compiled, and include the corresponding dynamometer loads in both direct fourth and overdrive fifth gear ratios, only the former being used in the engine tests.

The engine performance was checked periodically on the test bed, and any necessary adjustments, including routine servicing, were carried out following Jaguar-specified procedures.

Cylinder Pressure and Vibration

Channels 1 and 2 on the SANGAMO 3500 recorder were used to record the accelerometer and pressure transducer outputs respectively, with voice channel A used for notation purposes. The signals were monitored at all times using a 4-channel storage oscilloscope, the recording procedure being as follows:

- (i) Warm up equipment before data acquisition
- (ii) Transducer sensitivities set on the charge amplifiers according to calibration curves-this was checked with the accelerometer using a calibrator.
- (iii) All connections Freon gas-sprayed, to minimise drift.
- (iv) Charge amp. time constant set to 'Long', giving minimum drift, and amp. set to 'Reset' mode when not sampling.
- (v) With the tape recording the charge amps. were set in 'Operate' mode for data sampling, and the recording played back and checked for attenuation errors, with any necessary adjustments to recorder gain and zero controls made.
- (vi) A calibration signal consisting of a pure sine wave of 100 Hz and ± 1 V peak amplitude was recorded at the beginning of each recording, and used as a baseline for any corrections necessary when later analysing the signals on the computer.
- (vii) Finally, the transducer signals were recorded and notes made of all equipment settings.

Pressure and vibration data were thus obtained under the following conditions:

a) Engine vibration at constant 45 kph and 80 kph, giving engine speeds of 1220 rpm and 2180 rpm in direct fourth gear and overdrive respectively, and at road load conditions with the engine operating on:

6	cylinders	
5	:	(No. 1 off)
4	:	(No. 1,6 off)
3	:	(No. 1,2,3 off)
2	:	(No. 1,2,5,6 off)

The results provided a means of comparing vibration amplitude levels of the major harmonics at two representative vehicle cruising speeds, and the engine under all CSo modes.

b) Cylinder pressures were obtained at various engine speeds and loads, within the operating range of CSo between idle and 4000 rpm, light to medium 6-cylinder loads, in order to study the following:

- (i) Cyclic variation in peak cylinder pressures
- (ii) Behaviour of a cylinder when its injector is deactivated and then reinstated.

Vehicle Testing

A Jaguar vehicle with an engine specification similar to the engine on the test bed was tested at the Emission Control Department of JAGUAR CARS Ltd., Coventry. The vehicle was fitted with a means of disabling the injectors on the engine, enabling operation on any combination of cylinders.

The test procedure followed was the standard European 04-Cycle Test, consisting of four identical consecutive driving cycles, as shown in Figure 29, with exhaust emission levels and fuel consumption recorded. The Test has two phases, one comprising of the combined results of the first and second cycles, and the other of the last two cycles, giving Bag 1 and Bag 2 emission and fuel consumption results. Normally the vehicle would be tested from a 'cold-start' condition, having been heat-soaked overnight at a controlled ambient of 25 deg. C. In this case however, it was required to compare results with the engine operating under first, all six cylinders, and then with cylinder cut-off in operation.

The test vehicle therefore was first fully warmed up on the rolling road, and then put through the Euro Test, running on all six cylinders for the first Bag, and on 3-cylinders(1,2,3) at idle and cruises, and 4-cylinders(1,2,5,6) for the accelerations in the driving Cycles, in the second Bag. The idle speed of the engine on 3-cylinders was maintained the same as for the 6-cyl. mode, at 750 rpm., by bypassing the extra-air valve(see Appendix III) with a controlled air bleed.

While the vehicle was fitted with CSo the opportunity was taken to assess the driveability under both steady-state and transient (acceleration) conditions on the road. The results and conclusions of these tests are included in the following Sections of the Thesis.

4. TEST RESULTS AND DISCUSSION

ENGINE PERFORMANCE RESULTS

The engine was tested following the procedures outlined earlier, and baseline 6-cylinder results obtained, followed by results with cylinder disablement applied by statically deactivating a number of cylinders from one to four, their positions determined according to the firing order of the engine so as to give as evenly spaced firing intervals as possible.

Figures 30 to 34 show the fuel consumption loops obtained, and by combining them with the full load torque curves the engine performance maps shown in Figures 35 to 39 were constructed, for the engine running on 6, 5, 4, 3 and 2 cylinders respectively.

The fuel economy advantages of CSo lie in the low-to-medium load areas of the operating range of the engine for the reasons discussed earlier, and this fact is clearly shown by comparing brake specific fuel consumption values in those areas with the engine operating under different modes of CSo. Further testing at these high b.s.f.c. gradients, under constant speed vehicle road load conditions (see Figure 27), yielded the following results :

ENGINE OPERATING MODE	VEHICLE SPEED km/hr.						
	50	60	70	80	90	100	110
6-cyl. b.s.f.c.	870	760	650	555	515	500	455
5-cyl. "	790	670	550	450	430	420	410
4-cyl. "	495	470	460	460	430	405	395
3-cyl. "	640	525	480	465	465	450	390
2-cyl. "	655	560	485	450	445	500	-

Note: b.s.f.c. values shown in g/kW hr.

From the figures above the fuel economy gains shown in Figure 40 are deduced, and the following points are apparent:

- (i) Higher fuel consumption gains are available with CSo at low speeds and loads.
- (ii) As more cylinders are disabled the economy gains tend to decrease, with the exception of 5-cylinder operation.

- (iii) With 5, 4 and 3-cylinder operation the decrease in economy gain is halted at 85 to 100 km/hr, and in the case of 3-cylinders it is reversed above those vehicle speeds.

The first and second points follow from the basic principle of cylinder disablement in that the effect of dethrottling the engine, and hence increasing its efficiency, is greater at low speeds and loads where normally the 6-cylinder engine runs on very small throttle openings. At higher speeds and loads, corresponding to wider throttle angles, the gains in efficiency available by dethrottling the engine with CSO are reduced to a point where the remaining active cylinders approach maximum power conditions. The extra fuel enrichment required at these conditions diminishes any fuel consumption benefits offered by cylinder deactivation.

As more cylinders are disabled the power required to overcome frictional losses in the engine tends to remain the same(1, 10). As a result, the dethrottling effect of disabling too few cylinders, giving small increases in throttle angle, may be partly offset by the proportional increase of the power required as a percentage of that delivered by the remaining cylinders, to overcome those frictional losses. The power lost from the disabled cylinders would tend to amplify that effect, until enough cylinders were deactivated, the subsequent greater dethrottling effect overcoming the effect of relative increased frictional losses. This could explain the reason for the relatively low economy increases returned with only 1 cylinder disabled at low speeds, as shown by the 5-cylinder curve in Figure 40.

The reason for the variation in economy gains at higher speeds, mentioned in the final point, can be traced to the operational principles of the fuel injection system, detailed in Appendix III.:

The air drawn in by the engine operating on all 6 cylinders passes through the air meter enabling the control unit of the injection system to calculate the optimum fuel requirements of the engine. When the injectors of some cylinders are deactivated the remaining active cylinders operate at a higher load, corresponding to a higher throughput of air through the air meter. Some of this air is drawn in by the inactive cylinders but the control unit calculates and delivers injector pulses as if all the cylinders are operating at the same load. However, if we assume that both active and disabled cylinders draw in the same volume of air per stroke, the calculated fuel requirement for each cylinder will be the same as the actual requirement since the injector pulse width is determined by the quantity of air drawn in per engine stroke. The active cylinders therefore will receive the correct amount of fuel, while the ECU pulses to the injectors of the disabled cylinders will have no effect.

A similar argument applies to the ignition advance delivered by the distributor under CSo, with the disabled cylinders receiving the correct advance for the speed and inlet manifold vacuum they are operating at.

Having made the reasonable assumption of equal air flows through both active and disabled cylinders, it is clear that this is only an approximation since factors such as effective inlet manifold volume and exhaust pipe configuration will change the resonant qualities of the engine, as all cylinders share a common inlet manifold and exhaust system. As a result it is believed that at certain engine speeds, the application of CSo causes a slightly wrong air/fuel mixture to be calculated by the ECU. If the main reason is due to inlet and exhaust system resonance characteristics as stated, then the discrepancies will be more apparent near maximum torque engine speeds, as indeed is the case in Figure 40.

Tests were carried out with the engine at idle to determine economies attainable with CSo at this condition. The results, shown in Figure 41, showed gains ranging from 14% to over 100% in idling with 5 cylinders and 1 cylinder respectively. The high levels of engine vibration experienced with only 1 cylinder active however, make the latter gain unattainable in practice, the engine idling with the least vibration amplitudes in the 3-cylinder mode, with either cylinders 1,2,3 or 4,5,6 active.

The engine was also tested with cyclic cylinder disablement, the number of disabled cylinders remaining the same, but their positions being varied every few cycles of the engine. It was found that as the cycling frequency approached half the engine speed frequency, that is the thermodynamic cycle frequency of the engine, power output began to fall-off slightly and specific fuel consumption increased. This was found to be the result of some cylinders receiving half the required fuel and consequently misfiring. The reason for this lies in the way the injectors are triggered (Appendix III). With the Bosch L-Jetronic injection, half the required fuel is delivered every revolution of the engine by all the injectors. With rapid CSo cycling therefore, some cylinders received half the required amount of fuel on either deactivation or reactivation, the result of the fuel injection timing and cyclic CSo not being synchronized on a cycle-to-cycle basis. If however, the cycling of cut-off cylinders was done after a few cycles were completed, it was found that the effect of this mis-timing was not apparent.

The position of the disabled cylinders was found to play a significant part in the Hydrocarbon emissions of the whole engine. For example, with the engine running on four cylinders, it was found that, out of the three possible CSo sequences based on the firing order, that is No.'s 1,6 or 2,5 or 3,4 cylinders

deactivated, the lowest overall HC levels were obtained with cylinders 3 and 4 disabled. This is thought to be due to the tendency of a disabled cylinder to draw-in fuel vapour present in the inlet manifold, this effect being more pronounced if the deactivated cylinders are surrounded by active cylinders than if they are next to each other. The small amount of fuel thus entering the inactive cylinder is not enough to form a combustible mixture, and it results in unburned Hydrocarbons in the exhaust gases.

CYLINDER DISABLEMENT AND REACTIVATION

The pressures inside cylinder No. 1 were measured and recorded, as described in the previous Section, in order to study the behaviour of a cylinder when its injector is deactivated while the engine is running. In particular, it was desirable to investigate any delays that may occur in reactivating the cylinder following both short and prolonged periods of disablement, with the view of adjusting rapid cyclic disablement sequences accordingly, in addition to the effects of injection and CSo asynchronicity discussed above.

Figure 42 shows a typical cylinder pressure diagram obtained during low speed, light load conditions. The four phases of the thermodynamic cycle of the engine are clearly shown, with the induction stroke A, compression B, firing with flame front reaching the transducer at C, and finally exhaust stroke D. The reason for pressure peak C being lower than the compression pressure peak B is that by the time the combustion pressure wave reaches the transducer, which was positioned some distance from the spark plug, the cylinder pressure has been reduced due to the downward travel of the piston on its power stroke. With better cylinder filling at higher loads the pressure peak due to the combustion is far higher than that of the compression pressure, as shown in Figure 43.

With CSo operative, the cylinders of the engine would be deactivated under light to medium loads, in order to incur higher load operation of the remaining cylinders. Pressure diagrams were taken therefore under these conditions, at speeds ranging from low idle (just over 600 rpm) to 3500 rpm, covering the operating range of CSo. The computer plots obtained are shown in Figures 44 to 50 for the deactivation of the cylinder, and Figures 51 to 57 for its reactivation under the same engine speeds and loads.

First, from the deactivation diagrams it was found that when the injector of the cylinder was deactivated, that cylinder was disabled on the following, and subsequent power strokes, with no delay apparent under all speeds and loads tested. Second, on reactivation the cylinder appeared to fire normally on the next power stroke, following induction with the injector re-enabled.

Also, subsequent power strokes showed no greater cycle-to-cycle pressure variation than under normal operation. This would tend to indicate that cylinder disablement by injector deactivation could be implemented with rapid cycling of the disabled cylinders, provided the sequences are synchronized with the fuel injection timing, as discussed earlier.

Finally, it was found that when the cylinder was inactive for prolonged periods, and at various engine speeds and loads, its reactivation was always instant. Under vehicle operation however, particularly with an engine which has covered high mileage, it is expected that oil pull-over by the disabled cylinder could cause spark plug fouling over repeated long periods of inactivity(18), in addition to excessive cooling of the cylinder walls, and resulting in misfire on reactivation.

ENGINE VIBRATION

The accelerometer signal was analysed using the Auto Spectral Density (ASD) Function available with "DATS" on the PDP 11/34 computer in the Department. The program uses ensemble averaging of Fourier Transforms of overlapping sections of the input data to compute the ASD of a real-time history (Appendix I). The ASD of a signal is the mean square value of the signal distributed as a function of frequency, the output being in Units²/ Hz. In this case, one Unit is equal to a 1g level of acceleration.

The highest frequency of the first harmonic of the vibration from a 6 cylinder engine with a top speed of 6000 rpm is:

$$\frac{6000}{60} \times \frac{1}{2} \times 6 = 300 \text{ Hz.}$$

The engine vibration frequency spectrum therefore was analysed in the 0 to 300 Hz range, with particular attention given to high amplitude-low frequency harmonics caused by cylinder deactivation, bearing in mind that the natural frequency of the Jaguar engine on its mounts is approximately 17 Hz.

The results of the frequency analyses are shown in the form of ASD diagrams in Figures 58 to 61, showing vibration levels at 1220 rpm-road load, and Figures 62 to 65 at 2180 rpm-road load, corresponding to actual vehicle speeds of 45 km/hr and 80 km/hr in direct 4th gear respectively, and with the engine under different CSo modes.

The mean square acceleration values can be thought of as proportional to displacement at those frequencies if the engine is treated as a simple mass suspended on springs. In order to compare vibration severity with various numbers of cylinders active, the m.s. acceleration levels of the major harmonics are square-rooted, and compared with the acceleration levels at those frequencies with normal 6-cylinder operation. When this is done, the following results are obtained:

Engine Operating Mode	Order of Harmonic	1220 rpm, 45 km/hr		2180 rpm, 80 km/hr	
		g	Hz	g	Hz
6-cylinders	1st	2.8	60	3.0	108
	2nd	1.4	120	1.5	216
5-cylinders	1st	4.0	10	2.7	18
	2nd	2.5	20	1.0	36
4-cylinders	1st	9.4	20	2.1	36
	2nd	2.8	40	1.0	72
3-cylinders	1st	8.8	30	3.2	54
	2nd	2.2	60	2.0	108
2-cylinders	1st	10.0	20	5.2	36
	2nd	5.3	40	1.7	72

From the acceleration levels shown it is clear that high amplitude harmonics are introduced at low frequencies even in the higher engine speed, when one cylinder is disabled. In this particular case, with the 1st major harmonic at 18 Hz for 5-cylinders running at 2180 rpm, the frequency is very close to the natural frequency of the engine on its mounts, and this was apparent during testing to obtain vibration signals at that speed, with the engine amplitude increasing as the resonant speed was reached. In contrast, the engine mounts performed well at higher frequencies even when the acceleration levels were high, as is the case with 3-cylinder operation at 1220 rpm.

As a result therefore, of observing engine vibration and relating those observations to the figures above, it can be stated that the engine could be operated under CSo with minimum penalties in excessive vibration if the major harmonic frequencies could be kept away from the natural frequency range of the mounting system, say 15 to 20 Hz.

3-cylinders		1 - 3 - 2 -
	or	- 5 - 6 - 4
2-cylinders		1 - - 6 - -
	or	- - 3 - - 4
	or	- 5 - - 2 -

We have therefore,

5-cyl. active:

$$D = 1 \quad \frac{N \times 1}{120} = 15 \text{ Hz}$$

Thus the lower engine speed limit is $N_L = 1800 \text{ rpm.}$

similarly, $\frac{N \times 1}{120} = 20 \text{ Hz}$ so $N_U = 2400 \text{ rpm.}$

4-cyl. active: $D = 2,$ $N_L = 900 \text{ rpm.}$

and $N_U = 1200 \text{ rpm.}$

3-cyl. active: $D = 3,$ $N_L = 600 \text{ rpm.}$

and $N_U = 800 \text{ rpm.}$

2-cyl. active: $D = 2$ (considering the lowest freq. harmonic)
 $N_L = 900 \text{ rpm.}$

and $N_U = 1200 \text{ rpm.}$

Since the second order harmonics occur at twice the first order frequency, the lower engine speed values are reduced by half. Furthermore, assuming the lowest practical engine speed is 600 rpm (low idle), and the maximum CSo operating engine speed is 3500 rpm, the operating ranges of CSo at various modes become:

5-cylinders range : 2400 to 3500 rpm.

4-cylinders " : 1200 to 3500 rpm.

3-cylinders " : 800 to 3500 rpm.

2-cylinders " : 1200 to 3500 rpm.

It can be seen that the above results could be stored in the microprocessor memory of the CSo system, and the appropriate number of cylinders disabled at any given speed and load, for minimum excitation of the engine on its mounts.

VEHICLE TEST RESULTS

Figure 66 shows the Results Sheet from the hot European 04-Cycle Emission Test carried out on the vehicle. Bag 1 and Bag 2 tests were completed under identical conditions except with Bag 2 CSo was operating, the vehicle running on 3 cylinders at idle and the light-load cruises part of the driving cycles, and 4 cylinders during accelerations, as described in the last Section.

Of importance are the figures for the mass emissions levels per Bag tested, of Hydrocarbons, Oxides of Nitrogen, and Carbon Monoxide constituents, and of course the overall fuel consumption figures per Bag.

The results show that fuel consumption with CSo was decreased from 13.3 mpg to 18.5 mpg, representing a gain in economy of 39%. This was achieved with the simple method of manually disabling the injectors from inside the vehicle, and periodically rotating the disabled cylinders in order to maintain similar temperatures on all cylinders during the test.

The emission levels show the following trends, with cylinder disablement in operation:

Hydrocarbons	HC : Increased by 24 %
Oxides of Nitrogen	NOx : Increased by 43 %
Carbon Monoxide	CO : Decreased by 38 %

Considering CO first, its reduction with CSo is due to the oxidisation effect, in the exhaust, of the extra air pumped by the inactive cylinders, the effect being similar to an air injection pump system. NOx increases are mainly due to the higher combustion temperatures experienced in the active cylinders working at higher loads, with NOx formation being aided by the presence of extra Oxygen in the exhaust.

The increases in the HC emissions can be attributed to various factors, stemming mainly from the simplicity of the method of implementing cylinder disablement in this case. The main reason is believed to be the drawing-in of fuel vapour, present in the inlet manifold, by the inactive cylinders. The air/fuel mixture thus formed is too weak to burn, and the result is high levels of unburned Hydrocarbons in the exhaust gas.

Another likely reason for the increase in HC is the possibility of the fuel injection system being slightly affected by the disablement of cylinders, as discussed earlier in this Section, resulting in mixtures varying either side of stoichiometric. This could be determined by looking at the fuelling of individual cylinders with CSo in operation, by way of sample

probes in the exhaust ports of the cylinder, and analysing its exhaust gas composition. This has not been done here due to time and equipment considerations.

Also, the condition of the engine in the vehicle tested was not very representative, the vehicle having covered high mileage on testing, as indicated by the high emission levels of Bag 1, under normal 6-cylinder operation.

Extensive research on CSo by other manufacturers however, has shown that it is possible to overcome the emission level increases due to CSo using current, well established emission control techniques(12, 15, 17).

Finally, the test vehicle was assessed for driveability with cylinder disablement in operation, both by the author and colleagues in the Engine and Powertrain Development Dept. of JAGUAR CARS Ltd. The results are purely subjective, based on the opinions of the drivers, some of whom carry out frequent driveability assessments on prototype and production vehicles as part of their function within the Company.

Following limited driving sessions, comparisons were made between driveability, throttle response and vibration levels felt from inside the vehicle first, on 6-cylinders, and then with cylinder disablement using the techniques described earlier. General conclusions reached included the following:

- (i) Unexpectedly low, and almost fully acceptable levels of vibration were experienced in the car, with CSo in operation, the most noticeable difference being the change in exhaust note, particularly under load.
- (ii) When cylinders were switched over, either to increase or decrease the number of active cylinders according to power requirements, the transitions were felt only slightly, similar to an automatic transmission gear change. If too many cylinders were switched over at high loads however, the change in engine power was more apparent.
- (iii) Even with manual transmission, any harshness due to engine torque fluctuations under CSo was well isolated by the engine mountings, at least at low vehicle speeds.
- (iv) With complete injector disablement under deceleration conditions with closed throttle, giving fuel cut-off on standard L-Jetronic injection, it was found that smooth engine reinstatement could be achieved by reactivating cylinders gradually, as engine speed approached idle. The result was similar to 'soft' reinstatement, a case where some injection systems weaken the mixture prior to full fuel injection reinstatement, to prevent vehicle 'shunt'.

5. CONCLUSIONS

CONCLUSIONS

The engine performance results have shown that a spark ignition engine, fitted with electronic fuel injection, can be made to return high fuel economy gains with the application of cylinder disablement. These gains are at their highest at idle, and the low-to-medium speed and load operating ranges of the engine, and represent fuel consumption reductions of an order otherwise unattainable without major redesign of the engine and its control systems.

