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A test-bed facility for hybrid i c-engine/battery-electric road vehicle drive trains

by J. R. Bumby, BSc, PhD, CEng, MIEE and P. W. Masding, BSc

This paper describes the design and development of a test-bed facility for hybrid internal-combustion-engine/battery-electric vehicle power trains. The control hierarchy within the microprocessor control systems is discussed, and the influence this has on the software design is described. The instrumentation and computer software systems necessary for both data acquisition and drive train control are described. It is shown that drive train control over an urban cycle can be successfully achieved using a modified proportional-plus-integral controller.

Keywords: Hybrid electric vehicles, electric vehicles, automotive test-bed control.

List of symbols

g_f	Final drive ratio
I_{eq}	Inertia equivalent to vehicle mass, kg m^2
M	Vehicle mass, kg
r_D	Wheel rolling radius, m

1 Introduction

A hybrid electric vehicle combines the use of both an internal combustion engine (i c engine) and an electric traction drive in order to improve some aspect, or aspects, of the vehicle performance. Such hybrid drives have been considered intermittently for use in road vehicles ever since the invention of the i c engine. Although Pieper (1905) patented a hybrid drive with the sole purpose of improving the performance of the then limited i c-engine vehicle, it was not again considered seriously until the 1960s and early 1970s. At this time the vehicles were seen as one way of reducing the staggering exhaust emission problem of some North American cities, and a demonstration vehicle was built and successfully tested by 1976 (Wouk, 1976).

By the mid 1970s the 1973 oil crisis had focused attention on the hybrid drive as a means of reducing the amount of petroleum fuel used in the transport sector. The Ford Motor Company demonstrated how the hybrid drive, operating essentially as an engine management system, could improve fuel economy by 30–70% depending upon the vehicle type (Unnewehr *et al*, 1976). At the same time, a demonstration programme by Volkswagen (Miersch, 1978) in Europe was showing how the hybrid drive could be used to substitute electricity for petroleum fuel and eliminate exhaust emissions in environmentally sensitive areas.

This aim of substitution of petroleum with electricity was fundamental to the Electric and Hybrid Vehicle Research, Development and Demonstration Programme launched in the United States of America in 1976 (US Congress, 1976). Design contracts for a hybrid vehicle were placed with four manufacturers (Sandberg, 1980), the design produced by General Electric being selected for construction during the demonstration second phase (Burke and Miersch, 1981).

In Europe, Volkswagen has continued its work and has recognised the hybrid drive as the only general purpose electric-based drive that can be used in the road transport sector (Kalberlah, 1986). This view, shared by the authors (Forster and Bumby, 1988), arises because of the range problems associated with the electric vehicle and the time required to charge the traction batteries.

With the presence of two on-board power sources, optimum scheduling of the drive is best looked after by a microprocessor controller. This, in turn, implies the development of a 'drive-by-wire system' whereby the driver communicates his power demand via the accelerator pedal to the microprocessor controller. The microprocessor then schedules the instantaneous outputs of the power sources. However, the way in which the power should be scheduled is not clear and earlier work (Forster and Bumby, 1988; Bumby *et al*, 1984, 1985; Bumby and Forster, 1987; Burke and Somuah, 1980) has developed advanced computer simulation methods to investigate this problem. The work at Durham University demonstrated how power should be scheduled to meet driver demand, and postulated a possible sub-optimum control scheme to achieve this. To investigate how easily such a scheme can be incorporated into the hybrid drive, a full-scale laboratory test facility has been constructed in the School of Engineering and Applied Science at Durham University. It is the purpose of this paper to describe this test-bed facility, its instrumentation and overall control.

2 Hybrid-vehicle control hierarchy

Given that two power sources are available within the vehicle drive system, there are a number of ways in which they can be combined to produce torque output at the road wheels. However, earlier work (Bumby *et al*, 1984; Bumby and Forster, 1987) has shown the parallel arrangement of Fig 1 to have the greatest potential for use in a hybrid car. A similar arrangement has also been used by General Electric (Burke and Miersch, 1981), Volkswagen (Miersch, 1978) and Lucas (Harding *et al*, 1983).

