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MAY 1979

THE USAF ACADEMY FLYWHEEL-ELECTRIC CAR
PRELIMINARY DESIGN REPORT

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DAVID D. RATCLIFF

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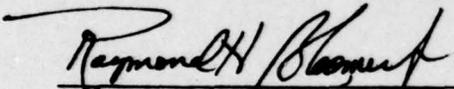
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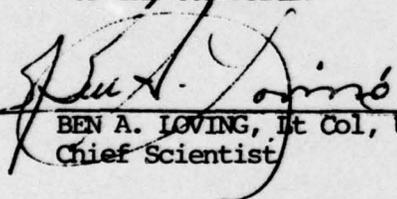
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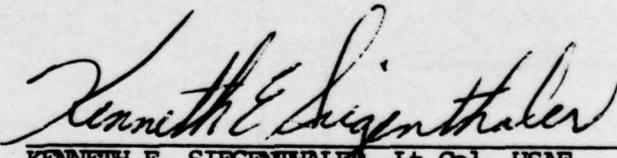
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members in the Department of Physics under funding provided by Frank J. Seiler Research Laboratory. The car design discussed appears to offer the possibility for a four-passenger urban vehicle with a range of 70-100 miles and acceleration performance comparable to that of current sub-compact cars. This performance is achieved with a simple driving system which is comparable to that in current automatic transmission cars.

The paper also details the benefits and problems resulting from the low-technology design chosen and provides trade-off analyses on some of the specific problems inherent in the use of a flywheel in the power train of a vehicle. Finally, the paper suggests future improvements which could lower the weight of the vehicle, make the transmission shifting more precise, and improve the performance of the car on grades.

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THE USAF ACADEMY FLYWHEEL-ELECTRIC CAR
PRELIMINARY DESIGN REPORT

By

Captain David D. Ratcliff

May 1979

Department of Physics
United States Air Force Academy, CO

PREFACE

The USAFA electric car project, originally begun as a conventional student involvement project, quickly evolved into an effort focused on the design of an electric vehicle which could more effectively use lead-acid batteries in a vehicle meant for personal transportation. Since available manpower, facilities, and funds were dwarfed by those of large research efforts funded by Department of Energy, we chose to use off-the-shelf technology and commercially available parts to design a vehicle with improved performance. We also chose to use simple construction techniques which put most of the car construction within the capability of cadet and faculty participants. The use of off-the-shelf parts and technology, and the use of simple construction techniques had an interesting impact on the relevance of any improvements made in the performance of electric cars:

1. We would be able to demonstrate that the car with improved performance could be built today without several years delay for research.

2. We would be able to show that the improved car could be built by a *small company* without a large research or tooling requirement.

Preliminary design and construction results which follow in this report indicate that it is indeed possible to build an electric car today, using lead-acid batteries, with significantly better combined range-acceleration performance than is characteristic of electric vehicles available at this time.

The author would like to express his appreciation to the Frank J. Seiler Research Laboratory for funding and considerable procurement

help, to the USAF Academy Physics Department for project sponsorship, and especially to the following cadets, without whose help the car could not have been built: (Class of 1978) M. Cordova, D. P. Lentz, T. A. Ball, S. L. Gilmore, Jr., K. R. Gronewald, G. Hackbarth, L. E. Hazlett, M. L. Lindsay, J. M. Sponable, M. D. VanSteenwyk, R. L. Wallace; (Class of 1979) M. P. Baudhuin, E. H. Browne, Jr., B. A. Busler; (Class of 1980) D. M. Phan.

The author also extends his appreciation to Major Thomas E. Kullgren, who provided considerable help in the design of the flywheel.

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INTRODUCTION

CURRENT ELECTRIC VEHICLE LIMITATIONS

The decline in availability of fossil fuels has revived interest in the electric car as a personal vehicle which can draw energy from alternate sources, such as coal, nuclear, solar, and hydroelectric power plants. Although the electric car does indeed solve the problem of converting to alternate fuels, currently available models have limitations which greatly lessen their appeal to consumers. Most of these limitations are imposed on electric cars by the use of lead-acid batteries as the energy storage medium. Lead-acid batteries are the only widely available batteries which are at present low enough in cost for use in electric vehicles for personal transportation. A great deal of battery research is currently aimed at providing alternate batteries with higher energy density, but there appears to be little hope for the appearance of such batteries in commercially available form for at least five years. The question posed by this constraint is then whether to wait for the availability of high energy density batteries or to redesign an electric vehicle to improve its performance with lead-acid batteries. There appear to be two arguments for the latter course. First, the decline of petroleum fuels appears to be rapid enough that any delay, even five years, in the implementation of conservation efforts is unwise. Second, it is quite probable that improvements made to the electric vehicle structure to make it operate more efficiently with lead-acid batteries will also improve the operation of a vehicle based on high energy density batteries and will thus be more than stop-gap efforts.

Two of the reasons for low acceptance of electric vehicles commercially available at this time are poor acceleration performance and short range. The power and battery current required for even modest acceleration of an electric car is very large compared to the power required for steady driving. Although this is true for all vehicles, it is especially true of an electric vehicle because of its battery mass. For instance, the maximum power required in the steady acceleration of a 2500 lb (1134 Kg) car to 30 mph (13.4 m/s) in 10 seconds is about 15 kilowatts at 100% efficiency. Assuming a battery array voltage of 96 volts, this acceleration requires 160 amps at 100% efficiency. A figure of 300 amps is more typical of a practical vehicle under these conditions due to energy conversion inefficiency. Such discharge rates drastically reduce the energy recovery from a lead-acid battery array.