From the results of this investigation into the application of cylinder disablement, the following conclusions can be drawn:

1. Fuel cut-off by the deactivation of the injectors on an engine with electronic fuel injection system, constitutes an effective means of dethrottling the engine at light loads.
2. The disablement, and subsequent reactivation of a cylinder by controlling its injector, appears to be instantaneous, under engine testing conditions; however, some delay could be experienced under actual driving conditions.
3. The L-Jetronic fuel injection system appears to compensate well for the deactivated cylinders in providing the correct fuelling to the active part of the engine, possibly requiring minor fuelling trim adjustments in order to keep the air/fuel mixture close to stoichiometric, at steady-state conditions.
4. The increase in specific load of the active cylinders, with the engine under CSo, can reduce the specific fuel consumption of the engine, from over 50% at idle to 20 - 40% approximately at light load, constant speed operation.
5. Engine vibration caused by CSo, can be reduced by:
 - (i) Arranging the disabled cylinders according to their firing order, to give evenly spaced firing intervals, and
 - (ii) Controlling the total number of disabled cylinders at any given engine speed, according to the findings of Section 4, to minimise excitation of the engine on its mounts.
6. Limited testing on a vehicle fitted with simple cylinder disablement showed the following:
 - (i) Fuel economy improvements of almost 40% are possible under city driving conditions.

- (ii) Increases in HC and NOx emissions experienced with CSo are of a relatively small order, and capable of being reduced to acceptable levels using existing emission control techniques, and better CSo control.
- (iii) Vibration levels experienced while driving the vehicle with CSo in operation, were very tolerable, suggesting that the implementation of CSo with a more refined, microprocessor-based system could result in the reduction of vibration to levels acceptable in a luxury passenger vehicle.

The use of a microprocessor development system in cylinder disablement showed the advantages of such a system in this application, namely:

- Flexibility and adaptability of the microprocessor system, giving the designer considerable freedom in tailoring the system to suit the exact requirements of the engine under CSo.
- Hardware compatibility with current and future engine management system, based on central processing units.
- Low unit cost and volume, making the system viable for mass production.

Considering cylinder disablement sequences, it has been shown that the number of active cylinders should be varied with engine speed for minimum vibration. In addition to this, the system could also provide rapid cyclic rotation of the disabled cylinders. However, that would introduce out of balance major harmonics at even lower frequencies, resulting in large amplitude vibrations as the natural frequency of the engine mounting system was approached.

As a result, it was concluded that rotation of the disabled cylinders, at all CSo modes, should occur periodically so as to maintain all cylinders warm, but without promoting further out of balance vibration. Thus, it is suggested that the rotating frequencies should be less than the minimum frequency that would cause vibration amplification, that is 15 Hz. In practice, it was found that the disabled cylinders could be cycled with a period of a few seconds, without detriment to engine performance and therefore avoiding further excitation of the engine on its mounts.

EXPANDING THE "HEKTOR" CSo SYSTEM

The HEKTOR microprocessor development system has the potential to form the basis for a sophisticated CSo system, provided its user memory is increased by at least a factor of 2, giving 8k RAM in total, as opposed to the 4.25 k RAM available at present. This increase in memory is necessary to accommodate the CSo program that would be required if all the features of CSo control suggested by the results of this research were to be incorporated into the system.

Figure 67 shows the next stage of the microprocessor system, suggested as a more complete CSo system for the engine tested.

Here, additional inputs to the microprocessor consist of engine coolant temperature, inlet manifold pressure, and a stepper motor position and actuation on the throttle valve, intervening with the physical link between the accelerator pedal and the throttle. The following method of cylinder disablement control is therefore suggested, based on the work covered:

The number of cylinders active at any time should be dependent on:

- (i) Engine Temperature
- (ii) Engine Speed
- (iii) Engine Load

The above parameters to be measured, and their effects on CSo control to be in the following way:

- (i) Engine Temperature : The desired effect of the engine temperature is to inhibit CSo when the engine is cold. To this end, a simple two-state temperature switch could be used in the engine coolant, providing a 'CSo-enable' signal to the microprocessor, once operating temperature is reached.
- (ii) Engine Speed : The current opto-switch arrangement on the engine could be used by the microprocessor for the calculation of engine speed, based on the time intervals between interrupts.
- (iii) Engine Load : The load requirements of the engine could be sensed by a pressure transducer in the inlet manifold, providing an analogue signal to the control system, which is proportional to manifold pressure and hence load.

Operation : With the CSo control system enabled by the signal

from (i), the number of cylinders could then be decided by the microprocessor based on the information from signals (ii) and (iii). The optimum number of cylinders would then be disabled according to tables stored in the system's memory, and compiled for the optimum fuel economy and vibration characteristics as described in Section 4 of this Thesis.

The wider throttle angles required when some cylinders are deactivated could be provided by the CSo system in a similar fashion, utilising a stepper motor connected to the throttle valve, and controlled by the microprocessor system. In this case, the accelerator pedal input to the throttle would be supplemented by the output of the stepper motor, effectively compensating for disabled cylinders automatically, without any driver input.

This throttle compensation system would require additional testing to determine optimum throttle positions for different CSo modes, and could also be used for increasing the engine speed when idling on say, three cylinders, by opening the throttle to a set position. Taking this concept further, this throttle compensation could be incorporated in a modern idle speed control system, as part of the engine management.

Finally, cylinder disablement control in this form could also be used with fuel injection systems utilising closed-loop feedback systems to maintain stoichiometric air/fuel ratio, Figure 68. With these systems a sensor is used to detect exhaust gas oxygen content, the sensor's voltage output characteristics being such that a step change in voltage occurs with a small change in oxygen concentration corresponding to either side of stoichiometric conditions. This voltage change is sensed by the injection control system, and is used to maintain correct fuelling at all driving conditions, this being necessary with exhaust catalytic converter applications.

In order for the oxygen sensor to operate effectively, its position in the exhaust system must be such as to allow the sensor(s) to detect a representative proportion of the exhaust gas from each cylinder of the engine, while at the same time being kept at operating temperatures, around 600 deg. C.

When CSo is applied to an engine with an oxygen sensor feedback system therefore, the extra air in the exhaust due to disabled cylinders will give the wrong information to the sensor, suggesting a very lean mixture and therefore resulting in incorrect fuelling to the active cylinders. This problem can be avoided in several ways, one method involving separate exhaust systems for the active and disabled parts of the engine(17). However, this method does not allow for rotating the disabled cylinders, as discussed earlier, and tends to be complex and expensive.

In the case of the Jaguar power unit used for this research, and

in common with most in-line 6 cylinder engines employing feedback systems, the oxygen sensor is positioned in the 'Y' junction of the exhaust down-pipe, near the exhaust manifolds and prior to the first catalyst, as shown in Figure 69. It is suggested therefore that, for CSo application the sensor is replaced with 2 sensors mounted slightly upstream of the 'Y' junction, each sensing exhaust gas from the front and rear 3-cylinder groups respectively.

The disablement modes in this case would allow for operation of the front cylinder group, cylinders 1,2,3, or the rear group 4,5,6, with the fuel injection control system switching between the appropriate oxygen sensors. Both sensors would be kept warm by periodic cycling of the cylinder groups.

This application of CSo is entirely in line with the findings of this research since the 3-cylinder CSo range extends, in terms of vibration qualities, from 800 rpm to the maximum operating CSo speed of 3500 rpm . The fuel economy benefits possible with 3 or 6 cylinders are still considerable, with maximum gains of 32% possible (see Section 4). The only disadvantage in this case would be the inability to switch individual cylinders gradually under power demand, and thus minimising torque fluctuations. One advantage gained by the use of CSo with catalyst systems is the air injection effect resulting from the pumping of the inactive cylinders, promoting oxidisation of exhaust pollutants.

With the world markets turning to lead-free fuels and catalysts for the passenger vehicles, in the interests of air pollution control, it is important that any fuel economy systems, researched for possible production applications in the future, take account of this trend. The cylinder disablement system suggested here could meet that requirement by the methods described above.

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FIGURES

V12

Firing Order:

1A, 6B, 5A, 2B, 3A, 4B,
6A, 1B, 2A, 5B, 4A, 3B **V8**

15486372

6

153624

4

1342

Fig 1 Disabled Cylinder Configurations on Various Engines
Based on Firing Order.

Valve Disablement

Mechanical (GM)

Fig 2 The EATON Valve Disablement Technique.

Hydraulic (Mitsubishi)

Fig 3 The Mitsubishi Colt Modulated Displacement System.

	<u>4 CYLINDER</u>	<u>8 CYLINDER</u>	<u>4 CYLINDER</u>
FUEL	.23	32	—
HC	.28	.47	—
CO	.29	.55	—
NO _x	.1	.1	—

Idle 600 rpm

(all mass flow values in grams per minute)

	<u>4 CYLINDER</u>	<u>8 CYLINDER</u>	<u>4 CYLINDER</u>
BSFC	290	350	—
BSHC	2.9	3.7	—
BSCO	2.8	4.3	—
BSNO _x	19	19	—

Light Acceleration
1400 rpm 120Nm

(all brake specific values in grams per kilowatt hour)

	<u>4 CYLINDER</u>	<u>8 CYLINDER</u>	<u>4 CYLINDER</u>
BSFC	305	395	—
BSHC	2.8	3.2	—
BSCO	3.9	7.1	—
BSNO _x	26	18	—

Road load
1800 rpm 100 Nm

(all brake specific values in grams per kilowatt hour)

Fig 4 Emissions from Ford 5.0L V8 with CSO

6 cyl S.I. engine

Fig 5 Six-cylinder 2L Engine Fuel Economy with Cso.

Mercedes Benz 500 SE

Fig 6 The Mercedes Cylinder Disablement System

FUEL CONSUMPTION L/100 km

IDLE CONSUMPTION L.

FUEL CONSUMPTION L/100 km.

Vso: Valve shut-off
Fso: Fuel shut-off

(Merc. Benz)

Fig 7 Mercedes Benz 500 SE Fuel Consumption

Fig 8 FORD 3X6 Throttle Body and Camplate.

Fig 9 FORD 3X6 Engine Throttle Pedal/Valve Angle Relationship.

Fig 10 FORD 3X6 Cso Effect on Torque.

**FE. Benefits -
ELA Mapping Points**

Fig 11 FORD 3X6 Fuel Economy Benefits.

Emission Effect -
ECE Cold Test

Fig 12 FORD 3X6 Euro-04 Cycle Emissions.

Fig 13 ALFA ROMEO 4X2 Cso System

BMW 323i

Fig 14 EGR System Combined with Cso. (BMW)

Twin Turbochargers with Intercooler System

Fig 15 The Toyota FX-1 Modulated Engine.

Fig 16 The Porsche V-8 CSo Mode and Emission Control.

Jaguar XJ12

Fig 17 Jaguar split-V12 Engine Fuel Economy Improvements

FIG 18 Fuel Supply System - LUT Test Bed

Fig 19 JAG 4.2L: LUT Test Bed Apparatus.

Fig 20 - Silicon-Controlled Rectifier (SCR)

Initial CSo System at L.U.T

1. ENGINE	7. INJECTOR POWER LINES
2. DYNAMOMETER	8. ELECTRONIC SWITCHES
3. MINICOMPUTER	9. ELEC. CONTROL UNIT
4. TELETYPE	10. INTERRUPT SIGNAL BUFFER
5. REV. COUNTER	11. PULSE SHAPER
6. FUEL FLOW METER	12. DISABLEMENT CONTROL SIGNALS

Fig 21. Stage 1. Minicomputer-based Cso (HP 2114B).

Fig 22. HEKTOR Microprocessor Development System.

```

;-----
;CYLINDER DISABLEMENT PROGRAM FOR 'HEKTOR' MICROPROCESSOR
;BOARD AND INTERFACE.
;DEVELOPED BY A. MANIAS AT LOUGHBOROUGH UNIVERSITY
;OF TECHNOLOGY 1984.
;(Written in 8085 Assembly Language).
;-----

```

```

;
KR: EQU 05BEH ; CHARACTER INPUT ROUTINE
TV: EQU 06COH ; DISPLAYS CHAR. IN REG. 'A'
PRSP: EQU 02E7H ; DISPLAYS SPACE
PRNL: EQU 02DAH ; CARR. RETURN-NEW LINE
PRB: EQU 035DH ; DISPLAYS 'A'
PRWD: EQU 0351H ; DISPLAYS 'HL' AS HEX
VEC: EQU 2F0DH ; EXTERNAL INTERRUPT ROUTINE

```

```

;
CALL PRNL

```

```

;
;HEADING PRINTING SUBROUTINE
;

```

```

MES: DB 'BINARY HEX ADDRESS@'
NOP
LXI H, MES
PRINT: MOV A, M
CPI '@'
CNZ TV
INX H
JNZ PRINT

```

```

;
;END OF PRINTING SUBROUTINE
;

```

```

CALL PRNL
LXI H, DATA ; DATA STORE ADDRESS(TOP)
START: NOP
MVI A, 00H ; CLEAR 'A' REGISTER
MVI B, 09 ; (COUNTER)
PUSH H
PUSH PSW

```

```

;
;DISABLING SEQUENCE SUBROUTINE
;

```

```

CHAR: DCR B ; DECREMENT COUNTER
CNZ TV ; DISPLAY INPUT
JNZ ZERO
POP PSW ; RETRIEVE 'A'
CALL PRSP
CALL PRSP
CALL PRSP
POP H ; RETRIEVE STORE ADDRESS
MOV M, A ; STORE 'A'
CALL PRB ; DISPLAY 'A' AS HEX
CALL PRSP
CALL PRSP
CALL PRSP
CALL PRWD ; DISPLAY STORE ADDRESS

```

```

INX H                ;INCREMENT STORE ADDRESS
CALL PRNL
JMP START           ;REPEAT FOR NEXT 'A'
;
;SUBROUTINES: CONVERTING HEX TO BINARY
;
ZERO: STC            ;SET CARRY TO 1
CMC                  ;CHANGE TO 0
CPI 30H              ;COMPARE 'A' WITH '0'
JNZ ONE
POP PSW              ;RETRIEVE 'A'
STC                  ;SET CARRY TO 1
CMC                  ;CHANGE TO 0
RLC                  ;ROTATE 'A' WITH CARRY
PUSH PSW
JMP CHAR             ;RETURN FOR NEXT BIT
;
ONE: STC             ;SET CARRY TO 0
CMC                  ;CHANGE TO 1
CPI 31H              ;COMPARE 'A' WITH '1'
JNZ ERR              ;(IDENTIFY ERROR)
POP PSW              ;RETRIEVE 'A'
STC                  ;SET CARRY TO '1'
RAL                  ;ROTATE 'A'
PUSH PSW
JMP CHAR             ;RETURN FOR NEXT BIT
;
ERR: CPI 52H         ;IDENTIFY 'RUN SEQ.' OPTION
JZ RUN
POP PSW
POP H
CALL PRNL
JMP START           ;IF ERROR RETYPE CHARACTER
;
;SUBROUTINES FOR SEQUENCE DATA RETRIEVAL
;
RUN: POP PSW         ;RETRIEVE DATA
POP H
LXI H, DATA        ;LOAD ADDRESS OF 1ST DATA
CALL PRNL
CALL PRNL
CALL PRNL
RDATA:MOV A, M       ;LOAD DATA
CPI 00H              ;TEST FOR END OF SEQUENCE
END
MVI B, 08            ;COUNTER FOR DISPLAYING BIN.
PUSH PSW
CALL PRWD            ;DISPLAY DATA STORE ADDRESS
CALL PRSP
CALL PRSP
POP PSW
;
;SUBROUTINES FOR DISPLAYING SEQ. IN BINARY FORM
;
BIN: RLC              ;IDENTIFY BIT AS '1' OR '0'

```

```

JC    ONE1
JNC   ZERO
CONT: INX    H           ;NEXT DATA STORE ADDRESS
CALL  PRNL
JMP   RDATA             ;(RETRIEVE NEXT SEQUENCE)
;
ONE1: PUSH PSW           ;(DISPLAY '1')
MVI   A, 31H
CALL  TV
POP   PSW
DCR   B
JNZ   BIN
JZ    CONT              ;RETURN FOR NEXT BIT
;
ZERO: PUSH PSW           ;(DISPLAY '0')
MVI   A, 30H
CALL  TV
POP   PSW
DCR   B
JNZ   BIN
JZ    CONT              ;RETURN FOR NEXT BIT
;
END:   CALL KR           ;INPUT CHARACTER
CPI   54H               ;IF 'T' GO TO TOP OF SEQUENCE
JZ    MES
CPI   4FH               ;IF 'O' OUTPUT SEQUENCE
JZ    OUT
CALL  PRNL
CALL  PRNL
JMP   START            ;OTHERWISE RETURN TO 'START'
;-----
;
;DISABLING SEQUENCE OUTPUT SUBROUTINES
;
OUT:   LXI   D, DATA    ;LOAD SEQUENCE
MAIN:  LXI   H, LOOP
SHLD  VEC              ;EXT. INTERRUPT SUB. ADDRESS
MVI   A, 19H           ;(I/O PORT INITIALISATION)
SIM
EI                      ;ENABLE INTERRUPT
JMP   MAIN
;
LOOP:  PUSH PSW
XCHG
MOV   A, M
CPI   00H
JZ    BEGIN
;(OUTPUT OF SEQUENCE)
XCHG
LXI   H, 0C000H
MVI   M, 0FH
INX   H
MOV   M, A
POP   PSW
RET

```


Fig 23. (Cont'd)

```
;
BEGIN:LXI  H, DATA ;(NEXT SEQUENCE)
MOV  A, M
JMP  CON
;
;-----
;
DATA: NOP           ;START OF DATA STORE ADDRESS
;
;-----
;END OF PROGRAM.
;-----
```

Fig 24 CSo Program Flowchart

Fig 25. Engine Vibration Data Analysis using
DATS Software on PDP11/34 Minicomputer.

```

(0001) C      PROGRAM JAGUAR
(0002) C
(0003)      DIMENSION REVS(100,5),WLBS(100,5),DTIME(100,5),POWER(100,5),
(0004) 1TORQUE(100,5),BSFC(100,5),A(100,5)
(0005) C
(0006)      READ(8,*)NN
(0007)      DO 30 J=1,5
(0008)      DO 10 I=1,NN
(0009)      READ(8,*)REVS(I,J),WLBS(I,J),DTIME(I,J)
(0010)      A(I,J)=REVS(I,J)*0.10472
(0011)      POWER(I,J)=(WLBS(I,J)*REVS(I,J))/536.41
(0012)      TORQUE(I,J)=(POWER(I,J)/A(I,J))*1000.0
(0013)      BSFC(I,J)=0.0373/(POWER(I,J)*DTIME(I,J))
(0014) 10 CONTINUE
(0015) C
(0016) C      PRINT OUT HEADINGS
(0017) C
(0018)      WRITE(7,100)
(0019) 100  FORMAT(1H1,' JAGUAR : CYLINDER DISABLEMENT : RESULTS',////)
(0020)      WRITE(7,200)
(0021) 200  FORMAT(' REVS : ENGINE SPEED(RPM)'' WLBS : BRAKE LOAD
(0022) 1(LBS)'' DTIME : TIME TAKEN FOR 50 MLS OF FUEL (SECS)''
(0023) 2' POWER : BRAKE POWER (KW)'' TORQUE: TORQUE(NM)''
(0024) 3' BSFC : BRAKE SPECIFIC FUEL CONSUMPTION (KG/KW.SECONDS)')
(0025)      WRITE(7,250)
(0026) 250  FORMAT(///' ENG. SPEED',8X,'BRK. LOAD',8X,'D.TIME',16X,'BRK.POWER
(0027) 1',5X,'ENG. TORQUE',3X,'BK.SP.F.C.'///)
(0028) C
(0029)      DO 20 I=1,NN
(0030)      WRITE(7,300)REVS(I,J),WLBS(I,J),DTIME(I,J),POWER(I,J),TORQUE(I,J)
(0031) 1,BSFC(I,J)
(0032) 300  FORMAT(//F10.2,5X),10X,2(F10.2,5X),E10.3)
(0033) 20 CONTINUE
(0034) 30 CONTINUE
(0035) C
(0036) C      GRAPH PLOTS
(0037) C
(0038) C
(0039)      CALL CIOFILN
(0040)      CALL FICOLE
(0041)      CALL PENSEL(1,0.,0)
(0042)      CALL AXIPLO(0,0.,0.,1,1,3,2,900.,3600.,0.,100.,
(0043) 1'REVE(RPM)',9,'P(KW)',5)
(0044)      CALL PLOTS(REVS,POWER,NN)
(0045)      CALL CHAMED
(0046)      READ(1,*)

```

Fig26.L.U.T Mainframe Results Calculations Program (PRIME).

```

(0047)      CALL PICCLE
(0048)  C
(0049)      CALL AXIPLD(0.0,0.,1,1,3,3,900.,3600.,50.,300.,
(0050)      1'REVS(RPM)',9,'TORQ(NM)',8)
(0051)      CALL PLOTS(REVS,TORQUE,NN)
(0052)      CALL CHAMOD
(0053)      READ(1,*)
(0054)      CALL PICCLE
(0055)  C
(0056)      CALL AXIPLD(0.0,0.,1,1,3,2,900.,3600.,0.00005,0.00015,
(0057)      1'REVS(RPM)',9,'BSFC',4)
(0058)      CALL PLOTS(REVS,BSFC,NN)
(0059)      CALL CHAMOD
(0060)      READ(1,*)
(0061)      CALL PICCLE
(0062)  C
(0063)      CALL AXIPLD(0.0,0.,1,1,4,2,0.,100.,0.00005,0.00015,
(0064)      1'POWER(KW)',9,'BSFC',4)
(0065)      CALL PLOTS2(POWER,BSFC,NN)
(0066)      CALL CHAMOD
(0067)      READ(1,*)
(0068)      CALL DEVEND
(0069)      CALL EXIT
(0070)      END
(0071)  C
(0072)  C
(0073)      SUBROUTINE PLOTS(XMAT,YMAT,N)
(0074)  C
(0075)      DIMENSION XMAT(100,5),YMAT(100,5),X(100),Y(100),ISYM(5)
(0076)      DATA ISYM/3,4,5,6,7/
(0077)  C
(0078)      DO 10 J=1,5
(0079)      NSYM=ISYM(J)
(0080)      DO 20 I=1,N
(0081)      X(I)=XMAT(I,J)
(0082)      Y(I)=YMAT(I,J)
(0083)  20  CONTINUE
(0084)      CALL GRASYM(X,Y,N,NSYM,0)
(0085)      CALL GRACUR(X,Y,N)
(0086)      CALL GRID(3,1,1)
(0087)  10  CONTINUE
(0088)      RETURN
(0089)      END
(0090)  C
(0091)      SUBROUTINE PLOTS2(XMAT,YMAT,N)
(0092)  C
(0093)      DIMENSION XMAT(100,5),YMAT(100,5),X(100),Y(100),ISYM(5)
(0094)  C
(0095)      DATA ISYM/3,4,5,6,7/
(0096)      DO 10 I=1,5
(0097)      NSYM=ISYM(I)
(0098)      DO 20 J=1,N
(0099)      X(J)=XMAT(J,I)
(0100)      Y(J)=YMAT(J,I)
(0101)  20  CONTINUE
(0102)      CALL GRASYM(X,Y,N,NSYM,0)
(0103)      CALL GRACUR(X,Y,N)
(0104)      CALL GRID(3,1,1)
(0105)  10  CONTINUE
(0106)      RETURN
(0107)      END
(0108)  C

```

Fig26. (Cont'd)

VEHICLE : JAGUAR 4.2 Litre Manual, 3.31 Final Drive
Direct 4th Gear and Overdrive Top.