With this parallel arrangement, either the electric traction motor or the i c engine is capable of driving the road

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*School of Engineering and Applied Science, University of

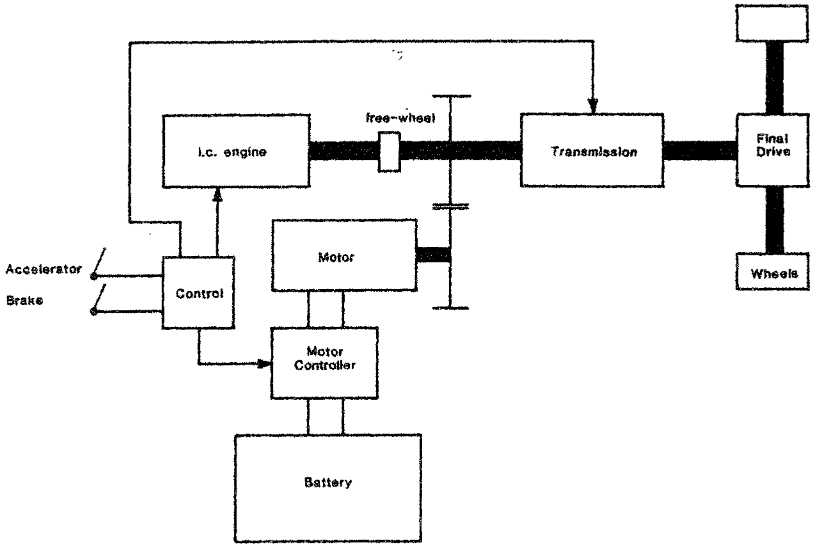


Fig 1 Parallel hybrid configuration

TABLE 1: Possible operating modes

Mode	Description
Electric mode	All propulsion power supplied by the electric-traction system
IC engine mode	All propulsion power supplied by the i c engine
Primary electric mode	The electric-traction system provides the principal torque but, when necessary, its maximum torque is augmented by the i c engine
Primary i c engine mode	The i c engine provides the principal torque but, when necessary, its maximum torque is augmented by the electric-traction system
Hybrid mode	Both the i c engine and the electric-traction system together, in some way, provide the propulsion power
Battery-charge mode	The i c engine provides both the propulsion power and power to charge the batteries with the traction motor acting as a generator
Regenerative braking	During braking the vehicle kinetic energy is returned to the battery, with the traction motor acting as a generator
Accelerator 'kick-down'	Essentially a primary i c-engine mode when increased torque is provided to give acceleration

transmission. Such an arrangement offers the potential to maximise the overall transmission efficiency between either prime mover and the road wheels while minimising the component count. If necessary, the i c engine can also drive the road wheels and the electric traction system, but now with the traction motor running as a generator. This enables the engine to charge the battery if required.

With the arrangement shown in Fig 1, the electric traction motor is connected permanently to the drive shaft, while the i c engine is connected through a 'one-way clutch' or 'freewheel'. Such a connection allows the traction motor to drive the road wheels when the engine is stationary, but the electric motor must turn with the road wheels regardless of the drive source. This arrangement guarantees that regenerative braking into the battery is immediately available when required. Thus, during braking, the i c-engine speed would reduce rapidly, owing to compression braking in the engine) and the vehicle controller would then allow vehicle kinetic energy to be returned to the battery via the electric traction system. Such use of regenerative braking substantially increases the overall drive-train efficiency.

The consequence of the 'free-wheel' in the i c-engine connection also means that the electric traction system can move the vehicle from rest, and the i c engine need only be started and synchronised with the drive shaft when load demand is high. It is at such low-speed low-load situations that the i c engine is inefficient compared with the electric traction system.

From this brief discussion it is apparent that the hybrid drive can be operated in a number of ways or modes. These possible modes are listed in Table 1 and described in detail in Forster and Bumby (1988). In addition, depending on the driving situation, battery state of charge, etc, the vehicle controller must be capable of deciding which mode of operation listed in Table 1 is most appropriate. Thus a control hierarchy can be defined as shown in Fig 2. At the top of the hierarchy is the main vehicle control algorithm which decides when different operating modes are to be used to meet the particular driving conditions. In general, this logic control is non-time-sensitive and, as will be seen in Section 5, can run very conveniently as the general background program

control algorithms (Table 1) form the next level in the hierarchy and decide how much torque, etc, should be produced at each instant from either of the two power sources. These algorithms interact directly with both the driver commands through brake- and accelerator-pedal movement, and communicate their requirements to the units responsible for the control of the drive-line components themselves. For example, they would send a torque demand to the chopper control unit on the DC drive system or a throttle position demand to the engine management system. These individual drive-train-component controllers may be microprocessor-based, hardwire-based or software control algorithms running in the same processor as the mode-control algorithms.

Operating around this vehicle control system is the overall test-bed control. Because the hybrid drive system must be exercised over driving cycles representative of urban, suburban and motorway conditions it is necessary computer, in order to obtain the maximum repeatability in results. Manual control of the test bed must also be possible. The overall arrangement of the test-bed control is shown in Fig 3. The following sections concentrate on the hardware and software associated with the test facility and the overall test-bed control.

3 The mechanical system

The layout of the laboratory test facility representing the hybrid drive arrangement of Fig 1 is shown in Fig 4. The mechanical arrangement divides into two parts: first, that which emulates the road load and the vehicle inertia; and second, the hybrid drive system itself.

Vehicle mass is represented by a variable-inertia flywheel with an inertia range between 2.02 and 15.57 kg m^2. As no final drive is present within the system, the vehicle mass is related to an equivalent rotating inertia by

$$I_{eq} = M\left(\frac{r_D}{g_f}\right)^2 \qquad \ldots(1)$$

where r_D is the wheel rolling radius and g_f the final drive ratio. Depending on wheel radius and final drive ratio, vehicles of up to about 2 tonnes can be represented.

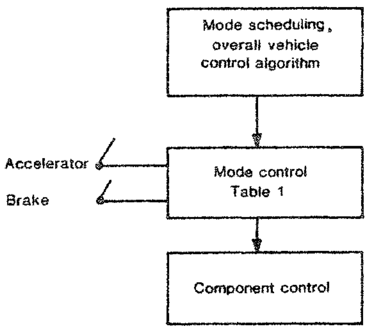
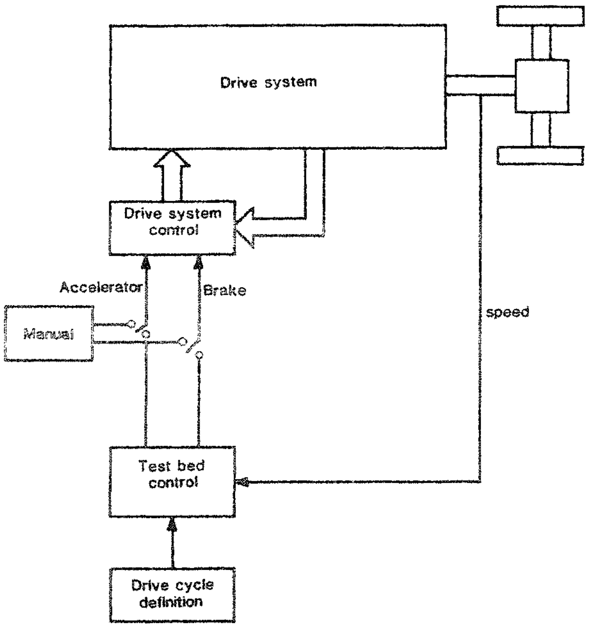


Fig 2 Control hierarchy



Energy loss equivalent to drag and rolling resistance is provided by a water-cooled dynamometer. This dynamometer can also be used to carry out load testing on both the i c engine and the electric motor. In selecting the dynamometer, significant attention was paid to low-speed torque capability which, for an electric traction system can be 200 to 300 N m.