<u>mph</u>	<u>hp-4th</u>	<u>rpm-4th</u>	<u>hp-5th</u>	<u>rpm-5th</u>
10	1.66	435	1.71	365
20	3.76	870	3.88	725
30	6.72	1305	6.93	1090
40	10.98	1740	11.33	1450
50	17.02	2180	17.50	1815
60	25.36	2615	26.17	2180
70	36.31	3050	37.47	2540
80	50.49	3485	52.10	2905
90	68.30	3920	70.45	3265
100	90.27	4355	93.15	3630
110	118.13	4790	121.91	3990
120	155.39	5225	160.35	4355

Fig 27 Road Load and Engine Speed Data - Jaguar 4.2L.

Fig28.JAG 4.2L: Road Load Curves in 4th and O/D Gears.

Operating cycle for the type I test

Fig 29. European Emission Test - Single Cycle

Fig30. Fuel
Consumption
Loops

Fig31.Fuel Consumption Loops

Fig: 32. Fuel Consumption Loops

Fig:33. Fuel Consumption Loops

Fig: 34. Fuel Consumption Curves

Fig 35. JAG 4.2L: Six-cylinder Engine Performance Map.

Fig36.JAG 4.2L: Five-cyl. Engine Performance Map.

Fig37. JAG 4.2L: Four-cyl. Engine Performance Map.

Fig 38. JAG 4.2L: Three-cyl Engine Performance Map

Fig 39. JAG 4.2L: Two-cyl Engine Performance Map

% FUEL ECONOMY GAIN

Fig40. Constant Speed Fuel Economy Gains at Vehicle Road Loads in Direct 4th Gear Ratio.

Fig44.JAG 4.2L: Cso Economy at Idle.

Fig 42 Single Cycle Cylinder Pressure Diagram - 1.

Fig 43 Single Cycle Cylinder Pressure Diagram - 2.

Fig44.Cylinder Deactivation - 1 (P1OFF)

Fig45.Cylinder Deactivation - 2 (P2OFF)

Fig46. Cylinder Deactivation - 3 (P3OFF)

Fig47. Cylinder Deactivation - 4 (P4OFF)

Fig 48. Cylinder Deactivation - 5 (P5OFF)

Fig49. Cylinder Deactivation - 6 (P6OFF)

Fig 50. Cylinder Deactivation - 7 (P7OFF)

Fig51.Cylinder Reactivation - 1 (P1ON)

Fig52.Cylinder Reactivation - 2 (P2ON)

Fig 53. Cylinder Reactivation - 3 (P3ON)

Fig 54. Cylinder Reactivation - 4 (P40N)

Fig55.Cylinder Reactivation - 5 (P50N).

Fig56. Cylinder Reactivation - 6 (P60N)

Fig57. Cylinder Reactivation - 7 (P70N)

6cyl

A**2/Hz

5cyl

A**2/Hz

Figure 58

6cyl.

A**2/Hz

4cyl.

A**2/Hz

Figure 59

6cyl.

A**2/Hz

3cyl.

A**2/Hz

Figure 60

6cyl.

A**2/Hz

2cyl.

A**2/Hz

Figure 61

A.S.D GRAPH @ 80 kph.

6cyl.

A**2/Hz

5cyl

A**2/Hz

Figure 62

6cyl.

A**2/Hz

4cyl.

A**2/Hz

Figure 63

6cyl.

$A \times X^2 / Hz$

3cyl.

$A \times X^2 / Hz$

Figure 64

6cyl.

A**2/Hz

2cyl

A**2/Hz

Figure 65

JAGUAR ENGINEERING -- JAGUAR CARS Ltd.
EMISSION CONTROL DEPARTMENT

EMISSION TEST NO. E4 7 9106
=====

30-1-85
=====

VEHICLE NO.	XJ31/60 CSO	BARO. (IN. HG.)	29.822	NOX FACTOR	0.8772	CONSINE	DYNAMOMETER
ODOMETER	MILES	WET BULB	16.5	REL HUMIDITY	25.9%	HOR 1002	SAMPLER
INERTIA WT.	LBS.	DRY BULB	29.0			NO. 7	ANALYSER
DYNO. H.P.		VAP. PRESSURE	1.18 IN HG.				

BAG 1	1.28 MILES	2.05KMS.	VMIX =	2069.6	CU. FT.	DILUTION FACTOR	14.6		
		EXHAUST SAMPLE	BACKGROUND SAMPLE		CORRECTED	MASS EMISSIONS		CONSUMPTION	
	RANGE	CHART	CHART	CONC.	CONCENTRATIONS	GMS. (BAG)		ML/GAL	LTR/100KM
HC	0 - 300 PPM	65.6	193.04	6.0	17.62	176.63	6.41	13.2768	21.2759
NOX	0 - 100 PPM	25.8	25.99	0.7	0.72	25.32	2.67		
CO	0 - 3000PPM	73.0	1382.59	1.2	8.36	1374.80	100.67		
CO2	0 - 3 %	34.2	0.76	2.5	0.05	0.72	829.09		

BAG 2	1.27 MILES	2.04KMS.	VMIX =	2075.2	CU. FT.	DILUTION FACTOR	19.9		
		EXHAUST SAMPLE	BACKGROUND SAMPLE		CORRECTED	MASS EMISSIONS		CONSUMPTION	
	RANGE	CHART	CHART	CONC.	CONCENTRATIONS	GMS. (BAG)		ML/GAL	LTR/100KM
HC	0 - 300 PPM	83.0	244.08	9.0	26.45	218.96	7.96	18.4782	15.2870
NOX	0 - 100 PPM	37.5	37.53	1.3	1.34	36.26	3.84		
CO	0 - 1000PPM	88.0	856.51	2.0	12.60	844.55	62.01		
CO2	0 - 3 %	26.5	0.56	2.5	0.05	0.52	601.28		

OVERALL RESULT
=====

	HC	NOX	HC+NOX	CO	CO2	ML/GAL	LTR/100KM.
	(	GM.	PER	TEST	)		
BAG 1	6.40620	2.6711	9.07730	100.671	829.09		
BAG 2	7.96286	3.8361	11.79896	62.010	601.28		
	-----	-----	-----	-----	-----		
	14.36906	6.5072	20.87625	162.681	1430.36	15.4515	18.2815

Fig 66. Emission Results from HOT EURO O4 test:
Bag 1: 6 cylinders, Bag 2: 3,4 cylinder active

Fig 67, Stage 2. Microprocessor-based Cso

Fig 68 Oxygen Sensor Feedback System .

Fig 69 4.2XK Downpipe Catalyst Modofication with CSo.

APPENDICES

APPENDIX I

Formulae for calculating the performance characteristics of an engine(22) :

$$(i) \text{ Brake power output } P = \frac{W \times N}{K_1}$$

where: W = Brake Load (lbs.)
 N = Engine Speed (rpm)
 K_1 = Brake Constant = 400 for bhp
 = 536.41 for kW

$$(ii) \text{ Torque output } T = W \times K_2$$

where: K_2 = Constant = 13.13 for lbft
 = 17.802 for Nm

$$(iii) \text{ Brake mean effective pressure (BMEP)}$$

$$\text{BMEP} = W \times \frac{K_3}{n}$$

where: K_3 = Constant = 317477 for N/m²
 = 46.046 for psi
 n = No. of Active Cylinders

$$(iv) \text{ Brake specific fuel consumption (BSFC)}$$

$$\text{BSFC} = \frac{134280}{P \times t} \quad \text{g / kW hr.}$$

where: t = Time for Consumption of
 50 ml of Fuel, in sec.
 P = Brake Power, in kW

or

$$\text{BSFC} = \frac{296}{P \times t} \quad \text{lbs / bhp hr.}$$

where: P = Brake Power, in bhp

Correction Factor:

$$C = \frac{29.92}{BR} \times \sqrt{\frac{460 + TP}{520}}$$

where: TP = Air Inlet Temperature, in deg F
 BR = Atmospheric Pressure, in ins. Hg

Auto Spectral Density

The Auto Spectral Density of a signal is the mean square value of the signal distributed as a function of frequency. In common with other densities derived from sampled data, it is a discrete quantity having the dimensions of Units²/ Hz. The overall mean square value therefore, is given by the sum of all the individual frequency components.

The mean square value, $\bar{x}^2$, of a signal $x(t)$, over a finite time T is given by

$$\bar{x}^2 = \frac{1}{T} \int_0^T x^2(t) dt.$$

Similarly, the mean square value may be represented as a distribution over frequency, giving the Spectral Density function $G_{xx}(f)$, where

$$\bar{x}^2 = \int_0^{\infty} G_{xx}(f) df.$$

This formula leads to one method of estimating the Spectral Density function by filtering the signal between two frequencies, f_1 and f_2 , and forming the mean square level of the output.

Hence,

$$\bar{x}^2(f_1, f_2) = \int_{f_1}^{f_2} G_{xx}(f) df.$$

An estimate of $G(f)$ can therefore be given by

$$\hat{G}_{xx}(f_1) = \frac{\bar{x}^2(f_1, f_2)}{f_1 - f_2}$$

This method of estimation shows that a A.S.D. has dimensions of Units²/ Hz, and that the method of estimating the S. D. function may be considered a filtering operation.

APPENDIX II

This section contains a paper written by Dr. G. G. Lucas, Mr. J. Hughes and the author, for the XX FISITA Congress held in Vienna on 6-11 May 1984, titled " The Application of a Microprocessor to engine cylinder disablement" and based on work covered in this Thesis.

The Application of a Microprocessor to engine cylinder disablement.

Application d'un microprocesseur à un moteur avec mise hors de Service de Cylindres

Die Anwendung eines Mikroprozessors zum Unbrauchbarmachen eines Autozylinders.

H.G. Lucas, J. Hughes and A. Manias.

The use of the throttle valve in the intake of the spark ignition engine is one reason for the lower part load efficiency of this engine when compared with the compression ignition engine. The need for the throttle valve can be avoided by the disablement of individual cylinders.

A microprocessor is being used to operate on the fuel injection to the inlet ports as a means to disable the cylinders. It is being programmed such that the cylinders disabled, cycle by cycle, can be varied in order to keep all the cylinders hot and to minimise the amplitude of the vibrations of the power unit on its mountings. Further, the number of cylinders disabled, cycle by cycle, can be varied in order to provide a fine control of engine power output.

The control system is described and the results of the experimental test work are presented. The paper also contains the theoretical modelling of the dynamics of the power unit on its mountings excited by the range of forcing torques expected from an engine with disabled cylinders. A six degree of freedom model is being used.

L'utilisation de la soupape d'accélérateur dans l'admission de l'allumage d'étincelle du moteur est une cause d'un plus bas rendement d'une partie de la charge de ce moteur quand on compare avec le moteur à allumage à compression. L'utilisation de la soupape d'accélérateur peut être évitée par la mise hors de service des cylindres séparément.

Un microprocesseur est utilisé pour agir sur l'injection du carburant aux pipes d'admission comme moyen pour mettre hors de service les cylindres. Il est programmé de telle manière que les cylindres mis hors de service, cycle après cycle, peuvent être changés dans le but de conserver tous les cylindres chauds et de minimiser l'amplitude des vibrations de l'unité de puissance sur ses supports. De plus, nombre des cylindres mis hors de service, cycle après cycle, peut être changé pour fournir un contrôle fin de la puissance de sortie du moteur. Dans le document le système de contrôle est décrit et les résultats des travaux expérimentaux sont présentés. Le document traite aussi le modèle théorique du comportement dynamique de l'unité de puissance sur ses supports excitée par une gamme de forces de torsion qui pourraient être produites par un moteur avec cylindres mis hors de service. Un modèle à six (6) degrés de liberté est utilisé.

Einer der Gründe für die geringere Ladefähigkeit dieses Motors im Vergleich mit dem der des Kompressionmotors ist der Gebrauch der Drosselklappe während der Aufnahme der Zündung des Verbrennungsmotors. Das Bedürfnis für eine Drosselklappe kann durch das Unbrauchbarmachen der einzelnen Zylinder verhindert werden.

Ein Mikroprozessor wird verwendet, um die Brennstoffeinspritzung in die Einlasshäfen laufen zu lassen, und dadurch die Zylinder unbrauchbar macht. Er ist so programmiert, daß die unbrauchbaren Zylinder, Motortakt nach Motortakt, variiert werden. Können sodaß alle Zylinder heiß bleiben, und damit die Amplitude der Vibrationen des Triebwerkes auf deren Motorträgern auf ein Minimum gebracht werden. Weiters kann die Anzahl der unbrauchbargemachten Zylinder, takt nach takt, variiert werden um eine genaue Kontrolle der Maschinenleistung sicher zu stellen.

Das Kontrollsystem ist beschrieben, und die Resultate der Experimentabprüfungen liegen auch vor. Die Abhandlung beinhaltet auch die theoretische Vorgabe der Dynamik des Triebwerkes auf deren Motorträgern, erregt durch die Reihe von Führungsrehkräften die von einem Motor mit unbrauchbargemachten Zylindern erwartet wird. Ein sechsfreies Freiheitsmodell wird dabei verwendet.

Lucas, Hughes and Manias.

ABSTRACT

The use of the throttle valve in the intake of the spark ignition engine is one reason for the lower part load efficiency of this engine when compared with the compression ignition engine. The need for the throttle valve can be avoided by the disablement of individual cylinders.

A microprocessor is being used to operate on the fuel injection to the inlet ports as a means to disable the cylinders. It is being programmed such that the cylinders disabled, cycle by cycle, can be varied in order to keep all the cylinders hot and to minimise the amplitude of the vibrations of the power unit on its mountings. Further, the number of cylinders disabled, cycle by cycle, can be varied in order to provide a fine control of engine power output.

The control system is described and the results of the experimental test work are presented. The paper also contains the theoretical modelling of the dynamics of the power unit on its mountings excited by the range of forcing torques expected from an engine with disabled cylinders. A six degree of freedom model is being used.

INTRODUCTION

The usual method of controlling the power output of the spark ignition engine is by throttling the intake. This has the effect of increasing the pumping losses and the proportion of energy to the coolant at low load. These engines therefore, when installed in passenger vehicles, spend the majority of their lives operating at a relatively low efficiency.

One way of increasing the economy range of the multi-cylinder S.I. engine is to allow the engine to operate on fewer cylinders at part-load. The increase in throttle angle required to compensate for the reduction in power has the effect of "dethrottling" the active cylinders, increasing the volumetric efficiency and decreasing the brake specific fuel consumption.

Several systems have been developed to selectively deactivate cylinders by several manufacturers in the past.

Eaton Corporation (1)* developed an electro-mechanical system which could disable the inlet and exhaust valves, increasing fuel economy by up to 25% when "driving" and 40% at idle. Bates, Dodsall and Smith (2) show that a V6 engine using this valve disabling system could operate on any number of cylinders. They reported fuel economy gains of up to 15% without degrading overall performance. Daimler-Benz AG (3) (4) developed electronically controlled systems enabling a V6-6-4 operation with fuel savings of up to 28% on the ICE cycle. Ford (5) showed that a V6 engine could be split, effectively, into two three-cylinder engines with separate intake systems, affording a fuel economy of 20% on the ICE cycle, with reasonable noise, vibration and harshness levels. Both Alfa Romeo (6) and Mitsubishi (7) have developed four-cylinder engines capable of operating on two cylinders, the former using fuel cut off and the facility to switch active and 'dead' cylinders at predetermined intervals. BMW (8), (9) utilise hot exhaust gases diverted into three deactivated cylinders of their six-cylinder engines, in order to keep these cylinders warm. The system has achieved a 25% economy gain over the European urban cycle. Watanabe and Fukutani (10) found also that six-cylinder engine vibration could be reduced at idle with three-cycle operation.

These investigations have, to date, adopted a rather conservative approach to engine cylinder disablement. Manufacturers have been content to disable three cylinders of a six cylinder engine or, as in the case of Alfa Romeo, to disable two cylinders of a four cylinder engine. The reason for this is simple; if a number of cylinders other than half the total number in the engine is disabled the vibration of the engine becomes unacceptable.

The use of a microprocessor to disable cylinders, either by operation on the fuel injection system or on the valve gear, provides the possibility of any disablement sequence to be used. The number of cylinders disabled, cycle-by-cycle, may also be varied to provide a fine control of power output.

In this paper, the effects of cylinder disablement on the performance map of the engine and on engine vibration are shown. A six degree of freedom model of the engine vibrating on its mounts is also discussed with a view to its use in minimising the increases in engine vibration.

* Number in parentheses designate references at end of paper.

FIGURE 1. TEST EQUIPMENT

TEST EQUIPMENT

The engine used for this investigation was a Jaguar XK6 six cylinder twin overhead camshaft engine, equipped with Bosch L-Jetronic electronic fuel injection system, the latter being an air-flow based system. The engine specification is listed in Table 1, and the layout of the equipment used is shown in Fig.1.

Table 1 - General specification of Test Power Unit

Jaguar XK6 4.2L Low Compression engine	
No. of cylinders	6 in line
Fuelling	Bosch L-Jetronic
Compression ratio	7.8:1
Rated Power Output	153 kW @ 5000 rpm
Rated Torque Output	321 Nm @ 3750 rpm

The engine was mounted on a test bed having an eddy current dynamometer, equipped with speed control. The special engine instrumentation consisted of a Kistler pressure transducer communicating with the engine combustion chamber and a D.J. Birchell accelerometer mounted on the outside of the head. A slotted disc was mounted on the crankshaft forward of the engine pulley to provide a t.d.c. indicator. A laboratory standard tape recorder was used to record the accelerometer output. The signal being then passed through anti-aliasing filters and an analogue/digital converter into the Department's POP 11/34 computer.

The disablement control system

Engine cylinder disablement was achieved by switching off the current supply to the fuel injectors. No attempt was made to operate on the rather compactly designed twin overhead camshaft valve gear system. Electronic Opto-coupled SCR's were mounted in the leads between the normal control system, which was not modified, and the individual injectors. These SCR's were operated, through a suitable interface, by an Intel 8085 based microprocessor development system. Fig.2 shows the system schematically. The slotted disc mounted on the crankshaft pulley in conjunction with an opto-switch provided the interrupt signal to the microprocessor.

The disablement program used as data a series of 6 bit

FIGURE 2. DISABLEMENT CONTROL SYSTEM

binary numbers, the six least significant bits of each being used to operate the SCR's. Any number of engine thermodynamic cycles, within the capacity of the microcomputer's memory, could be accommodated in the sequence. The series of binary numbers was terminated by a row of zeros, signifying a return to the start of the series and a repeat of the sequence. In this manner, any combination of the number of cylinders disabled cycle by cycle and any number of cycles in the sequence could be provided.

Such an arrangement is versatile and ideal for research purposes. The software arrangement of a practical, production system will be, of necessity, much more complex. Some idea of the factors which a practical system will have to accommodate are given in Appendix 1.