The drive system incorporates both a Ford 1100 cc petrol engine and a Lucas Chloride DC traction motor (the type used in the Bedford CF and Freight Rover *Sherpa* 1-tonne panel vans (Manghan and Edwards, 1983)). Both the i c engine and the electric traction motor are connected to the same drive point by a toothed-belt drive. To improve drive performance a belt drive with a trapezoidal tooth section and a ground back has been used.

The i c engine is connected to the common drive point through a friction clutch, free-wheel, short drive shaft and torque transducer. The DC system is similarly connected via a flexible coupling and torque transducer. The drive system is then connected through a standard four-speed transmission to the variable-inertia flywheel.

As the electric-motor drive shaft is subjected to both motoring and regenerative braking torque, a flexible coupling with zero backlash must be used. In this instance a 'tyre'-type coupling has been used because of its positive drive nature, ease of connection and its ability to lightly damp the high-frequency torques produced in the drive shaft due to the armature and field chopper control systems. The electric motor is connected electrically to the lead–acid traction battery via the appropriate Lucas Chloride control unit. This control unit employs a thyristor armature chopper with field weakening being provided by a transistor field chopper. A summary of the drive system ratings is given in Table 2. It should be made clear that the components used in assembling the drive train were those most readily available but yet still representative of the components ideally required for a mid-range European passenger car. Forster and Bumby (1988) and Bumby and Forster (1987) discuss these ideal ratings in more detail. Perhaps the component that shows greatest discrepancy is the lead–acid battery system, with a weight of about 1 tonne. In practice, a lead–acid battery pack of 400 kg (or preferably a nickel–zinc battery of 200 kg) would be used (Bumby and Forster, 1987).

Braking is provided both by regenerative braking from the electric drive system and by air-brakes in the variable-inertia flywheel.

4 Instrumentation and control equipment

4.1 Computing equipment

4.1.1 Motorola M68000 system

The M68000 microprocessor system is the heart of the drive-train control system and has two main tasks to perform. First, it must implement the hybrid-vehicle control strategy which means controlling the electric traction system, i c engine and transmission in the most efficient way to meet driver demand. Second, during a test, it must act as a data logger.

The M68000 system has been designed with all the interface hardware necessary to perform these tasks. Specifically, it includes a M68000 processing unit operating at 8 MHz, 192k of random-access memory, four

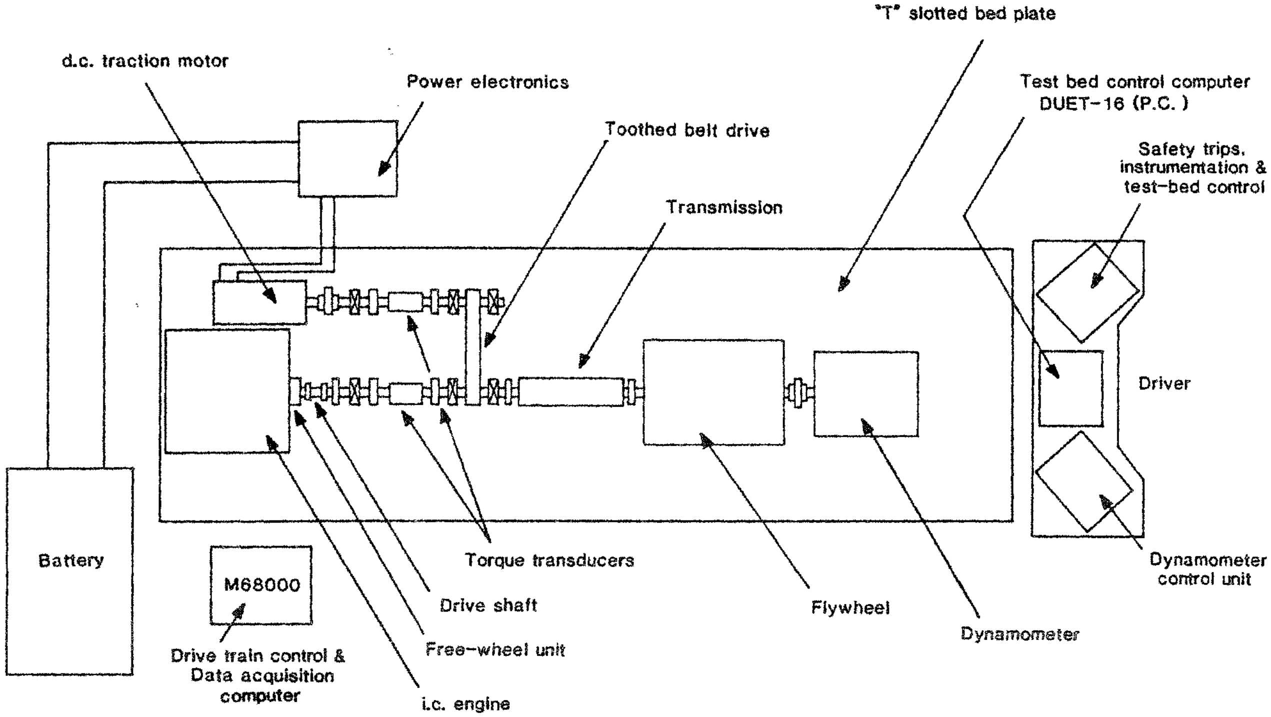


Fig 4 Test-bed layout

TABLE 2: Basic test-bed component ratings

Component	**Description**
Traction motor	Lucas Chloride separately excited DC motor, Type MT286 37 kW (1/2 h)
Motor control	Lucas Chloride Type Mk. III B current controlled SCR armature chopper and transistor field chopper
Batteries	Lucas Chloride Type EV5C, 216 V, 184 Ah (5 h rate)
Engine	Ford 1100 cc petrol engine 32 kW at 5500 rev/min 71 Nm at 3000 rev/min
Transmission	4-speed manual 1st 3.656 : 1 2nd 2.185 : 1 3rd 1.425 : 1 4th 1 : 1
Flywheel	Variable inertia 2.02 to 15.57 kg m^2
Dynamometer	Froude Consine EC38TA water-cooled dynamometer Max torque 475 N m

channel, 12-bit analogue-to-digital converter board [ADC] with interrupt facility, eight 12-bit digital-to-analogue converters [DAC] and finally two standard timer/counter chips [STC] each with five 16-bit counter/timers. These devices are shown in Fig 5. This interface hardware, when connected to suitable signal-conditioning circuits, gives the M68000 system the ability to gather data from the rig and respond with control outputs.

Software for the M68000 is written mostly in the 'C' programming language, with small amounts of software written in M68000 assembler. This is necessary for mani-

'C' programming language is particularly useful for real-time control applications as it is at a sufficiently high level to allow complex control structures to be written easily, and yet compiles efficiently to produce fast execution times. 'C' also interfaces easily with M68000 assembler routines with a simple system of parameter transfer between the two. All program development is carried out on a M68020 development system and downline loaded into the M68000.

4.1.2 The DUET 16 personnel computer

This computer does not carry out any direct control of the drive train. Its purpose is to interact with the operator for overall rig control, to display graphically, in real time, selected test results and, when a test is complete, to accept data from the M68000 system and display selected data after suitable analysis.

All the PC software is written in BASIC. Although BASIC suffers from slow running speed and lack of structure, its interactive nature and ease of use in graph plotting has proven extremely useful for displaying results. The DUET has a useful range of peripheral devices including a dual disk drive, a colour graphics monitor and a dot-matrix printer which is used to obtain hard copy of selected graphs.

4.2 Instrumentation

Instrumentation on the test bed falls into two categories: first, that necessary for protection; and second, that necessary for data acquisition and test-bed control. In some instances signals necessary for control are also required for protection. In the most important cases, separate transducers are used for each application. Thus hardwired, failsafe, electronic protection is provided in

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