Discussion of Engine Test Results

The number of cylinders disabled was varied from one to four. In each case the disabled cylinders were both cycled and held fixed. No difference in power output or fuel consumption was discerned when cycling the disabled cylinders except when the frequency of the cyclic rotation approached the frequency of the thermodynamic cycles of the engine. At such frequencies the deactivated cylinders tended to fire occasionally, particularly at low loads, due to the presence of fuel vapour in the manifold.

In the tests the speed, load and number of cylinders firing were varied, measurements being made of fuel flow rate and vibration. The performance maps were plotted from these data and appear as figure 3. A cursory glance at a few points along a typical load line drawn shows that it is in the areas of steep gradient of the specific fuel consumption contours that the benefits of cylinder disablement lie. To highlight the economy gains figures 4 and 5 have been produced. These show the reduction in fuel consumption as a percentage of that achieved with normal cylinder operation. Figure 4 was obtained by interpolation from the performance maps, figure 5 is the result of additional testing and shows the gain in fuel consumption to be expected at an idle speed of

FIGURE 3. ENGINE PERFORMANCE MAPS.

Figure 3a. 6 Cyl. Firing.

Figure 3b. 5 Cyl. Firing.

Figure 3c. 4 Cyl. Firing.

Figure 3d. 3 Cyl. Firing.

Figure 3e. 2 Cyl. Firing.

750 rev/min.

FIGURE 4. CONSTANT SPEED ECONOMY GAINS

FIGURE 5. ECONOMY GAIN AT IDLE

Given that the relative inertial and frictional losses increase with the number of deactivated cylinders the advantages of engine cylinder disablement decrease with increases in speed. This is shown in figure 4. Maximum benefit is obtained when cylinders are deactivated at idle. However if more than three cylinders are disabled the engine vibration becomes unacceptable. This situation could be improved by increasing the idle speed. Note that at 1000 rev/min with 2 cylinders firing the improvement in fuel consumption would still be around 58%.

From the limited number of test results obtained so far it can be confirmed that engine cylinder disablement can provide the very worthwhile reductions in brake specific fuel consumption expected from an unthrottled engine at low load operation.

Such an implementation of engine cylinder disablement, where any number of cylinders can be disabled, does however introduce problems with engine vibration. Figure 6a shows the calculated torque output trace from a six cylinder engine with all cylinders active. The following five

figures show what happens to the torque output as cylinders are progressively disabled. These diagrams were generated as an intermediate output from the simulation program described in Appendix 2. They show how low frequency pulsations are introduced both into the driveline torque and the engine vibration. The increase in torque fluctuation as cylinders are disabled can also be seen. This gives rise to the increase in vibration experienced during engine cylinder disablement.

FIGURES 7. SPECTRAL ANALYSIS OF ENGINE VIBRATION AT 1200 rev/min

FIGURES 6. ENGINE TORQUE DIAGRAMS

Figure 6a. 6 Cyl. Firing

Figure 6b. 5 Cyl. Firing

Figure 6c. 4 Cyl. Firing

Figure 6d. 3 Cyl. Firing

Figure 6e. 2 Cyl. Firing

Figure 6f. 1 Cyl. Firing

POSSIBLE FUTURE CYLINDER DISABINMENT CONTROL SYSTEM

APPENDIX 2

Dynamic Model

Dynamic Model

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{pmatrix}$$

$$\begin{bmatrix} C_{xx} & C_{xy} & C_{xz} & C_{x\theta} & C_{x\phi} & C_{x\psi} \\ C_{yx} & C_{yy} & C_{yz} & C_{y\theta} & C_{y\phi} & C_{y\psi} \\ C_{zx} & C_{zy} & C_{zz} & C_{z\theta} & C_{z\phi} & C_{z\psi} \\ C_{\theta x} & C_{\theta y} & C_{\theta z} & C_{\theta\theta} & C_{\theta\phi} & C_{\theta\psi} \\ C_{\phi x} & C_{\phi y} & C_{\phi z} & C_{\phi\theta} & C_{\phi\phi} & C_{\phi\psi} \\ C_{\psi x} & C_{\psi y} & C_{\psi z} & C_{\psi\theta} & C_{\psi\phi} & C_{\psi\psi} \end{bmatrix} \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{pmatrix} +$$

$$\begin{bmatrix} K_{xx} & K_{xy} & K_{xz} & K_{x\theta} & K_{x\phi} & K_{x\psi} \\ K_{yx} & K_{yy} & K_{yz} & K_{y\theta} & K_{y\phi} & K_{y\psi} \\ K_{zx} & K_{zy} & K_{zz} & K_{z\theta} & K_{z\phi} & K_{z\psi} \\ K_{\theta x} & K_{\theta y} & K_{\theta z} & K_{\theta\theta} & K_{\theta\phi} & K_{\theta\psi} \\ K_{\phi x} & K_{\phi y} & K_{\phi z} & K_{\phi\theta} & K_{\phi\phi} & K_{\phi\psi} \\ K_{\psi x} & K_{\psi y} & K_{\psi z} & K_{\psi\theta} & K_{\psi\phi} & K_{\psi\psi} \end{bmatrix} \begin{pmatrix} x \\ y \\ z \\ \theta \\ \phi \\ \psi \end{pmatrix} = 0 \quad (1)$$

$$\text{Inertia torque} = \frac{8Br^2w'}{2} \left[\frac{1}{2n} \sin(n\omega t) - \sin(2\omega t) - \frac{3}{2n} \sin(3\omega t) \right] \quad (2)$$

$$\text{Inertia torque} = \frac{8Br^2w'}{2} \left[\frac{1}{2n} \sin(n\omega t) - \sin(2\omega t) - \frac{3}{2n} \sin(3\omega t) \right] \quad (2)$$

$$\text{Gas torque} = fgr \sin(\omega t) + \frac{1}{2} \cos(\omega t) \quad (3)$$

$$\text{Torque} = \text{gas torque} + \text{inertia torque} + \text{dynamometer load}$$

This torque acts about the crankshaft axis so the forcing function for equation 1 is:

[4] [7]

where $[A]$ is the 3×3 transformation matrix necessary to describe the torque vector $\{T\}$ in a co-ordinate system coincident with the principal axes of the engine. It should be noted the force vector is zero.

Figure 8 ENGINE VIBRATION SIMULATION PROGRAM FLOWCHART

Figure 9 FORCES ACTING ON THE ENGINE

APPENDIX 3

Solution of the Equations of Motion

In order that the equations detailed in Appendix 2 may be solved it is necessary to determine certain properties of the engine and gearbox assembly and also to collect certain data from the engine. Of most interest are the centre of gravity, orientation of the principal axes and the principal moments of inertia. It will also be necessary to represent the cylinder pressure diagram mathematically. The means by which this information was obtained will now be discussed.

If a rigid body is suspended from a single point it will adopt an orientation such that its centre of gravity will lie on a line drawn through that point and normal to be ground. The engine can therefore be suspended from three different points in turn, the relevant lines being constructed on engine drawings. The centre of gravity then lies at their intersection.

A rigid body, suspended as in Fig.10 and allowed to oscillate with free angular vibration, will have its suspension axis a principal axis when the period of vibration is a minimum.

Given that we have a reasonable idea of the position of the axes we can suspend the engine as shown in Fig.10. The slider can then be used to adjust the position about which the engine rotates. Figure 11 shows the results. The engine is then rotated through 90° and the process repeated. This locates the position of one axis. It is necessary to make one further measurement to locate the orthogonal axes system. Using the same equipment the engine is suspended from each principal axes in turn and the principal moments of inertia calculated.

It is possible to represent any waveform by a series of sine waves of differing amplitude and phase, i.e. a fourier series.

Cylinder pressure from number 1 cylinder is logged via a Kistler pressure transducer and charge amplifier. The signal is passed through an A/D and stored in a ISI 11/23 micro-computer. Figure 12 shows the data logging system. Results are averaged in the ISI to reduce the effects of cyclic variation, 100 cycles normally being taken. Once the data has been collected it is transferred by a direct line to the PDP computer. Initiation of the data logging is by a TDC indicator in the form of a slotted disc and opto switch mounted on the crankshaft. Signal conditioning enables either TDC or 360° before TDC to be chosen as the start point in the cycle. The PDP computer is used to run an FFT analysis on the data to give results of the form:

$$2A \cos (2\pi f t + B)$$

where A is half the amplitude of the sine wave, f its frequency and B its phase angle.

On running the simulation program the appropriate value for the cylinder pressure is obtained by summing these sine waves. The phase angle is multiplied by $n\pi/3$ where n is the cylinder number (0-5) for correct handling of the firing interval between cranks.

FIGURE 10. EQUIPMENT TO DETERMINE THE LOCATION OF THE PRINCIPAL AXES.

FIGURE 11. PERIODIC TIME OF ANGULAR VIBRATION ABOUT ENGINE AXIS.

FIGURE 12. CYLINDER PRESSURE DATA LOGGING INSTRUMENTATION.

APPENDIX III

Bosch L-Jetronic Fuel Injection - Principle of Operation

The L-Jetronic is a pulsed fuel injection system employing electronic control. The controlling parameters, representing the fuel requirements of the engine, are sensed by transducers and relayed in the form of low-current signals to the electronic control unit which then calculates the optimum opening times for the injectors. The injectors are operated electro-mechanically, and inject fuel under pressure onto the inlet valves of the engine.

The main control parameters for the determination of the injection pulse duration are the quantity of air entering the engine, and engine speed.

Operation:

Figures 1 and 2 show the main components of the injection system and their relevant positions on the engine respectively, and described in Table 1. An electrically driven pump delivers the fuel through a filter and provides the pressure. This pressure is controlled by the pressure regulator so that there is a constant pressure difference between the fuel pressure and the inlet manifold. This is achieved by connecting the inlet manifold to the spring chamber of the pressure regulator, thus making the fuel delivery of the injectors dependent only on the injector pulse duration.

The pump delivers more fuel than the engine requires at maximum power, the excess fuel being returned to the tank by the pressure regulator.

The inlet air flows from the air filter via the air meter and the throttle valve, into the plenum chamber and then to each cylinder through inlet tracts. There is one fuel injector for each of the cylinders, and this is sited near the inlet valve, for driveability and emissions reasons resulting from precise fuel delivery to each cylinder. However, as a consequence, when starting the engine at low ambient temperature the injected fuel has little chance of mixing with the incoming air and vapourising due to the short distance to the cylinder. Thus, a further injector, giving particularly good fuel atomisation, the 'cold start' injector is fitted in the plenum chamber and activated during low-temperature starts.

The injected fuel quantity is determined from measurements of inlet air quantity and engine speed. The air fuel diagram, shown in Figure 3, illustrates the relationship.

The air drawn in by the engine works on restricting flap in the air meter, and a flap angle A , corresponding to a particular air

The engine vibration during the tests was logged and analysed using the Department's PDP computer running a proprietary software package. The engine speed was 1200 rev/min or 10 thermodynamic cycles/second. This frequency of 10Hz is therefore the fundamental frequency of engine vibration at that speed. The salient results of the spectral analysis are shown in fig.7 and are summarised in Table 2.

Table 2 - Dominant frequencies (1200 rev/min)

No. of Cyl.Active	Dominant frequencies (Hz)
6	60
5	10
4	20
3	30
2	20

These frequencies should be studied in conjunction with the torque diagrams, figure 6. The dominant frequency of engine vibration is the same as the lowest frequency of torque pulsations introduced by the disablement of cylinders.

This is the major disadvantage of engine cylinder disablement systems and the reason why only limited use has been made of them to date. Disabling half the total number of engine cylinders has been favoured because it introduces torque and vibration frequencies of half those experienced under normal operation. Any other number of deactivated cylinders introduces lower frequencies.

Two approaches may be employed to minimize this increase in vibration. A cyclic disablement sequence could be adopted to minimise the vibration or the engine isolation system redesigned. If a cyclic disablement sequence is favoured we are limited to running on 6,4,3 or 2 cylinders. With either 5 or 1 cylinder operation there is insufficient scope to optimize the disablement sequence. At 1200 rev/min with 5 cylinder static operation the dominant frequency of vibration is 10Hz. Any cycling of the cylinders introduces lower frequency components of vibration. With 4,3 or 2 cylinder operation there is much greater scope for optimizing the sequence. To this end a mathematical model of the engine has been developed. This is described in appendix 2 and enables the vibration of the engine to be investigated for different disablement sequences. Appendix 3 details how the orientation of the principal axes, principal moments of inertia and representation of the cylinder pressure waveforms were obtained. Random disablement of cylinders could be used but this could lead to an increase in engine vibration due to the transient vibration introduced.

Redesign of the engine isolation system either by choosing an isolator unit with more appropriate properties or by relocating the isolator positions to achieve a greater degree of motion decoupling would obviously reduce the transmission of the vibration.

Conclusions

The results of our investigations show the potential of engine cylinder disablement in providing very worthwhile fuel savings. To maximise its advantages the system should offer the possibility of disabling any number of cylinders and of disabling different numbers of cylinders on different thermodynamic cycles. The ease with which fuel shut off

may be accomplished and the fact that the overall performance of the vehicle remains unaffected, makes such a system commercially attractive.

Engine vibration and, to a lesser extent, emissions have prevented such an implementation to date. A final solution to this problem of engine vibration is expected to incorporate cyclic disablement sequences, a re-designed engine isolation system and, perhaps, increased flywheel inertia. The latter to reduce torque and speed fluctuations in the driveline.

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flow Q is obtained. A potentiometer operated by the restricting flap converts this angular position A to a voltage U , with the relationship between voltage U and airflow Q per unit time being reciprocal. In the control unit this voltage is divided by the engine speed to give air quantity per stroke, q , and hence the fuel injection pulse duration, t .

$$\text{i.e.} \quad t \propto q$$

$$\text{or} \quad t \propto \frac{Q}{n} \quad \text{where } n = \text{engine speed}$$

$$t \times n \propto Q$$

The speed information is given in the form of the time interval between consecutive ignition sparks. The pulses generated in the control unit energise the injectors so that by the above relationship the injected fuel quantity, q_i , depends on air flow and engine speed as:

$$q_i \propto t \propto q \propto Q/n$$

The fuel injectors are connected in parallel and thus activated simultaneously, but at different phases of the thermodynamic cycle for the individual cylinders. In order to reduce this timing discrepancy one half of the required fuel quantity is injected for each engine revolution. Consequently, injection pulses are triggered directly from the ignition low-tension circuit, and in the case of the Jaguar 6-cylinder engine each injection pulse is triggered every third ignition spark.

Additional Controls

When cold starting and during subsequent running, the engine requires a greatly enriched mixture. During cranking, the enrichment is provided by the cold start injector if the engine temperature is below a fixed value, set by the thermo-time switch which also limits the energisation period according to temperature, to prevent possible flooding of the engine.

During the warm up phase the enrichment is controlled by the water temperature probe (thermistors), located in the engine coolant. During cold starting and running, a greater air flow is required to maintain idle speed, in addition to the enriched air/fuel mixture. This additional air is controlled by the extra-air valve, whose variable aperture is changed by means of a bi-metal strip according to the temperature of an electrically heated coil.

Idle and full-load running conditions are further optimised by the use of a throttle-controlled switch, and an adjustable bypass on the air flow meter permitting further trimming of the

mixture at low air flow conditions such as idle. An additional mixture adjustment is provided by a temperature sensor mounted in the air inlet mainstream, to compensate for variations in air density due to ambient and under-bonnet temperatures.

The purpose of the electronic control unit (ECU), is to supply impulses of specifically defined length to the electromagnetic injection valves. Figure 4 shows a functional block diagram of the unit.

The injection control multivibrators are triggered twice per camshaft revolution by the pulse shaper and frequency divider integrated circuit. This shapes the low-tension pulses and divides the frequency of these pulses by 3 (6-cylinder engine), producing two trigger pulses per camshaft revolution. The output t' from the division multivibrator is a pulse time equal to approximately half the injection duration, which is lengthened by a multiplication factor K by the multiplier stage of the ECU. The factor K is approximately 2 for a hot running engine, but is increased for idle, full-load, cold running, starting and so on, so that the injector pulse time t is:

$$t \propto K \times t'$$

In addition, the multiplier stage adds a time t'' to t to compensate for the 'dead' time of the injectors, which varies with battery voltage, so that the final injection time T is produced:

$$T = t + t''$$

The Bosch L-Jetronic fuel injection system is widely used in the form described above on current mass-production passenger vehicles, and is particularly suited to the application of Cylinder Disablement, as described in the Thesis.

TABLE 1. BOSCH FUEL INJECTION - MAIN COMPONENTS

(FIG 1. AND 2.)

1. Air Meter
2. Extra Air Valve
3. Main Injector
4. Cold Start Injector
5. Fuel Pressure Regulator
6. Fuel Rail
7. Throttle Switch
8. Idle Air Adjustment (and Overrun Valve)
9. Coolant Temperature Sensor
10. Ignition Coil
11. Thermotime Switch
12. Double Relay
13. Electronic Control Unit (ECU)
14. Idle Mixture Adjustment
15. Fuel Pump
16. Fuel Tanks
17. Fuel Filter
18. Oxygen Sensor
19. Air Inlet Temperature Sensor
20. Battery

Fig 1. Bosch 'L' Jetronic Fuel Injection System

Fig 2.

Jaguar 4.2 litre XK Six
Cylinder Engine and Location
of Main Elect. Fuel Injection
Components

Fig 3 Bosch L-Jetronic Air Flow Diagram.

Fig 4 Electronic Control Unit Function - Block Diagram

APPENDIX IV

Data Sheets

This appendix contains copies of the Product Specification Sheets relating to the microprocessor system CPU, a Toshiba TMP8085A chip, and the main interface board chip, a Am8155/Am8156 RAM and I/O device shown in Figures 1 and 2 respectively.

SINGLE CHIP MICROPROCESSOR

1 CHANNEL SILICON GATE MOS

TMP8085AP

GENERAL DESCRIPTION

The TMP8085A is a new generation, complete 8 bit parallel central processing unit (CPU). Its instruction set is 100% software compatible with the TMP9080A (8080A) microprocessor, and it is designed to improve the present 8080's performance by higher system speed. Its high level of system integration allows a minimum system of three IC's: TMP8085A

(CPU), TMP8155P/TMP8156P (RAM) and TMP8755 AC (EPROM)/TMP8355P (ROM). The TMP8085A uses a multiplexed data bus. The address is split between the 8 bit address bus and the 8 bit data bus. The on-chip address latches of TMP8155P/TMP8156P/TMP8755AC/TMP8355P memory products allow a direct interface with TMP8085A.

FEATURES

- 100% Software Compatible with TMP9080A
- 1.3 μ s Instruction Cycle
- Single +5V Power Supply
- On-Chip Clock Generator (with External Crystal or RC Network)
- On-Chip System Controller; Advanced Cycle status information available for Large System Control
- 4 Vectored Interrupts (One is Non-maskable) Plus an TMP9080A compatible interrupt
- Decimal, Binary and Double Precision Arithmetic
- Serial In/Serial Out Port
- Direct Addressing Capability to 64K Bytes of Memory
- Compatible with Intel's 8085A

BLOCK DIAGRAM

Fig. 1. TMP8085A Functional Block Diagram

PIN CONNECTION (TOP VIEW)

Fig. 2. TMP8085A Pinout Diagram

Fig 1 TOSHIBA TMP8085AP Central Processing Unit
Data Sheet

PIN NAME AND PIN DESCRIPTION

X₁, X₂ (Input)

Crystal, LC, or RC network are connected to X₁ and X₂ to drive the internal clocking generator. X₁ and X₂ can also be driven from an externally derived frequency source. The input frequency is divided by 2 to give the processor's internal operating frequency.

CLK (Output)

Clock output for use as a system clock. The period of CLK is twice the X₁, X₂ input period.

RESET IN (Input)

The RESET Input initializes the processor by clearing the program counter, instruction register, SOD latch, Interrupt Enable flip-flop and HLDA flip-flop. The address and data buses and the control lines are 3-stated during RESET and because of the asynchronous nature of RESET, the processor's internal registers and flags may be altered by RESET with unpredictable results. RESET IN is a Schmitt-triggered input, allowing connection to an RC network for power on RESET delay. The TMP9085A is held in the reset condition as long as RESET IN is applied.

RESET OUT (OUTPUT)

The RESET OUT signal indicates that the TMP-9085A is being reset. It can be used as a system reset. It is synchronized to the processor clock and lasts an integral number of clock periods.

SOD (Output)

Serial output data line. The output SOD is set or reset as specified by the SIM instruction.

SID (Input)

Serial input data line. The data on this line is loaded into accumulator bit 7 whenever a RIM instruction is executed.

INTR (Input)

INTERRUPT REQUEST signal provides a mechanism for external devices to modify the instruction flow of the program in progress. It is sampled only during the next to the last clock cycle of an instruction and during Hold and Halt states. If it is recognized, the processor will complete the execution of the current instruction, and then the Program Count-

er (PC) will be inhibited from incrementing and an INTA will be issued. During this cycle a RESTART or CALL instruction can be inserted to jump to the interrupt service routine. The INTR is enabled and disabled by software. It is disabled by RESET and immediately after an interrupt is accepted.

INTA (Output)

INTERRUPT ACKNOWLEDGE: Occurs in response to an Interrupt input and indicates that the processor will be ready for an interrupt instruction on the data bus. It is used instead of (and has the same timing as) RD during the instruction cycle after an INTR is accepted.

RST 5.5 }
RST 6.5 } (Inputs)
RST 7.5 }

RESTART INTERRUPTS: These three inputs have the same timing as INTR except they cause an internal RESTART to be automatically inserted. These interrupts have a higher priority than INTR. The priority of these interrupts is ordered as shown Table 1. They may be individually masked out using the SIM instruction.

TRAP (Input)

Trap interrupt is a nonmaskable RESTART interrupt. It is sampled at the same time as INTR or RST 5.5 - 7.5. It is unaffected by any mask or Interrupt Enable. It has the highest priority of any interrupt.

AD₀ - AD₇ (Input/Output, 3-state)

Lower 8 bits of the memory address (or I/O address) appear on the bus during the first clock cycle (T₁ state) of a machine cycle. It then becomes the data bus during the second and third clock cycles.

A₈ - A₅ (Output, 3-state)

The most significant 8 bits of the memory address or the 8 bits of the I/O address, 3-stated during Hold and Halt modes and during RESET.

Fig 1 (cont'd)

S₀, S₁ and IO/ $\overline{M}$ (Output)

Machine cycle status:

IO/ $\overline{M}$	S ₁	S ₀	Status
0	1	1	Opcode fetch
0	1	0	Memory read
0	0	1	Memory write
1	1	0	I/O read
1	0	1	I/O write
1	1	1	Interrupt Acknowledge
TS	0	0	Halt
TS	X	X	Hold
TS	X	X	Reset

Note: TS = 3-state (high impedance)

X = unspecified

ALE (Output)

Address Latch Enable: It occurs during the first clock state of a machine cycle and enables the address to be latched into the on-chip latch of peripheral chips. The falling edge of ALE can be used to strobe the status information. ALE is never 3-state.

 $\overline{WR}$ (Output, 3-state)

WRITE control: A low level on $\overline{WR}$ indicates the data on the Data Bus is to be written into the selected memory or I/O location. Data is set up at the trailing edge of $\overline{WR}$. It is 3-stated during Hold and Halt modes and during RESET.

 $\overline{RD}$ (Output, 3-state)

READ control: A low level on $\overline{RD}$ indicates the selected memory or I/O device to be read and that the Data Bus is available for the data transfer, 3-stated during Hold and Halt modes and during RESET.

READY (Input)

When READY is absent (low), indicating that the external operation is not complete, the processor will enter the Wait state. It will wait an integral number of clock cycles for READY to go high before completing the read or write cycle.

HOLD (Input)

The Hold input allows an external signal to cause the processor to relinquish control over the address bus and the data bus. When Hold goes active, the processor completes its current operation, activates the HLDA output, and puts the Address, Data, $\overline{RD}$,

$\overline{WR}$, and IO/ $\overline{M}$ lines into their high-impedance state. Internal processing can continue. The Holding device can then utilize the address and data buses without interference. The processor can regain the bus only after the Hold is removed.

HLDA (Output)

The Hold Acknowledge output signal is a response to a Hold input. It indicates that the processor has received the HOLD request and it will relinquish the bus in the next cycle. HLDA goes low after the Hold request is moved. The processor takes the bus one half clock cycle after HLDA goes low.

VCC

+5 volt supply

VSS

Ground Reference

FUNCTIONAL DESCRIPTION

The TMP8085A is a complete 8-bit parallel central processor. Its basic clock speed is 3 MHz. Also it is designed to fit into a minimum system of three IC's: The CPU (TMP8085A), a RAM I/O (TMP8155P or TMP8156P), and a ROM or EPROM I/O chip (TMP8355P or TMP8755AC).

The TMP8085A is provided with internal 8-bit registers and 16-bit registers. The TMP8085A has eight addressable 8-bit registers: Six of them can be used either as 8-bit registers or as 16-bit register pairs. In addition to the register pairs, the TMP8085A contains two more 16-bit registers. The TMP8085A register set is as follows:

- The accumulator (A Register) is the centre of all the accumulator instructions, which include arithmetic, logic, load and store, and I/O instructions.
- The program counter (PC) always points to the memory location of the next instruction to be executed.
- General — purpose registers BC, DE, and HL may be used as 8-bit registers or as three 16-bit registers, interchangeably, depending on the instruction being performed.
- The stack pointer (SP) is a special data pointer that always points to the stack too (next available stack address).
- The flag register contains five one-bit flags, each of

Fig 1 (cont'd)

which records processor status information and may also control processor operation.

The five flags in the TMP8085A CPU are shown below:

(MSB)

D7	D6	D5	D4	D3	D2	D1	D0
S	Z		AC		P		C

- The carry flag (C) is set and reset by arithmetic operations. An addition operation that results in an overflow out of the high-order bit of the accumulator sets the carry flag. The carry flag also acts as a "borrow" flag for subtract instruction.
- The auxiliary carry flag (AC) indicates overflow out of bit 3 of the accumulator in the same way that C flag indicates overflow out of bit 7. This flag is commonly used in BCD arithmetic.
- The sign flag (S) is set to the condition of the most significant (MSB) bit of the accumulator following the execution of arithmetic or logic instructions.
- The zero flag (Z) is set if the result generated by certain instructions is zero.
The zero flag is cleared if the result is not zero.
- The parity flag (P) is set to 1 if the parity (number of 1-bits) of the accumulator is even. If odd, it is cleared.

In the TMP8085A microprocessor contains the functions of clock generation, system bus control, and interrupt priority selection, in addition to execution of the instruction set. The TMP8085A uses a multiplexed Data Bus. The address is split between the higher 8-bit Address Bus and the lower 8-bit Address/Data Bus. During the first T state (T₁ clock cycle) of a machine cycle the lower order address is sent out on the Address/Data Bus. These lower 8 bits may be latched externally by the Address Latch Enable signal (ALE). During the rest of the machine cycle the data bus is used for memory or I/O data.

INTERRUPT AND SERIAL I/O

The TMP8085A has 5 interrupt inputs: INTR, RST 5.5, RST 6.5, RST 7.5 and TRAP. INTR is identical in function to 8080A INT. Each of three RESTART inputs 5.5, 6.5, 7.5 has a programmable mask. TRAP is also a RESTART interrupt but it is non-maskable.

The three RESTART interrupts cause the internal

execution of RESTART if the interrupts are enabled and if the interrupt mask is not set. The nonmaskable TRAP causes internal execution independent of the state of the interrupt enable or masks.

There are two different types of inputs in the restart interrupts. RST 5.5 and RST 6.5 are high level-sensitive like INTR and are recognized with the same timing as INTR. RST 7.5 which is rising edge-sensitive.

For RST 7.5, only a pulse is required to set an internal flip flop which generates the interrupt request. The RST 7.5 request flip flop remains set until the request is serviced. Then it is reset automatically. This flip flop may also be reset by using the SIM instruction or by issuing a RESET IN to the TMP8085A. The RST 7.5 internal flip flop will be set by a pulse on the RST 7.5 pin even when the RST 7.5 interrupt is masked out.

The interrupts are arranged in a fixed priority that determines which interrupt is to be recognized if more than one is pending: TRAP-highest priority, RST 7.5, RST 6.5, RST 5.5, INTR-lowest priority. This priority scheme does not take into account the priority of a routine that was started by a higher priority interrupt. RST 5.5 can interrupt a RST 7.5 routine if the interrupts were reenabled before the end of the RST 7.5 routine.

The TRAP interrupt is useful for catastrophic errors such as power failure or bus error. It is not affected by any flag or mask. The TRAP input is both edge and level sensitive. The TRAP input must go high and remain high until it is acknowledged. It will not be recognized again until it goes low, then high again. This avoids any false triggering due to noise or logic glitches.

The TRAP interrupt is special in that it disables interrupts, but preserves the previous interrupt enable status. Performing the first RIM instruction following a TRAP interrupt allows you to determine whether interrupts were enabled or disabled prior to the TRAP. All subsequent RIM instruction provide current interrupt enable status. Performing a RIM instruction following INTR, or RST 5.5 - 7.5 will provide current interrupt enable status, revealing that interrupts are disabled.

The serial I/O system is also controlled by the RIM and SIM instructions. SID is read by RIM, and SIM sets the SOD data.

Fig 1 (cont'd)

Table 1. Interrupt Priority, Restart Address, and Sensitivity

Name	Priority	Address Branched to When Interrupt Occurs	Type Trigger
TRAP	1	24 (Hex.)	Rising edge and high level until sampled.
RST 7.5	2	3C (Hex.)	Rising edge (latched).
RST 6.5	3	34 (Hex.)	High level until sampled.
RST 5.5	4	2C (Hex.)	High level until sampled.
INTR	5	See Note (2)	High level until sampled.

Notes: (1) The processor pushes the PC on the stack before branching to the indicated address.
 (2) The address branched to depends on the instruction provided to the TMP8085A when the interrupt is acknowledged.

BASIC TIMING

The execution of each instruction by the TMP-8085A consists of a sequence of from one to five machine cycles, and each machine cycle consists of a minimum of from three to six clock cycles. Most machine cycles consist of three T states, (cycles of the CLK output) with the exception of opcode fetch, which normally has either four or six T states (unless WAIT or HOLD states are forced by the receipt of READY or HOLD inputs). Any T state must be one of ten possible states, shown in Table 3.

At the beginning of every machine cycle, the TMP-8085A sends out three status signals (IO/ $\overline{M}$, S_1 , S_0) that define what type of machine cycle is about to

take place. The TMP8085A also sends out a 16-bit address at the beginning of every machine cycle to identify the particular memory location or I/O port, that the machine cycle applies to.

The special timing signal, ADDRESS LATCH ENABLE (ALE), is used as a strobe to sample the lower 8-bits of address on the AD₀-AD₇ lines. ALE is present during T₁ of every machine cycle. Control lines $\overline{RD}$ ($\overline{INTA}$) and $\overline{WR}$ become active later, at the time when the transfer of data is to take place.

Figure 3 shows an instruction fetch, memory read and I/O write cycle (as would occur during processing of the OUT instruction).

Table 2. TMP8085A Machine Cycle Chart

MACHINE CYCLE	IO/ $\overline{M}$	S_1	S_0	$\overline{RD}$	$\overline{WR}$	$\overline{INTA}$
OPCODE FETCH	0	1	1	0	1	1
MEMORY READ	0	1	0	0	1	1
MEMORY WRITE	0	0	1	1	0	1
I/O READ	1	1	0	0	1	1
I/O WRITE	1	0	1	1	0	1
ACKNOWLEDGE OF INTR	1	1	1	1	1	0
BUS IDLE	0	1	0	1	1	1
DAD						
ACK. OF						
RST, TRAP	1	1	1	1	1	1
HALT	TS	0	0	TS	TS	1

NOTE: 0 = Logic "0", 1 = Logic "1", TS = High Impedance

Table 3. TMP8085A Machine State Chart

MACHINE STATE	S_1, S_0	$IO/\overline{M}$	$A_8 - A_{15}$	$AD_0 - AD_7$	$\overline{RD}, \overline{WR}$	$\overline{INTA}$	ALE
T ₁	X	X	X	X	1	1	1*
T ₂	X	X	X	X	X	X	0
T _{WAIT}	X	X	X	X	X	X	0
T ₃	X	X	X	X	X	X	0
T ₄	1	0†	X	TS	1	1	0
T ₅	1	0†	X	TS	1	1	0
T ₆	1	0†	X	TS	1	1	0
T _{RESET}	X	TS	TS	TS	TS	1	0
T _{HALT}	0	TS	TS	TS	TS	1	0
T _{HOLD}	X	TS	TS	TS	TS	1	0

- NOTES: (1) 0 = Logic "0", 1 = Logic "1", TS = High Impedance, X = Unspecified
 (2) *ALE not generated during 2nd and 3rd machine cycles of OAD instruction
 (3) † $IO/\overline{M} = 1$ during T₄ - T₆ of INA machine cycle

Fig 1 (cont'd)

DRIVING THE X1 AND X2 INPUTS

You may drive the clock inputs of the TMP8085A with a crystal, an LC tuned circuit, an RC network or an external clock source. The driving frequency must be at least 1 MHz, and must be twice the desired internal clock frequency.

A. Quartz Crystal Clock Driver

If a crystal used, it must have the following characteristics.

- Parallel resonance at twice the clock frequency desired
- C_S (shunt capacitance) ≤ 7 pF
- R_S (equivalent shunt resistance) ≤ 75 Ohms

Note a value of the external capacitors C_1 and C_2 between X_1 , X_2 and ground. In case of the crystal frequency above 4 MHz, it is recommended that you choose a value of 10 pF for C_1 and C_2 and less than 4 MHz, 20 pF capacitors are recommended.

B. LC Tuned Circuit Clock Driver

A parallel-resonant LC circuit may be used as the frequency-determining network for the TMP8085A, providing that it has a frequency tolerance of Less than 10%. The components are chosen from the formula.

$$f = \frac{1}{2\pi \sqrt{L(C_{ext} + C_{int})}}$$

The use of an LC circuit is not recommended for frequencies higher than approximately 5 MHz.

C. RC Circuit Clock Driver

An RC circuit may be used as the frequency-determining network for the TMP8085A if maintaining a precise clock frequency is of no importance. Variations in the on-chip timing generation can cause a wide variation in frequency when using RC circuit. The driving frequency generated by the circuit shown is approximately 3 MHz. It is not recommended that frequencies greatly higher or lower than this be attempted.

D. External Clock Driver Circuit

POWER ON AND RESET IN

The TMP8085A is not guaranteed to work until 10 ms after V_{CC} reaches 4.75 V. It is suggested that RESET IN be kept low during this period.

Note that the 10 ms period does not include the time it takes for the power supply to reach its 4.75 V level.

Fig 1 (cont'd)

INSTRUCTION SET

Symbols and Abbreviations

SYMBOLS		DEFINITION
ddd,sss	The bit pattern designating one of the registers A, B, C, D, E, H, L (ddd=destination, sss=source):	
	ddd or sss	REGISTER NAME
	111	A
	000	S
	001	C
	010	D
	011	E
	100	H
	101	L
	110	M (Memory)
r, r1, r2	One of the registers A, B, C, D, E, H, L	
d8	8-bit data quantity	
d16	16-bit data quantity	
addr8	8-bit address of an I/O device	
addr	16-bit address quantity	
RP	The bit pattern designating one of the register pairs B, D, H, SP:	
	REGISTER PAIR	
	RP	rP (rPH) (rPL)
	00	B B-C
	01	D D-E
	10	H H-L
	11	SP SP
B2	The second byte of the instruction	
B3	The third byte of the instruction	
0	Affected	
S	Set	
R	Reset	
-	Not affected	

Fig 1 (cont'd)

Data Transfer

Mnemonic	Instruction Code								Operation	Bytes	States	Flag				
	D7	D6	D5	D4	D3	D2	D1	D0				C	Z	S	P	AC
MOV r1, r2	0	1	d	d	d	S	S	S	(r1) ← (r2)	1	4	-	-	-	-	-
MOV M, r	0	1	1	1	0	S	S	S	[(H) (L)] ← (r)	1	7	-	-	-	-	-
MOV r, M	0	1	d	d	d	1	1	0	(r) ← [(H) (L)]	1	7	-	-	-	-	-
MVI r, d8	0	0	d	d	d	1	1	0	(r) ← (B ₂)	2	7	-	-	-	-	-
MVI M, d8	0	0	1	B ₂		1	1	0	[(H) (L)] ← (B ₂)	2	10	-	-	-	-	-
				B ₂												
				B ₂												
LDA addr	0	0	1	B ₂		0	1	0	(A) ← [(B ₂) (B ₂)]	3	13	-	-	-	-	-
				B ₂												
				B ₂												
LDAX B	0	0	0	0	1	0	1	0	(A) ← [(B) (C)]	1	7	-	-	-	-	-
LDAX D	0	0	0	1	1	0	1	0	(A) ← [(D) (E)]	1	7	-	-	-	-	-
LHLD addr	0	0	1	B ₂		0	1	0	(L) ← [(B ₂) (B ₂)]	3	16	-	-	-	-	-
				B ₂												
				B ₂												
LXI H, d16	0	0	1	B ₂		0	0	1	(H) ← (B ₂)	3	10	-	-	-	-	-
				B ₂												
				B ₂												
LXI D, d16	0	0	0	B ₂		0	0	1	(D) ← (B ₂)	3	10	-	-	-	-	-
				B ₂												
				B ₂												
LXI B, d16	0	0	0	B ₂		0	0	1	(B) ← (B ₂)	3	10	-	-	-	-	-
				B ₂												
				B ₂												
LXI SP, d16	0	0	1	B ₂		0	0	1	(SP) _H ← (B ₂)	3	10	-	-	-	-	-
				B ₂												
				B ₂												
SHLD addr	0	0	1	B ₂		0	1	0	[(B ₂) (B ₂)] ← (L)	3	16	-	-	-	-	-
				B ₂												
				B ₂												
STA addr	0	0	1	B ₂		0	1	0	[(B ₂) (B ₂)] ← (A)	3	13	-	-	-	-	-
				B ₂												
				B ₂												
STAX B	0	0	0	0	0	0	1	0	[(B) (C)] ← (A)	1	7	-	-	-	-	-
STAX D	0	0	0	1	0	0	1	0	[(D) (E)] ← (A)	1	7	-	-	-	-	-
SPHL	1	1	1	1	1	0	0	1	(SP) ← (H) (L)	1	6	-	-	-	-	-
XCHG	1	1	1	0	1	0	1	1	(H) ← (D)	1	4	-	-	-	-	-
XTHL	1	1	1	0	0	0	1	1	(L) ← (SP)	1	16	-	-	-	-	-
IN addr8	1	1	0	B ₂		0	1	1	(A) ← (data)	2	10	-	-	-	-	-
				B ₂												
				B ₂												
OUT addr8	1	1	0	B ₂		0	1	1	(data) ← (A)	2	10	-	-	-	-	-
				B ₂												
				B ₂												

Fig 1 (cont'd)

Branch

Mnemonic	Instruction Code								Operation	Bytes	States	Flag				
	O7	O6	O5	O4	O3	O2	O1	O0				C	Z	S	P	AC
JMP addr	1	1	0	0	0	0	1	1	(PC) ← (B ₃) (B ₂)	3	10	-	-	-	-	-
JNZ addr	1	1	0	B ₂	0	0	1	0	IF Z = 0 (PC) ← (B ₃) (B ₂). If Z = 1 (PC) ← (PC) + 3	3	7/10	-	-	-	-	-
				B ₃												
JZ addr	1	1	0	B ₂	0	1	0	0	IF Z = 1 (PC) ← (B ₃) (B ₂). If Z = 0 (PC) ← (PC) + 3	3	7/10	-	-	-	-	-
				B ₃												
JNC addr	1	1	0	B ₂	1	0	0	1	If C = 0 (PC) ← (B ₃) (B ₂). If C = 1 (PC) ← (PC) + 3	3	7/10	-	-	-	-	-
				B ₃												
JC addr	1	1	0	B ₂	1	1	0	1	If C = 1 (PC) ← (B ₃) (B ₂). If C = 0 (PC) ← (PC) + 3	3	7/10	-	-	-	-	-
				B ₃												
JPO addr	1	1	1	B ₂	0	0	0	1	If P = 0 (PC) ← (B ₃) (B ₂). If P = 1 (PC) ← (PC) + 3	3	7/10	-	-	-	-	-
				B ₃												
JPE addr	1	1	1	B ₂	0	1	0	1	If P = 1 (PC) ← (B ₃) (B ₂). If P = 0 (PC) ← (PC) + 3	3	7/10	-	-	-	-	-
				B ₃												
JP addr	1	1	1	B ₂	1	0	0	1	If S = 0 (PC) ← (B ₃) (B ₂). If S = 1 (PC) ← (PC) + 3	3	7/10	-	-	-	-	-
				B ₃												
JM addr	1	1	1	B ₂	1	1	0	1	If S = 1 (PC) ← (B ₃) (B ₂). If S = 0 (PC) ← (PC) + 3	3	7/10	-	-	-	-	-
				B ₃												
CALL addr	1	1	0	B ₂	0	1	1	0	[(SP) - 1] ← (PCH) [(SP) - 2] ← (PCL) (SP) ← (SP) - 2 (PC) ← (B ₃) (B ₂)	3	18	-	-	-	-	-
				B ₃												
CNZ addr	1	1	0	B ₂	0	0	1	0	If Z = 0, the actions specified in the CALL instruction are performed. If Z = 1 (PC) ← (PC) + 3	3	9/18	-	-	-	-	-
				B ₃												

Fig 1 (cont'd)

CZ addr	1	1	0	0	1	1	0	0	If Z = 1, the actions specified in the CALL instruction are performed. If Z = 0, (PC) ← (PC) + 3	3	9/18	-	-	-	-	-
CNC addr	1	1	0	1	0	1	0	0	If C = 0, the actions specified in the CALL instruction are performed. If C = 1 (PC) ← (PC) + 3	3	9/18	-	-	-	-	-
				B ₁												
				B ₂												
CC addr	1	1	0	1	1	1	0	0	If C = 1, the actions specified in the CALL instruction are performed. If C = 0 (PC) ← (PC) + 3	3	9/18	-	-	-	-	-
				B ₁												
				B ₂												
CPO addr	1	1	1	0	0	1	0	0	If P = 0, the actions specified in the CALL instruction are performed. If P = 1 (PC) ← (PC) + 3	3	9/18	-	-	-	-	-
				B ₁												
				B ₂												
CPE addr	1	1	1	0	1	1	0	0	If P = 1, the action specified in the CALL instruction are performed. If P = 0 (PC) ← (PC) + 3	3	9/18	-	-	-	-	-
				B ₁												
				B ₂												
C ^o addr	1	1	1	1	0	1	0	0	If S = 0, the actions specified in the CALL instruction are performed. If S = 1 (PC) ← (PC) + 3	3	9/18	-	-	-	-	-
				B ₁												
				B ₂												
CM addr	1	1	1	1	1	1	0	0	If S = 1, the action specified in the CALL instruction are performed. If S = 0 (PC) ← (PC) + 3	3	9/18	-	-	-	-	-
				B ₁												
				B ₂												
RET	1	1	0	0	1	0	0	1	(PCL) ← ((SP)) (PCH) ← ((SP) + 1) (SP) ← (SP) + 2	1	10	-	-	-	-	-
RNZ	1	1	0	0	0	0	0	0	If Z = 0, the actions specified in the RET instruction are performed. If Z = 1 (PC) ← (PC) + 1	1	6/12	-	-	-	-	-
RN	1	1	0	0	1	0	0	0	If Z = 1, the actions specified in the RET instruction are performed. If Z = 0 (PC) ← (PC) + 1	1	6/12	-	-	-	-	-

Fig 1 (cont'd)

RNC	1	1	0	1	0	0	0	0	If C = 0, the actions specified in the RET instruction are performed. If C = 1 (PC) ← (PC) + 1	1	6/12	-	-	-	-	-
RC	1	1	0	1	1	0	0	0	If C = 1, the actions specified in the RET instruction are performed. If C = 0 (PC) ← (PC) + 1	1	6/12	-	-	-	-	-
RPO	1	1	1	0	0	0	0	0	If P = 0, the actions specified in the RET instruction are performed. If P = 1 (PC) ← (PC) + 1	1	6/12	-	-	-	-	-
RPE	1	1	1	0	1	0	0	0	If P = 1, the actions specified in the RET instruction are performed. If P = 0 (PC) ← (PC) + 1	1	6/12	-	-	-	-	-
RP	1	1	1	1	0	0	0	0	If S = 0, the actions specified in the RET instruction are performed. If S = 1 (PC) ← (PC) + 1	1	6/12	-	-	-	-	-
RM	1	1	1	1	1	0	0	0	If S = 1, the actions specified in the RET instruction are performed. If S = 0 (PC) ← (PC) + 1	1	6/12	-	-	-	-	-
PCHL	1	1	1	0	1	0	0	1	(PCH) ← (H) (PCL) ← (L)	1	6	-	-	-	-	-
RST	1	1	A	A	A	1	1	1	[(SP) - 1] ← (PCH) [(SP) - 2] ← (PCL) (SP) ← (SP) - 2 (PC) ← (00000000 00AAA000)	1	12	-	-	-	-	-

Fig 1 (cont'd)

Arithmetic

Mnemonic	Instruction Code								Operation	Bytes	States	Flag				
	D7	D6	D5	D4	D3	D2	D1	D0				C	S	Z	P	AC
ADD r	1	0	0	0	0	S	S	S	$(A) \leftarrow (A) + (r)$	1	4	0	0	0	0	0
ADC r	1	0	0	0	1	S	S	S	$(A) \leftarrow (A) + (r) + (C)$	1	4	0	0	0	0	0
ADD M	1	0	0	0	0	1	1	0	$(A) \leftarrow (A) + [(H) (L)]$	1	7	0	0	0	0	0
ADC M	1	0	0	0	1	1	1	0	$(A) \leftarrow (A) + [(H) (L)] + (C)$	1	7	0	0	0	0	0
ADI d8	1	1	0	0	0	1	1	0	$(A) \leftarrow (A) + (B_2)$	2	7	0	0	0	0	0
				B_2												
ACI d8	1	1	0	0	1	1	1	0	$(A) \leftarrow (A) + (B_2) + (C)$	2	7	0	0	0	0	0
				B_2												
DAD rp	0	0	R	P	1	0	0	1	$(H) (L) \leftarrow (H) (L) + (rH) (rL)$	1	10	0	-	-	-	-
SUB r	1	0	0	1	0	S	S	S	$(A) \leftarrow (A) - (r)$	1	4	0	0	0	0	0
SBB r	1	0	0	1	1	S	S	S	$(A) \leftarrow (A) - (r) - (C)$	1	4	0	0	0	0	0
SUB M	1	0	0	1	0	1	1	0	$(A) \leftarrow (A) - [(H) (L)]$	1	7	0	0	0	0	0
SBB M	1	0	0	1	1	1	1	0	$(A) \leftarrow (A) - [(H) (L)] - (C)$	1	7	0	0	0	0	0
SUI d8	1	1	0	1	0	1	1	0	$(A) \leftarrow (A) - (B_2)$	2	7	0	0	0	0	0
				B_2												
SBI d8	1	1	0	1	1	1	1	0	$(A) \leftarrow (A) - (B_2) - (C)$	2	7	0	0	0	0	0
				B_2												
DAA	0	0	1	0	0	1	1	1	The 8-bit number in the accumulator is adjusted to form two 4-bit BCD digits by the following process. Accumulator 7 4 3 0 X Y C AC 1. If $Y \geq 10$ or $AC = 1$, $(A) \leftarrow (A) + 6$ 2. If $X \geq 10$ or $C = 1$ $(A)_{4-7} \leftarrow (A)_{4-7} + 6$	1	4	0	0	0	0	0

Fig 1 (cont'd)

Logical Instruction

Mnemonic	Instruction Code								Operation	Bytes	States	Flag				
	D7	D6	D5	D4	D3	D2	D1	D0				C	Z	S	P	AC
ANA r	1	0	1	0	0	S	S	S	$(A) \leftarrow (A) \wedge (r)$	1	4	R	0	0	0	S
ANA M	1	0	1	0	0	1	1	0	$(A) \leftarrow (A) \wedge [(H)(L)]$	1	7	R	0	0	0	S
ANI d8	1	1	1	0	0	1	1	0	$(A) \leftarrow (A) \wedge (B_2)$	2	7	R	0	0	0	S
				B_2												
XRA r	1	0	1	0	1	S	S	S	$(A) \leftarrow (A) \vee (r)$	1	4	R	0	0	0	R
XRA M	1	0	1	0	1	1	1	0	$(A) \leftarrow (A) \vee [(H)(L)]$	1	7	R	0	0	0	R
XRI d8	1	1	1	0	1	1	1	0	$(A) \leftarrow (A) \vee (B_2)$	2	7	R	0	0	0	R
				B_2												
ORA r	1	0	1	1	0	S	S	S	$(A) \leftarrow (A) \vee (r)$	1	4	R	0	0	0	R
ORA M	1	0	1	1	0	1	1	0	$(A) \leftarrow (A) \vee [(H)(L)]$	1	7	R	0	0	0	R
ORI d8	1	1	1	1	0	1	1	0	$(A) \leftarrow (A) \vee (B_2)$	2	7	R	0	0	0	R
				B_2												
CMP r	1	0	1	1	1	S	S	S	$(A) - (r)$	1	4	0	0	0	0	0
CMP M	1	0	1	1	1	1	1	0	$(A) - [(H)(L)]$	1	7	0	0	0	0	0
CPI d8	1	1	1	1	1	1	1	0	$(A) - (B_2)$	2	7	0	0	0	0	0
				B_2												
CMA	0	0	1	0	1	1	1	1	$(A) \leftarrow (\bar{A})$	1	4	-	-	-	-	-
RLC	0	0	0	0	0	1	1	1	$(An+1) \leftarrow (An)$ $(A_0) \leftarrow (A_7)$ $(C) \leftarrow (A_7)$	1	4	0	-	-	-	-
RRC	0	0	0	0	1	1	1	1	$(An) \leftarrow (An+1)$ $(A_7) \leftarrow (A_0)$ $(C) \leftarrow (A_0)$	1	4	0	-	-	-	-
RAL	0	0	0	1	0	1	1	1	$(An+1) \leftarrow (An)$ $(C) \leftarrow (A_7)$ $(A_0) \leftarrow (C)$	1	4	0	-	-	-	-
RAR	0	0	0	1	1	1	1	1	$(An) \leftarrow (An+1)$ $(C) \leftarrow (A_0)$ $(A_7) \leftarrow (C)$	1	4	0	-	-	-	-

Increment and Decrement

Mnemonic	Instruction Code								Operation	Bytes	States	Flag				
	D7	D6	D5	D4	D3	D2	D1	D0				C	Z	S	P	AC
INR r	0	0	d	d	d	1	0	0	$(r) \leftarrow (r) + 1$	1	4	-	0	0	0	0
INR M	0	0	1	1	0	1	0	0	$[(H)(L)] \leftarrow [(H)(L)] + 1$	1	10	-	0	0	0	0
INX rp	0	0	R	P	0	0	1	1	$(rH)(rL) \leftarrow (rH)(rL) + 1$	1	6	-	-	-	-	-
DCR r	0	0	d	d	d	1	0	1	$(r) \leftarrow (r) - 1$	1	4	-	0	0	0	0
DCR M	0	0	1	1	0	1	0	1	$[(H)(L)] \leftarrow [(H)(L)] - 1$	1	10	-	0	0	0	0
DCX rp	0	0	R	P	1	0	1	1	$(rH)(rL) \leftarrow (rH)(rL) - 1$	1	6	-	-	-	-	-

Fig 1 (cont'd)

Stack

Mnemonic	Instruction Code								Operation	Bytes	States	Flag																				
	D7	D6	D5	D4	D3	D2	D1	D0				C	Z	S	P	AC																
PUSH <i>rp</i>	1	1	R	P	0	1	0	1	{(SP) - 1} ← (rH) {(SP) - 2} ← (rL) (SP) ← (SP) - 2 Note: Register pair <i>rp</i> = SP may not be specified.	1	12	-	-	-	-	-																
PUSH PSW	1	1	1	1	0	1	0	1	{(SP) - 1} ← (A) {(SP) - 2} ← <table border="1"><tr><td>D7</td><td>D6</td><td>D5</td><td>D4</td><td>D3</td><td>D2</td><td>D1</td><td>D0</td></tr><tr><td>S</td><td>Z</td><td>X</td><td>AC</td><td>X</td><td>P</td><td>X</td><td>C</td></tr></table> (MSB)	D7	D6	D5	D4	D3	D2	D1	D0	S	Z	X	AC	X	P	X	C	1	12	-	-	-	-	-
D7	D6	D5	D4	D3	D2	D1	D0																									
S	Z	X	AC	X	P	X	C																									
POP <i>rp</i>	1	1	R	P	0	0	0	1	(SP) ← (SP) - 2 (rL) ← {(SP)} (rH) ← {(SP) + 1} (SP) ← (SP) + 2	1	10	-	-	-	-	-																
POP PSW	1	1	1	1	0	0	0	1	(C) ← {(SP)} ₀ (P) ← {(SP)} ₁ (AC) ← {(SP)} ₄ (Z) ← {(SP)} ₅ (S) ← {(SP)} ₇ (A) ← {(SP) + 1} (SP) ← (SP) + 2	1	10	0	0	0	0	0																

Control

Mnemonic	Instruction Code								Operation	Bytes	States	Flag				
	D7	D6	D5	D4	D3	D2	D1	D0				C	Z	S	P	AC
HLT	0	1	1	1	0	1	1	0	Halt	1	5	-	-	-	-	-
STC	0	0	1	1	0	1	1	1	$(C) \leftarrow 1$	1	4	0	-	-	-	-
CMC	0	0	1	1	1	1	1	1	$(C) \leftarrow (\bar{C})$	1	4	0	-	-	-	-
EI	1	1	1	1	1	0	1	1	Enable interrupts Note: Interrupts are not recognized during the EI instruction.	1	4	-	-	-	-	-
DI	1	1	1	1	0	0	1	1	Disable interrupts Note: Interrupts are not recognized during the DI instruction.	1	4	-	-	-	-	-
NOP	0	0	0	0	0	0	0	0	No operation is performed.	1	4	-	-	-	-	-
RIM	0	0	1	0	0	0	0	0	$(A) \leftarrow$ $d_7 = SID$ $d_6 = I7$ $d_5 = I6$ $d_4 = I5$	1	4	-	-	-	-	-

Fig 1 (cont'd)

									$d_3 = 1E$ $d_2 = M7$ $d_1 = M6$ $d_0 = M5$ IF (A) ₄ = 1; SOD = (A) ₇ , IF (A) ₃ = 1; M ₇ = (A) ₂ , M ₆ = (A) ₁ ; M ₅ = (A) ₀ , IF (A) ₄ = 1; RST7.5 RESET						
SIM	0	0	1	1	0	0	0	0		1	4	-	-	-	-

ABSOLUTE MAXIMUM RATINGS

Symbol	Item	Ratings*
V _{CC}	V _{CC} Supply Voltage	-0.5V to 7.0V
P _D	Power Dissipation	1.5W
T _{solder}	Soldering Temperature (Soldering Time 10 sec.)	250°C
T _{stg}	Storage Temperature	-55°C to 150°C
T _{opr}	Operating Temperature	0°C to 70°C

D.C. CHARACTERISTICS

TA = 0°C to 70°C, V_{CC} = 5V ± 5%

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Units
V _{IL}	Input Low Voltage		-0.5		0.8	V
V _{IH}	Input High Voltage		2.0		V _{CC} + 0.5	V
V _{OL}	Output Low Voltage	I _{OL} = 2mA			0.45	V
V _{OH}	Output High Voltage	I _{OH} = -400μA	2.4			V
I _{CC}	Power Supply Current				170	mA
I _{IL}	Input Leakage	V _{IN} = V _{CC}			± 10	μA
I _{LO}	Output Leakage	0.45 ≤ OUT ≤ V _{CC}			± 10	μA
V _{ILR}	Input Low Level (RESET)		-0.5		0.8	V
V _{IHR}	Input High Level (RESET)		2.4		V _{CC} + 0.5	V
V _{HT}	Hysteresis (RESET)		0.25			V

Fig 1 (cont'd)

A.C. CHARACTERISTICS

TA = 0°C to 70°C, V_{CC} = 5V ± 5%, V_{SS} = 0V

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Units
t _{CYC}	CLK Cycle Period		320		2000	ns
t _L	CLK Low Time — Standard 150pF Loading — Lightly Loaded [2]		80 100			ns ns
t _H	CLK High Time — Standard 150pF Loading — Lightly Loaded [2]		120 150			ns ns
t _r , t _f	CLK Rise and Fall Time				30	ns
t _{XKR}	X ₁ Rising to CLK Rising		30		120	ns
t _{XKF}	X ₁ Falling to CLK Falling		30		150	ns
t _{AC}	A ₈₋₁₅ Valid to Leading Edge of Control [1]		270			ns
t _{ACL}	A ₀₋₇ Valid to Leading Edge of Control		240			ns
t _{AD}	A ₀₋₁₅ Valid to Valid Data In				575	ns
t _{AFR}	Address Float after Leading Edge of READ (INTA)				0	ns
t _{AL}	A ₈₋₁₅ Valid before Trailing Edge of ALE [1]	CL = 150pF t _{CYC} = 320ns	115			ns
t _{ALL}	A ₀₋₇ Valid before Trailing Edge of ALE		90			ns
t _{ARY}	READY Valid from Address Valid			220		ns
t _{CA}	Address (A ₈₋₁₅) Valid after Control		120			ns
t _{CC}	Width of Control Low (RD, WR, INTA) Edge of ALE		400			ns
t _{CL}	Trailing Edge of Control to Leading Edge of ALE		50			ns
t _{OW}	Data Valid to Trailing Edge of WRITE		420			ns
t _{HABE}	HLOA to Bus Enable			210		ns
t _{HABF}	Bus Float after HLOA			210		ns
t _{HACK}	HLOA Valid to Trailing Edge of CLK		110			ns
t _{HCH}	HOLD Hold Time		0			ns
t _{HDS}	HOLD Setup Time to Trailing Edge of CLK		170			ns
t _{INH}	INTR Hold Time		0			ns
t _{INS}	INTR, RST and TRAP Setup Time to Falling Edge of CLK		160			ns
t _{LA}	Address Hold Time after ALE		100			ns
t _{LC}	Trailing Edge of ALE to Leading Edge of Control		130			ns
t _{LCK}	ALE Low during CLK High		100			ns
t _{LDR}	ALE to Valid Data during Read			460		ns
t _{LW}	ALE to Valid Data during Write			200		ns
t _{LL}	ALE Width		140			ns
t _{LRV}	ALE to READY Stable			110		ns
t _{RAE}	Trailing Edge of READ to Re-Enabling of Address		150			ns
t _{RD}	READ (or INTA) to Valid Data			300		ns
t _{RV}	Control Trailing Edge to Leading Edge of Next Control		400			ns
t _{ROH}	Data Hold Time After READ/INTA		0			ns
t _{RVH}	READY Hold Time		0			ns
t _{RVS}	READY Setup Time to Leading Edge of CLK		110			ns
t _{WD}	Data Valid After Trailing Edge of WRITE		100			ns
t _{WDL}	LEADING Edge of WRITE to Data Valid			40		ns

- Notes: 1. A₈₋₁₅ address pins apply to IO/M, S₀ and S₁ except A₈₋₁₅ are undefined during T₁ — T₅ of OF cycle whereas IO/M, S₀, and S₁ are stable.
 2. Loading equivalent to 50 pF + 1 TTL input.
 3. All timings are measured at output voltage V_L = 0.8V, V_H = 2.0V.
 4. To calculate timing specifications at other value of t_{CYC} use Table 4.

Fig 1 (cont'd)

Table 4. Bus Timing Specification as t_{CYC} Dependent

t_{AL}	$(1/2) T - 45$	MIN	t_{CC}	$(3/2 + N) T - 80$	MIN
t_{LA}	$(1/2) T - 60$	MIN	t_{CL}	$(1/2) T - 110$	MIN
t_{LL}	$(1/2) T - 20$	MIN	t_{ARY}	$(3/2) T - 260$	MAX
t_{LCK}	$(1/2) T - 60$	MIN	t_{HACK}	$(1/2) T - 50$	MIN
t_{LC}	$(1/2) T - 30$	MIN	t_{HABF}	$(1/2) T + 50$	MAX
t_{AD}	$(5/2 + N) T - 225$	MAX	t_{HABE}	$(1/2) T + 50$	MAX
t_{RD}	$(3/2 + N) T - 180$	MAX	t_{AC}	$(2/2) T - 50$	MIN
t_{RAE}	$(1/2) T - 10$	MIN	t_L	$(1/2) T - 80$	MIN
t_{CA}	$(1/2) T - 40$	MIN	t_H	$(1/2) T - 40$	MIN
t_{OW}	$(3/2 + N) T - 60$	MIN	t_{RV}	$(3/2) T - 80$	MIN
t_{WD}	$(1/2) T - 60$	MIN	t_{LDR}	$(4/2) T - 180$	MAX

Note: N is equal to the total WAIT states.
 $T = t_{CYC}$

Fig. 4 Clock Timing Waveform

Fig. 5 Read Operation

Fig. 6 Write Operation

Fig. 7 Read Operation with Wait Cycle (Typical)
- Same Ready Timing Applies to Write Operation

Fig. 8 Interrupt and Hold Timing

Fig 1 (cont'd)

OUTLINE DRAWING

- Notes: 1. This dimension shows the center of curvature of legs.
 2. This dimension shows spread of legs.
 3. The pitch of legs is 2.54 and the tolerance is ± 0.25 from the theoretical center of each leg obtained having leg No. 1 and leg No. 40 as the reference.

Fig 1 (cont'd)

Am8155/Am8156
2048-Bit Static MOS RAM With I/O Ports and Timer
Advanced Micro Devices

PRODUCT SPECIFICATION

April 1981

Fig2. Am8156 Interface Chip Data Sheet.

FUNCTIONAL PIN DEFINITION

The following describes the functions of all of the Am8155/Am8156 pins.

RESET

The Reset signal is a pulse provided by the Am8085 to initialize the system. Input high on this line resets the chip and initializes the three I/O ports to input mode. The width of RESET pulse should typically be 800ns. (Two Am8085A clock cycle times).

AD₀-AD₇

These are 3-state Address/Data lines that interface with the CPU lower 8-bit Address/Data Bus. The 8-bit address is latched into the address latch on the falling edge of the ALE. The address can be either for the memory section or the I/O section depending on the polarity of the IO/ $\overline{M}$ input signal. The 8-bit data is either written into the chip or read from the chip depending on the status of WRITE or READ input signal.

CE OR $\overline{CE}$

Chip Enable: On the Am8155, this pin is $\overline{CE}$ and is ACTIVE LOW. On the Am8156, this pin is CE and is ACTIVE HIGH.

$\overline{RD}$

Input low on this line with the Chip Enable active enables the AD₀₋₇ buffers. If IO/ $\overline{M}$ pin is low, the RAM content will be read out to the AD bus. Otherwise the content of the selected I/O port will be read to the AD bus.

$\overline{WR}$

Input low on this line with the Chip Enable active causes the data on the AD lines to be written to the RAM or I/O ports depending on the polarity of IO/ $\overline{M}$.

ALE

Address Latch Enable: This control signal latches both the address on the AD₀₋₇ lines and the state of the Chip Enable and IO/ $\overline{M}$ into the chip at the falling edge of ALE.

IO/ $\overline{M}$

IO/Memory Select: This line selects the memory if low and selects the IO if high.

PA₀-PA₇

These 8 pins are general purpose I/O pins. The in/out direction is selected by programming the Command/Status Register.

PB₀-PB₇

These 8 pins are general purpose I/O pins. The in/out direction is selected by programming the Command/Status Register.

PC₀-PC₅

These 6 pins can function as either input port, output port, or as control signals for PA and PB. Programming is done through the C/S Register. When PC₀₋₅ are used as control signals, they will provide the following:

- PC₀ - A INTR (Port A Interrupt)
- PC₁ - A BF (Port A Buffer full)
- PC₂ - $\overline{A}$ STB (Port A Strobe)
- PC₃ - B INTR (Port B Interrupt)
- PC₄ - B BF (Port B Buffer Full)
- PC₅ - $\overline{B}$ STB (Port B Strobe)

TIMER IN

This is the input to the counter timer.

TIMER OUT

This pin is the timer output. This output can be either a square wave or a pulse depending on the timer mode.

V_{CC}

+5 volt supply.

V_{SS}

Ground reference.

MAXIMUM RATINGS above which useful life may be impaired

Storage Temperature	-65°C to +150°C
Ambient Temperature Under Bias	-55°C to +125°C
V _{CC} with Respect to V _{SS}	-0.5V to +7.0V
All Signal Voltages with Respect to V _{SS}	-0.5V to +7.0V
Power Dissipation	1.5W

The products described by this specification include internal circuitry designed to protect input devices from damaging accumulations of static charge. It is suggested, nevertheless, that conventional precautions be observed during storage, handling and use in order to avoid exposure to excessive voltages.

DC CHARACTERISTICS

Parameters	Description	Test Conditions	Min.	Typ.	Max.	Units
V _{IL}	Input Low Voltage		-0.5		0.8	Volts
V _{IH}	Input High Voltage		2.0		V _{CC} +0.5	Volts
V _{OL}	Output Low Voltage	I _{OL} = 2mA			0.45	
V _{OH}	Output High Voltage	I _{OH} = -400μA	2.4			Volts
I _{IL}	Input Leakage	V _{IH} = V _{CC} to 0V			±10	μA
I _{LO}	Output Leakage Current	0.45V < V _{OUT} < V _{CC}			±10	μA
I _{CC}	V _{CC} Supply Current				180	mA
I _{IL} (CE)	Chip Enable Leakage	Am8155 Am8156 V _{IH} = V _{CC} to 0V		+100 -100		μA

I_{OL} = 1.6mA for Am8155DM and Am8156DM

Fig2. (Cont'd)

OPERATING RANGE

Part Number	Ambient Temperature	V _{CC}	V _{SS}
Am8155/Am8155-2 Am8156/Am8156-2	0°C ≤ T _A ≤ +70°C	+5.0V ± 5%	0V
Am8155DM Am8156DM	-55°C ≤ T _A ≤ +125°C	+5.0V ± 10%	0V

AC CHARACTERISTICS

Parameters	Description	Am8155/Am8156 Am8155DM/Am8156DM		Am8155-2/Am8156-2		Units
		Min	Max	Min	Max	
t _{AL}	Address to Latch Setup Time	50		30		ns
t _{LA}	Address Hold Time after Latch	80		30		ns
t _{LC}	Latch to READ/WRITE Control	100		40		ns
t _{AO}	Valid Data Out Delay from READ Control		170		140	ns
t _{AD}	Address Stable to Data Out Valid		400		330	ns
t _{LL}	Latch Enable Width	100		70		ns
t _{DOF}	Data Bus Float After READ	0	100	0	80	ns
t _{CL}	READ/WRITE Control to Latch Enable	20		10		ns
t _{CC}	READ/WRITE Control Width	250		200		ns
t _{OW}	Data In to WRITE Setup Time	150		100		ns
t _{WO}	Data In Hold Time After WRITE	0		0		ns
t _{RV}	Recovery Time Between Controls	300		200		ns
t _{WP}	WRITE to Port Output		400		300	ns
t _{PI}	Port Input Setup Time	70		50		ns
t _{PH}	Port Input Hold Time	50		10		ns
t _{SBF}	Strobe to Buffer Full		400		300	ns
t _{SS}	Strobe Width	200		150		ns
t _{BE}	READ to Buffer Empty		400		300	ns
t _{SI}	Strobe to INTR On		400		300	ns
t _{RO}	READ to INTR Off		400		300	ns
t _{PSS}	Port Setup Time to Strobe-Strobe	50		0		ns
t _{PMS}	Port Hold Time After Strobe	120		100		ns
t _{SE}	Strobe to Buffer Empty		400		300	ns
t _{WBF}	WRITE to Buffer Full		400		300	ns
t _{WI}	WRITE to INTR Off		400		300	ns
t _{TL}	TIMER-IN to TIMER-OUT Low		400		300	ns
t _{TH}	TIMER-IN to TIMER-OUT High		400		300	ns
t _{RDE}	Data Bus Enable from READ Control	10		10		ns
t ₁	TIMER-IN Low Time	80		40		ns
t ₂	TIMER-IN High Time	120		70		ns

Note: Test Condition: 150pF Load.

Fig 2. (Cont'd)

INPUT/OUTPUT SECTION

The I/O section of the Am8155/8156 consists of four registers as described below.

- **Command/Status Register (C/S)** - This register is assigned the address XXXXX000. The C/S address serves the dual purpose.

When the C/S register is selected during WRITE operation, a command is written into the command register. The contents of this register are not accessible through the pins.

When the C/S (XXXXX000) is selected during a READ operation, the status information of the I/O ports and the timer become available on the AD₀₋₇ lines.

- **PA Register** - This register can be programmed to be either input or output ports depending on the status of the contents of the C/S Register. Also depending on the command, this port can operate in either the basic mode or the strobed mode (see timing diagram). The I/O pins assigned in relation to this register are PA₀₋₇. The address of this register is XXXXX001.

- **PB Register** - This register functions the same as PA Register. The I/O pins assigned are PB₀₋₇. The address of this register is XXXXX010.

- **PC Register** - This register has the address XXXXX011 and contains only 6 bits. The 6 bits can be programmed to be either input ports, output ports or as control signals for PA and PB by properly programming the AD₂ and AD₃ bits of the C/S register.

When PC₀₋₅ is used as a control port, 3 bits are assigned for Port A and 3 for Port B. The first bit is an interrupt that the Am8155 sends out. The second is an output signal indicating whether the buffer is full or empty, and the third is an input pin to accept a strobe for the strobed input mode. See Table 1.

When the 'C' port is programmed to either ALT3 or ALT4, the control signals for PA and PB are initialized as follows:

Control	Input Mode	Output Mode
BF	Low	Low
INTR	Low	High
STB	Input Control	Input Control

The set and reset of INTR and BF with respect to STB, WR and RD timing is shown in Figure 8.

To summarize, the register's assignments are:

Address	Pins	Functions	No. of Bits
XXXXX000	Internal	Command/Status Register	8
XXXXX001	PA ₀₋₇	General Purpose I/O Port	8
XXXXX010	PB ₀₋₇	General Purpose I/O Port	8
XXXXX011	PC ₀₋₅	General Purpose I/O Port or Control Lines	6

Table 1. Table of Port Control Assignment.

Pin	ALT 1	ALT 2	ALT 3	ALT 4
PC0	Input Port	Output Port	A INTR (Port A Interrupt)	A INTR (Port A Interrupt)
PC1	Input Port	Output Port	A BF (Port A Buffer Full)	A BF (Port A Buffer Full)
PC2	Input Port	Output Port	A STB (Port A Strobe)	A STB (Port A Strobe)
PC3	Input Port	Output Port	Output Port	B INTR (Port B Interrupt)
PC4	Input Port	Output Port	Output Port	B BF (Port B Buffer Full)
PC5	Input Port	Output Port	Output Port	B STB (Port B Strobe)

The following diagram shows how I/O Ports A and B are structured within the Am8155 and Am8156:

Am8155/Am8156
One Bit of Port A or Port B

MO8-073

- Notes:
1. Output Mode
 2. Simple Input
 3. Strobed Input
 4. = 1 for output mode
= 0 for input mode.

Read Port = $(\overline{IO/\overline{M}} = 1) \cdot (\overline{RD} = 0) \cdot (CE \text{ active}) \cdot (\text{Port address selected})$

Write Port = $(\overline{IO/\overline{M}} = 1) \cdot (\overline{WR} = 0) \cdot (CE \text{ active}) \cdot (\text{Port address selected})$

Note in the diagram that when the I/O ports are programmed to be output ports, the contents of the output ports can still be read by a READ operation when appropriately addressed.

Note also that the output latch is cleared when the port enters the input mode. The output latch cannot be loaded by writing to the port if the port is in the input mode. The result is that each time a port mode is changed from input to output, the output pins will go low. When the Am8155/8156 is RESET, the output latches are all cleared and all 3 ports enter the input mode.

When in the ALT 1 or ALT 2 modes, the bits of Port C are structured like the diagram above in the simple input or output mode, respectively.

Reading from an input port with nothing connected to the pins will provide unpredictable results.

TIMER SECTION

The timer is a 14-bit down counter that counts the timer input pulses and provides either a square wave or pulse when terminal count (TC) is reached.

The timer has the I/O address XXXXX100 for the low order byte of the register and the I/O address XXXXX101 for the high order byte of the register.

To program the timer, the COUNT LENGTH REG is loaded first, one byte at a time, by selecting the timer addresses. Bits 0-13 will specify the length of the next count and bits 14-15 will specify the timer output mode. The value loaded into the count length register can have any value from 2_4 through $3FFF_4$ in bits 0-13.

There are four modes to choose from:

- 0 - Puts out low during second half of count
- 1 - Square wave
- 2 - Single pulse upon TC being reached
- 3 - Repetitive single pulse everytime TC is reached and automatic reload of counter upon TC being reached, until instructed to stop by a new command loaded into C/S.

Bits 6-7 of Command/Status Register Contents are used to start and stop the counter. There are four commands to choose from (See the further description on Command/Status Register.).

C/S7 C/S6

0	0	NOP - Do not affect counter operation.
0	1	STOP - NOP if timer has not started; stop counting if the timer is running.
1	0	STOP AFTER TC - Stop immediately after present TC is reached (NOP if timer has not started).
1	1	START - Load mode and CNT length and start immediately after loading (if timer is not presently running). If timer is running, start the new mode and CNT length immediately after present TC is reached.

Figure 4. Timer Format.

M2 and M1 define the timer mode as follows:

M2	M1	
0	0	Puts out low during second half of count.
0	1	Square wave, i.e., the period of the square wave equals the count length programmed with automatic reload at terminal count.
1	0	Single pulse upon TC being reached.
1	1	Automatic reload, i.e., single pulse everytime TC is reached.

Note: In case of an asymmetric count, i.e., 9, larger half of the count will be high, the larger count will stay active as shown in Figure 5.

Note: 5 and 4 refer to the number of clock cycles in that time period.

Figure 5. Asymmetric Count.

The counter in the Am8155 is not initialized to any particular mode or count when hardware RESET occurs, but RESET does stop the counting. Therefore, counting cannot begin following RESET until a START command is issued via the C/S register.

From the ACCOMMODATION SECRETARY

EASTER VACATION ARRANGEMENTS 1986

BEGINNING OF VACATION

ALL STUDENTS ARE PERMITTED TO STAY IN THEIR PRESENT HALLS UNTIL 1300 HOURS ON SATURDAY, 22nd MARCH BUT FOR THE CONVENIENCE OF CLEANING YOU MUST VACATE YOUR ROOMS BY 1000 HOURS. KEYS TO YOUR ROOMS IN FALKNER/EGGINGTON COURTS AND WILLIAM MORRIS WILL BE AVAILABLE AFTER 1300 HOURS ON SATURDAY 22nd MARCH. KEYS WILL BE ISSUED AGAINST A DEPOSIT AND MUST BE RETURNED WHEN YOU LEAVE.

END OF VACATION

TERM RESTARTS ON 28th APRIL 1986. YOU MAY RETURN TO YOUR TERM TIME ACCOMMODATION ON SATURDAY 26th APRIL.

ROOMS MUST BE CLEARED BY 0930 HOURS ON SATURDAY AND KEYS RETURNED BY 1000 HOURS ON SATURDAY, 26th APRIL.

YOU SHOULD ENSURE THAT YOUR ROOM IS LOCKED WHEN YOU LEAVE IT.

Figure 7. Am8155/8156 Read/Write Timing Diagrams.

Fig 2. (Cont'd)

WAVEFORMS (Cont.)

A. STROBED INPUT MODE.

MOB-079

B. STROBED OUTPUT MODE.

Figure 8. Strobed I/O Timing.

MOB-079

BASIC INPUT MODE.

MOB-080

BASIC OUTPUT MODE.

MOB-081

*Data bus timing is shown in Figure 7.

Figure 9. Basic I/O Timing Waveform.

WAVEFORMS (Cont.)

MOS-082

Note 1: The timer output is periodic if in an automatic reload mode (M_1 mode bit = 1).

Figure 10. Timer Output Waveform Countdown from 5 to 1.

Fig 2. (Cont'd)

PHYSICAL DIMENSIONS

40-Pin Cardip

40-Pin Molded DIP

Reference Symbol	Min.	Max.
A	100	200
B	275	300
C	275	300
D	200	215
E	2.000	2.100
F	3.40	3.60
G	200	220
H	200	220
I	200	220
J	200	220
K	200	220
L	200	220
M	200	220
N	200	220
O	200	220
P	200	220
Q	200	220
R	200	220
S	200	220
T	200	220
U	200	220
V	200	220
W	200	220
X	200	220
Y	200	220
Z	200	220

Reference Symbol	Min.	Max.
A	100	200
B	275	300
C	275	300
D	200	215
E	2.000	2.100
F	3.40	3.60
G	200	220
H	200	220
I	200	220
J	200	220
K	200	220
L	200	220
M	200	220
N	200	220
O	200	220
P	200	220
Q	200	220
R	200	220
S	200	220
T	200	220
U	200	220
V	200	220
W	200	220
X	200	220
Y	200	220
Z	200	220

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Fig 2. (Cont'd)

APPENDIX V

HEKTOR Microprocessor Development System - CSo Software

The HEKTOR microprocessor software is based on the 8085 Assembly Language, the types of Instructions available with this language shown in Figure 1. The Instruction set is quite comprehensive, and is listed in Figure 2. The memory of the HEKTOR system contains 4 x 1k of Random Access Memory, which is allocated for the user read/write operations, the RAM addresses being at 3000-3FFF Hex. The remainder of the memory map is taken by the system software, as shown in Figure 3.

The CSo program was written in assembler using the text buffer and Editor facilities of the system. The text was then translated into machine code using the system's ROM Assembler, a three-pass operation where, during the third and final pass the machine code is produced, and stored in the machine code buffer allocated in the free area of the memory, following the text buffer.

The assembled version of the CSo program is shown in its memory-mapped form in Figure 4. In this form, the information given in the program listing includes the entry points for the system routines used, a complete list of which is given in Figure 5.

Further to the description and flowchart of the CSo program given in Section 3, HEKTOR's Interrupt system, and in particular Interrupt RST7.5 with Vector address 2F0D/2F0E Hex., Figure 6, was used in conjunction with the signal output from the crankshaft-mounted opto-switch, via the interface, to initiate the output of CSo sequences to the S.C.R.'s.

The Origin/Entry address of the program is 3A2F Hex., that is the program, once loaded into the machine code buffer can be executed from the MONITOR status by entering:

G3A2F <CR>

The operator then has the following choices:

- (i) Input new CSo sequences, as described in Section 3, by entering '1' or '0'.
- (ii) Display all CSo sequences, by entering 'R' .
- (iii) Move the stack pointer to the top CSo sequence Table address, by entering 'T' .
- (iv) Enable the Interrupts, and hence output the sequences to the S.C.R.'s, by entering 'O' .

The CSo sequences entered by the above method are stored in the user part of the memory, beginning at address :

DATA : 3B41 Hex.

The user memory, although expanded from standard by 0.256K of RAM on the interface 8155/8156 chip, it still needs further expansion in order to be able to use other Interrupts (RST5.5, RST6.5), to incorporate further refinements to the CSo system as has been discussed in Section 5.

Data Copy Group		XRA	Logical EXCLUSIVE-OR register/memory contents with A register contents		166
MOV	Copy data between register/memory and register/memory	XRI	Logical EXCLUSIVE-OR operand data with A register contents		
MVI	Copy operand data to register/memory	CMP	Compare register/memory contents with A register contents		
LDA } LDAX }	Copy data from memory to A register	CPI	Compare operand data with A register contents		
STA } STAX }		RLC	Rotate A register contents left, and into Carry		
LHLD	Copy data from memory to HL register pair	RRC	Rotate A register contents right, and into Carry		
SHLD	Copy data from HL register pair to memory	RAL	Rotate A register and Carry contents left		
LXI	Copy operand data to register pair	RAR	Rotate A register and Carry contents right		
XCHG	Exchange data between HL and DE register pairs	CMA	Complement A register contents		
XTHL	Exchange data between HL register pair and top of stack	CMC	Complement Carry contents		
		STC	Set Carry contents to 1		
Arithmetic Group					
ADD	Add register/memory contents to A register contents	Program Sequence Control Group			
ADI	Add operand data to A register contents	Jump if:	Call if:	Return if:	Condition is:
ADC	Add register/memory and Carry contents to A register contents	JC	CC	RC	Carry (Carry=1)
ACI	Add operand data and Carry contents to A register contents	JNC	CNC	RNC	No Carry (Carry=0)
SUB	Subtract register/memory contents from A register contents	JZ	CZ	RZ	Zero (Zero=1)
SUI	Subtract operand data from A register contents	JNZ	CNZ	RNZ	Not Zero (Zero=0)
SBB	Subtract register/memory and Carry contents from A register contents	JP	CP	RP	Plus (Sign=0)
SBI	Subtract operand data and Carry contents from A register contents	JM	CM	RM	Minus (Sign=1)
INR	Increment register/memory contents by 1	JPE	CPE	RPE	Parity even (Parity=1)
DCR	Decrement register/memory contents by 1	JPO	CPO	RPO	Parity odd (Parity=0)
INX	Increment register pair contents by 1	JMP	CALL	RET	Unconditionally
DCX	Decrement register pair contents by 1	PCHL	Copy data from HL register pair to Program Counter		
DAD	Add register pair contents to HL register pair contents	RST	Call routine at restart address		
DAA	Adjust A register contents for BCD result following addition	Stack Operation Group			
		PUSH	Push register pair contents onto the stack		
		POP	Pop top of stack data into register pair		
		SPHL	Copy data from HL register pair to Stack Pointer		
Logical Group					
ANA	Logical AND register/memory contents with A register contents	Input/Output Group			
ANI	Logical AND operand data with A register contents	IN	Copy data from I/O device to A register		
ORA	Logical OR register/memory contents with A register contents	OUT	Copy data from A register to I/O device		
ORI	Logical OR operand data with A register contents	Machine Control Group			
		EI	Enable interrupt system		
		DI	Disable interrupt system		
		RIM	Copy Interrupt Status data to A register		
		SIM	Copy A register contents to Interrupt Control		
		HLT	Halt processor		
		NOP	No operation		

Fig 1 Summary of 8085 Instruction Types.

<i>Hexadecimal address</i>	<i>Corresponding physical device</i>	<i>Principal usage by system software</i>	<i>Address range used by software</i>
0000-1FFF	2x4K ROM devices	storage of system programs/ routines	0000-1FFF
2000-27FF	none	none	none
2800-2BFF	TV output data port	TV interface	2800 only
2C00-2FFF	1/4K RAM in 8155 device	workspace/stack for system programs	2F00-2FFF
3000-3FFF	4x1K RAM devices	user read/write memory	3000-3FFF
4000-7FFF	(external 1/4K periph. board)	none	none
8000-9FFF	same devices as for addresses 0000 to 1FFF		0000-1FFF
A000-A7FF	none	none	none
A800-ABFF	same devices as for addresses 2800 to 2BFF		2800 only
AC00-AFFF	I/O ports of 8155 device	keyboard, TV, cassette control	AC00-AC05
B000-BFFF	same devices as for addresses 3000 to 3FFF		3000-3FFF
C000-FFFF	none	none	none

Fig 3 HEKTOR Memory Map

PASS 1

.PASS 2

PASS 3

```

0001 ;DISABLEMENT SEQUENCE PROGRAM.
3A2F 0002 KR: EQU 05BEH
3A2F 0003 TV: EQU 06COH
3A2F 0004 PRSP: EQU 02E7H
3A2F 0005 PRNL: EQU 02DAH
3A2F 0006 PRB: EQU 035DH
3A2F 0007 PRWD: EQU 0351H
3A2F 0008 VEC: EQU 02FODH
0009 ;
3A2F CDDA02 0010 CALL PRNL
3A32 40 0011 MES: DB 'BINARY HEX ADDRESS@'
3A45 00 0012 NOP
3A46 21323A 0013 LXI H,MES
3A49 7E 0014 PRINT: MOV A,M
3A4A FE40 0015 CPI '@'
3A4C C4C006 0016 CNZ TV
3A4F 23 0017 INX H
3A50 C2493A 0018 JNZ PRINT
0019 ;END OF PRINTING SUBROUTINE
3A53 CDDA02 0020 CALL PRNL
3A56 21413B 0021 LXI H,DATA
3A59 00 0022 START: NOP
3A5A 3E00 0023 MVI A,00H
3A5C 0609 0024 MVI B,09
3A5E E5 0025 PUSH H
3A5F F5 0026 PUSH PSW
0027 ;
3A60 05 0028 CHAR: DCR B
3A61 C4BE05 0029 CNZ KR
3A64 C4C006 0030 CNZ TV
3A67 C28C3A 0031 JNZ ZERO
3A6A F1 0032 POP PSW
3A6B CDE702 0033 CALL PRSP
3A6E CDE702 0034 CALL PRSP
3A71 CDE702 0035 CALL PRSP
3A74 E1 0036 POP H
3A75 77 0037 MOV M,A
3A76 CD5D03 0038 CALL PRB
3A79 CDE702 0039 CALL PRSP
3A7C CDE702 0040 CALL PRSP
3A7F CDE702 0041 CALL PRSP
3A82 CD5103 0042 CALL PRWD
3A85 23 0043 INX H
3A86 CDDA02 0044 CALL PRNL
3A89 C3593A 0045 JMP START
0046 ;SUBROUTINES:
3A8C 37 0047 ZERO: STC
3A8D 3F 0048 CMC

```

3A8E	FE30	0049		CPI	30H
3A90	C29B3A	0050		JNZ	ONE
3A93	F1	0051		POP	PSW
3A94	37	0052		STC	
3A95	3F	0053		CMC	
3A96	07	0054		RLC	
3A97	F5	0055		PUSH	PSW
3A98	C3603A	0056		JMP	CHAR
		0057	;		
3A9B	37	0058	ONE:	STC	
3A9C	3F	0059		CMC	
3A9D	FE31	0060		CPI	31H
3A9F	C2A93A	0061		JNZ	ERR
3AA2	F1	0062		POP	PSW
3AA3	37	0063		STC	
3AA4	17	0064		RAL	
3AA5	F5	0065		PUSH	PSW
3AA6	C3603A	0066		JMP	CHAR
		0067	;		
3AA9	FE52	0068	ERR:	CPI	52H
3AAB	CAB63A	0069		JZ	RUN
3AAE	F1	0070		POP	PSW
3AAF	E1	0071		POP	H
3AB0	CDDA02	0072		CALL	PRNL
3AB3	C3593A	0073		JMP	START
		0074	;		
3AB6	F1	0075	RUN:	POP	PSW
3AB7	E1	0076		POP	H
3AB8	21413B	0077		LXI	H, DATA
3ABB	CDDA02	0078		CALL	PRNL
3ABE	CDDA02	0079		CALL	PRNL
3AC1	CDDA02	0080		CALL	PRNL
3AC4	7E	0081	RDATA:	MOV	A, M
3AC5	FE00	0082		CPI	00H
3AC7	CA013B	0083		JZ	END
3ACA	0608	0084		MVI	B, 08
3ACC	F5	0085		PUSH	PSW
3ACD	CD5103	0086		CALL	PRWD
3AD0	CDE702	0087		CALL	PRSP
3AD3	CDE702	0088		CALL	PRSP
3AD6	F1	0089		POP	PSW
3AD7	07	0090	BIN:	RLC	
3AD8	DAE53A	0091		JC	ONE1
3ADB	D2F33A	0092		JNC	ZERO
3ADE	23	0093	CONT:	INX	H
3ADF	CDDA02	0094		CALL	PRNL
3AE2	C3C43A	0095		JMP	RDATA
		0096	;		
3AE5	F5	0097	ONE1:	PUSH	PSW
3AE6	3E31	0098		MVI	A, 31H

3AE8	CDC006	0099		CALL	TV
3AEB	F1	0100		POP	PSW
3AEC	05	0101		DCR	B
3AED	C2D73A	0102		JNZ	BIN
3AF0	CADE3A	0103		JZ	CONT
		0104	;		
3AF3	F5	0105	ZERO:	PUSH	PSW
3AF4	3E30	0106		MVI	A,30H
3AF6	CDC006	0107		CALL	TV
3AF9	F1	0108		POP	PSW
3AFA	05	0109		DCR	B
3AFB	C2D73A	0110		JNZ	BIN
3AFE	CADE3A	0111		JZ	CONT
		0112	;		
3B01	CDBE05	0113	END:	CALL	KR
3B04	FE54	0114		CPI	54H
3B06	CA323A	0115		JZ	MES
3B09	FE4F	0116		CPI	4FH
3B0B	CA173B	0117		JZ	OUT
3B0E	CDDA02	0118		CALL	PRNL
3B11	CDDA02	0119		CALL	PRNL
3B14	C3593A	0120		JMP	START
		0121	;		
3B17	11413B	0122	OUT:	LXI	D,DATA
3B1A	21273B	0123	MAIN:	LXI	H,LOOP
3B1D	220D2F	0124		SHLD	VEC
3B20	3E19	0125		MVI	A,19H
3B22	30	0126		SIM	
3B23	FB	0127		EI	
3B24	C31A3B	0128		JMP	MAIN
		0129	;		
3B27	F5	0130	LOOP:	PUSH	PSW
3B28	EB	0131		XCHG	
3B29	7E	0132		MOV	A,M
3B2A	FE00	0133		CPI	00H
3B2C	CA3A3B	0134		JZ	BEGIN
3B2F	23	0135	CON:	INX	H
3B30	EB	0136		XCHG	
3B31	2100C0	0137		LXI	H,0C000H
3B34	360F	0138		MVI	M,0FH
3B36	23	0139		INX	H
3B37	77	0140		MOV	M,A
3B38	F1	0141		POP	PSW
3B39	C9	0142		RET	
		0143	;		
3B3A	21413B	0144	BEGIN:	LXI	H,DATA
3B3D	7E	0145		MOV	A,M
3B3E	C32F3B	0146		JMP	CON
		0147	;		
3B41	00	0148	DATA:	NOP	

ORIGIN; ENTRY = 3A2F; 3A2F

KR	=	05BE	TV	=	06C0	PRSP	=	02E7	PRNL	=	02DA
PRB	=	035D	PRWD	=	0351	VEC	=	2F0D	MES	=	3A32
PRINT	=	3A49	START	=	3A59	CHAR	=	3A60	ZERO	=	3A8C
ONE	=	3A9B	ERR	=	3AA9	RUN	=	3AB6	RDATA	=	3AC4
BIN	=	3AD7	CONT	=	3ADE	ONE1	=	3AE5	ZERO	=	3AF3
END	=	3B01	OUT	=	3B17	MAIN	=	3B1A	LOOP	=	3B27
CON	=	3B2F	BEGIN	=	3B3A	DATA	=	3B41			

<i>Address</i>	<i>Name</i>	<i>Comment</i>
0000	MONC	monitor 'cold' entry
0057	MONW	monitor 'warm' entry
02D1	PRERR	displays error message
02DA	PRNL	new line on display
02E7	PRSP	displays space
0302	PRCOL	displays colon
030A	PRMES	displays string of characters
0347	PRWI	displays 4 hex digits, HL=pointer
0351	PRWD	displays 4 hex digits, contents of HL
0359	PRBI	displays 2 hex digits, HL=pointer
035D	PRB	displays 2 hex digits, contents of A
0375	CRS	saves data on cassette
0409	CRL	loads/verifies data on cassette
049B	CRON	starts cassette motor
04A4	CROFF	stops cassette motor
04BB	KBUF	accepts line from keyboard
05BE	KR	accepts key from keyboard
062E	KSTAT	tests if key pressed
0660	KLUC	converts lower to upper case
0666	KGRAF	converts to graphic code
067D	SOUT	serial line output
06C0	TV	sends character to TV
0732	DELAY1	short delay
073A	DELAY2	long delay
08DD	EDITC	editor entry (cold)
08E4	EDITW	editor entry (warm)
0D16	BCDSUB	BCD subtraction
0D29	BCDADD	BCD addition
0DA0	ASSEM	assembler entry
1816	DMUL	binary multiplication
1831	DDIV	binary division
197B	TMS	tune machine (standard tune)
1986	TMU	tune machine (user tune)
1FFF	-	end of system ROM

Fig 5 System Routines - ROM Entry Points.

<i>Source of Interrupt</i>	<i>Name</i>	<i>ROM Address</i>	<i>Vector Address</i>	<i>Default Handler Address</i>	<i>Handler function</i>
RESET key	RST0	0000	—	0000	Initialize system
(program)	RST1	0008	2F01/ 2F02	0000	..
(program)	RST2	0010	2F01/ 2F02	0000	..
(program)	RST3	0018	2F01/ 2F02	0000	..
(program)	RST4	0020	2F01/ 2F02	0000	..
(program)	RST5	0028	2F01/ 2F02	0000	..
(program)	RST6	0030	2F01/ 2F02	0000	..
break point	RST7	0038	2F0A/ 2F0B	01ED	Saves status, removes break point exit to monitor
timer	TRAP	0024	2F10/ 2F11	0206	Saves status, exit to monitor
BUSY	RST5.5	002C	2F04/ 2F05	0000	Initialize system
BREAK key	RST6.5	0034	2F07/ 2F08	01D0	Saves status, exit to monitor
(ext)	— RST7.5	003C	2F0D/ 2F0E	0000	Initialize system

Fig 6 HEKTOR Interrupt Sources, Vectors and Handlers.

APPENDIX VI

Product Specification

This appendix contains the product specification and calibration curve of the KISTLER pressure transducer used in monitoring cylinder pressures.

QUARZKRISTALL DRUCKAUFNEHMER, MINIATURSONDE QUARTZ PRESSURE TRANSDUCER, MINIATURE PROBE

6121 3.0121 4.73 1

Miniatur Druckaufnehmer für universellen Einsatz in Brennkraftmaschinen, Raketen, Explosionskammern usw. Arbeitet zuverlässig bei Umgebungstemperaturen bis 350°C und erträgt intermittierende Flammtemperaturen bis 2500°C.

Miniature pressure transducer for universal application on internal combustion engines, rockets, explosion chambers etc. Works reliably in ambient temperatures of up to 350°C and withstands intermittent flash temperatures of up to 2500°C.

- Neues Polystable® Quarzkristallelement
New Polystable® quartz element

- Betriebstemperatur bis 350°C. Normalerweise keine Wasserkühlung nötig.
Operating temperature up to 350°C. Normally no watercooling required.

- Empfindlichkeit ändert sich weniger als ±0,5 % im Bereich 100...300°C.
Sensitivity varies less than ±0,5 % in the range 100...300°C.

- Unempfindlichkeit auf hohe Flammtemperaturen.
Insensitive to high flash temperatures

- Masseisolierte Ausführung
Groundinsulated design

Type 6121

Technische Daten

Technical data

Messbereich	measuring range	bar	0...250
kalibrierte Teilbereiche	calibrated partial ranges	bar	0...25
		bar	0...2,5
max. Druck	max. pressure	bar	350
Empfindlichkeit	sensitivity	pC/bar	14
Eigenfrequenz	resonant frequency	kHz	60
Frequenzgang ±1 %	frequency response ±1 %	kHz	6
Linearität	linearity	% FSO	< ±1,0
Hysterese	hysteresis	% FSO	< 0,5
Beschleunigungsempfindlichkeit	acceleration sensitivity		
achsial	axial	bar/g	0,003
normal zur Achse	transverse	bar/g	0,0005
Schock und Vibration	shock and vibration	g	< 2000
Temperaturkoeffizient der Empfindlichkeit	temperature coefficient of the sensitivity	°C ⁻¹	< ±10 ⁻⁴
kalibriert im Bereich	calibrated in range	°C	20...350
Betriebstemperaturbereich	operating temperature range	°C	-80...350
Transient Temperaturfehler (Propanflamme intermittierend auf Front, 10 Hz)	transient temperature error (propane flame intermittent on front, 10 Hz)	bar	< 0,005
Isolation: bei 20°C	insulation: at 20°C	Ω	> 10 ¹³
bei 350°C	at 350°C	Ω	> 10 ¹⁰
Masseisolation	groundinsulation	Ω	> 10 ⁸
Gewicht	weight	g	9,5

1 bar = 10⁵ N·m⁻² = 1,019...at = 14,50...psi; 1 at = 1 kp·cm⁻² = 1 kgf·cm⁻² = 0,980665 bar; 1 psi = 0,06894...bar; 1 in = 25,4 mm

Polystable® Quarzkristallelemente sind international durch Patente geschützt
Polystable® quartz elements are internationally patented

Fig 1. KISTLER Pressure Transducer Data and Calibration Sheet.

ALLGEMEINE BESCHREIBUNG

Das Polystable® Quarzkristallelement, das Kernstück des Aufnehmers, ist das Ergebnis mehrjähriger Forschungsarbeiten und hat sich im praktischen Einsatz bereits bewährt.

Polystable® Quarzkristallelemente sind selbst bei hohen mechanischen Beanspruchungen und hohen Temperaturen sicher gegen Zwillingsbildung und gewährleisten damit Stabilität. Zudem bleibt der piezoelektrische Koeffizient über einen Temperaturbereich von -80 bis 350°C innerhalb von $\pm 1,5\%$.

Aufnehmer mit Polystable® Quarzkristallelementen können daher universell eingesetzt werden und kommen z.B. im Motorenbau ohne Wasserkühlung aus, was einfache und zuverlässige Messungen ergibt.

Der Aufnehmer hat ein Gehäuse aus korrosionsfestem CrNi-Stahl und ist dicht verschweisst. Ein keramisch isolierender Stecker gewährleistet auch bei extremen Temperaturen die notwendige Isolation.

Die patentierte Doppelmembrane ist mit keramischer Frontplatte ausgerüstet, wodurch das Messresultat auch durch hohe intermittierende Flammttemperaturen nicht beeinflusst wird.

GENERAL DESCRIPTION

The Polystable® Quartz Element, the heart of the transducer, is the result of years of research and has been extensively field tested.

Polystable® quartz elements are safe against twinning even under high mechanical loads and high temperatures and thus assure stability.

In addition, the piezoelectric coefficient remains within $\pm 1,5\%$ over a temperature range from -80 to 350°C.

Transducers with Polystable® quartz elements therefore find universal applications and do not require watercooling as e.g. on internal combustion engines, thus resulting in simpler and more reliable measurements.

The transducer has a housing of corrosion resistant CrNi-steel and is welded tight. A connector with ceramic insulation maintains high insulation even under extreme temperatures.

The patented double diaphragm has a ceramic frontplate which keeps pressure measurements unaffected by high intermittent flash temperatures.

Einbaubeispiele

Examples of mounting

Type 6121A1

Type 6121A2

Type 6433
M10 X 1
x = 50 mm

Type 6433sp
M10 X 1
x = 20...150 mm

Type 6434
3/8\" X 24 UNF
x = 50 mm

Type 6434sp
3/8\" X 24 UNF
x = 20...150 mm

Type 6435
M10 X 1
x = 50 mm

Type 6435sp
M10 X 1
x = 20...150 mm

Type 6436
3/8\" X 24 UNF
x = 50 mm

Type 6436sp
3/8\" X 24 UNF
x = 20...150 mm

Standardform. Die Oberwurfmutter kann nach Lösen des Sprungringes entfernt werden.
Bis 200°C: tetraonisierte Kabel,
über 200°C: Metallkabel.

Standard form. The retaining nut may be removed after loosening the circlip.
Up to 200°C: tetraonisierte cables
over 200°C: metal cables.

Sondenform durch aufschraubbares einfaches Verlängerungsstück Typ 6433 für lange Bohrungen oder Durchführung durch Wasserkanäle etc.
Standardlänge x = 50 mm, Sonderlängen x = 20...150 mm kurzfristig lieferbar.

Probe form by simple screw-on extension piece type 6433 for long bores or for crossing cooling ducts in an engine.
Standard length x = 50 mm, special lengths x = 20...150 mm available on short notice.

Sondenform durch aufschraubbaren Verlängerungsadapter Typ 6435 Steckanschluss maximiert.
Für Anwendungen in langen Bohrungen, wo Wandtemperaturen 250°C überschreiten.
Standardlänge x = 50 mm, Sonderlängen x = 20...150 mm kurzfristig lieferbar.

Probe form by screw-on extension adapter. Connector groundinsulated. For applications in long bores and where wall temperatures exceed 250°C.
Standard length x = 50 mm, special lengths x = 20...150 mm available on short notice.

Fig 1. (Cont'd)

Druckaufnehmer
Capteur de pression
Pressure transducer

Type 6123 SN 156719

Kalibrierter Bereich Gamme étalonnée Calibrated range	[bar]	0...200	0...20	0...2	Betriebstemperaturbereich Gamme de temp. d'utilisation (°C) Working temperature range
Empfindlichkeit Sensibilité Sensitivity	[pC/bar]	-16,1	-16,35	-16,2	Kalibriert bei Étalonné à Calibrated at
Linearität Linéarité Linearity	< ± % FSO	0,3	0,3	0,3	20 °C by He Date 4.8.82

1 bar = 10⁵ N/m² = 1.019716 kg/cm² = 14.5038 psi
1 at = 1 kg/cm² = 10⁴ N/m² = 0.980665 bar
1 psi = 0.0689476 bar

0	25	50	75	100	125	150	175	200	225	250	
	0	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25
		0	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25

Abhängigkeit der Empfindlichkeit
von der Temperatur
Sensibilité en fonction
de la température
Sensitivity versus temperature

Fig 1. (Cont'd)

APPENDIX VII

Product Specification

This appendix contains the product specification and calibration sheet for the D. J. BIRCHALL A/20/T accelerometer used for the recording of engine vibration.

Piezo-Ceramic Accelerometers Specification

	High Charge					General Purpose		
Model Type	AM1	AM1T	AM1	AM1T	AM5	AM5T	AM5T1	AM5B
Charge mode	Compression	Compression	Konic	Konic	Konic	Konic	Konic	Konic
Charge Sensitivity pC/g	300	300	250	250	38	38	38	9
Capacitance pF	1,500	1,500	1800	1800	1800	1800	1800	850
Resonant Frequency kHz	12	12	10	10	27	27	27	58
Charge Acc Error % Maximum	5	5	5	5	5	5	5	5
Temperature Range °C	-55 to 300	-55 to 300	-55 to 300	-55 to 300	-55 to 300	-55 to 300	-55 to 300	-55 to 300
Normal Charge Deviation at 100°C Temperature %	15	15	15	15	15	15	15	15
Pyroelectric Output pC/°C Output Frequency Hz	0.17 001	0.17 001	0.08 001	0.08 001	0.20 002	0.20 002	0.20 002	0.15 005
Normal Shear Stress Sensitivity Equivalent g @ 250 cps	24	24	3	3	2.8	2.8	2.8	2.8
Maximum Continuous Shear Acceleration g	300	300	1,800	1,000	1,000	1,000	1,000	2,800
Case Seal	Welded	Welded	Welded	Welded	Welded	Welded	Welded	Welded
Mounting	Hole for 1/4 UNF Stud	Hole for 1/4 UNF Stud	Hole for 10/32 Stud	Hole for 10/32 Stud	Hole for 10/32 Stud	Hole for 10/32 Stud	Mounts on Threaded Stud 7mm long	Mounts on Threaded Stud 7mm long
Connector	Microdot	Microdot	Microdot	Microdot	Microdot	Microdot	Microdot (Case Isolated)	Microdot
Weight (gm)	180	195	80	80	17.5	18	25	7
Case material	S/Steel B5570 303S21	S/Steel B5570 303S21	S/Steel B5570 303S21	S/Steel B5570 303S21	S/Steel B5570 303S21	S/Steel B5570 303S21	S/Steel B5570 303S21	S/Steel B5570 303S21
Pyroelectric sensitivity table at 5 different rates the Charge Frequency

All Accelerometers shown have 'Konic' elements with the exception of the A/D1 and A/D1/T. The 'Konic' element has low sensitivity to base bending (often encountered when accelerometer is mounted on surface with temperature different to the ambient temperature). As charge is generated by the shear stress in the piezo ceramic tube Konic accelerometers have low cross axis and pyroelectric sensitivities.

Konic Accelerometers have excellent shock characteristics and ringing and 'Repeatability' stand comparison with accelerometers of other manufacture made specifically for shock testing

Fig 1. Specification of Vibration Accelerometer Used.

Accelerometer Calibration Certificate

D.J. Birchall Ltd.,
Finchley Avenue
Industrial Estate,
Mildenhall, Suffolk.

Telephone: Mildenhall 712288

Date 9.2.82

UNIT	A/2G/T	Ser. No.	684						
CHARGE SENSITIVITY pC pK/g pK				32.9					
VOLTAGE SENSITIVITY mV pK/g pK (Load pF)									
CAPACITANCE pF				1664					
FREQUENCY c/s	20	200	4000						
Response %	0	0	+ 1						
<div style="display: flex; align-items: center;"> <div style="margin-left: 20px;"> <p>POLAR CROSS-AXIS ERROR, FREQ. c/s 100</p> <p>2% max</p> </div> </div>									
TEMP (T) °C	-50	0	20	100	150	200	250	300	
NORMALISED CHARGE SENSITIVITY $\frac{QT}{Q20}$									
NORMALISED CAPACITANCE $\frac{CT}{C20}$									
<p>OUTPUT VOLTAGE (e) WITH LOAD CL - $e = \frac{QT}{CT + CL}$</p>									

Fig 2. Vibration Accelerometer Calibration Sheet.