When a lead-acid battery is operated at the relatively fast discharge rates characteristic of electric vehicles, less energy is recovered from the battery than at slower rates. Although there are several contributing factors, the predominant reason for this is localized electrolyte depletion in the plate assembly. In a lead-acid battery, only the electrolyte in the immediate region of the plates is active in the electrochemical reaction. At slow discharge rates, on the order of 20 hours, diffusion of fresh electrolyte into the plate assembly is rapid enough to replace depleted electrolyte near the plates. In a rapid discharge of about 2 hours, diffusion rates are

too slow for replenishment and the electrolyte becomes locally depleted near the plates. The battery seems to be depleted even though there is still capacity left in the unreacted plates and in fresh electrolyte outside the plates. If the battery is allowed to "rest" for a while, more energy can be withdrawn. This mode of operation is of little use in a vehicle, so the energy is effectively lost. A peripheral experiment was done in this research effort which investigated the use of ultrasonic vibration to alleviate this problem. The results are discussed in Appendix B.

PROBLEM SOLUTIONS

One solution to the problem is called "load-leveling". As indicated before, the average current demand in an electric car is significantly lower than the peak demands during acceleration. If the peak demands are supplied by a separate short-term energy storage subsystem which can be energized slowly from the batteries, the batteries will continually operate in the more efficient medium current range. The short term energy storage could be mechanical in form such as in compressed springs or gases, or in flywheels. It could also be electrical, as in the case of charged capacitors or inductors. Of these options, only the flywheel, a low technology option, and the superconducting inductor, a high technology option appear to have the energy storage density required of a vehicle system. In keeping with the low technology approach selected for the USAFA effort, a flywheel energy storage system was selected for load leveling.

The flywheel aids the car in several ways. The acceleration performance is considerably improved because the short-term power output of a flywheel is limited only by the strength of the flywheel and transmission. The flywheel can be charged slowly from the batteries and motor, and then discharged rapidly for acceleration. The flywheel also improves the range performance of the car. This effect comes from the increased energy recovery from the battery when peak loading is removed and from a process called "energy regeneration". In a conventional car, the kinetic energy of the car is converted into waste heat in the stopping process. In some electric cars a portion of this energy is returned to the batteries by using the traction motor as a generator. The rate of energy transfer, or power, involved in this process is quite high, however, and only about 10% of the kinetic energy of the car can be regenerated in this way without damaging the batteries with excessively high charge rates. The flywheel-transmission subsystem in the USAFA car system is essentially symmetrical in that acceleration and deceleration are of the same magnitude. The transfer of energy during deceleration speeds up the flywheel and prepares it for the next acceleration. The overall in-out energy conversion process can be up to 70% efficient in a well-designed transmission, a considerable improvement. There is some energy loss in the type of transmission required for flywheel coupling, so the range improvement will be most apparent in urban driving with several stops per mile. There is no improvement in steady driving performance of a vehicle when a flywheel is added to the drive train.

DESIGN CONSIDERATIONS

Although a flywheel can improve the performance of an electric vehicle, there are some practical problems that it presents to the designer. The flywheel rotates most rapidly when the car is stopped and more slowly when the car is moving. Thus during an acceleration the flywheel shaft, which is slowing down, must be coupled in torque to the rear axle, which is speeding up. The transmission must then be continuously variable, or capable of an infinite number of "gear" ratios between neutral and driving speed. Some provisions for reverse drive must also be provided in a practical drive system. A continuously variable transmission system tends to be less efficient than its geared counterpart. A second problem with a flywheel is that it shares with the internal combustion engine the requirement for idling, or motion when the car is stopped. The conventional electric car has practically no idling losses, so the energy losses during idling of the flywheel must be made small for the system to be competitive. A third concern in designing a vehicle with a large flywheel in it is the gyroscopic torque associated with the rotation of the axis of the flywheel as the car changes its orientation in space. These torques couple to the body of the car and interact with the suspension. Unless they are carefully controlled, they may adversely affect the handling of the car. Finally, the large mass of the flywheel rotating at high speed levies a requirement for precise dynamic balancing of the flywheel to prevent vibration from the flywheel from coupling to the car.

THE USAFA FLYWHEEL-ELECTRIC CAR DESIGN

CHASSIS

The USAFA prototype was constructed on a Volkswagen 1200 (Bug) frame. The frame uses a central spine with an attached floor pan. The transaxle was removed from the frame and the original gear train and casing were disassembled. The ring and pinion drive for the differential in the rear axle were removed and replaced with the lower half of a 1-inch-pitch roller chain drive. The hemispherical supports for the insides of the half-axle housings were removed from the original transaxle case and machined for bolting onto the sides of the chain case. The rear axle was then reassembled and the chain case mounted on the car such that the position of the hemispherical supports was unchanged from the original transaxle. Thus, except for the substitution of a chain drive, the operation of the rear axle assembly is identical to that of the original car. Because of the added weight in the rear due to the flywheel and transmission, air-adjustable shock absorbers were substituted for the original shock absorbers.

The framework of the car was constructed of tubular and angle steel stock welded into a body shape similar to that of the Volkswagen "Thing". This relatively angular, box-like frame was easy to construct and provided room for the transmission, flywheel, motor and batteries in addition to four passengers. Considerable streamlining could be accomplished in a commercial version of the car.

The skin of the car will eventually be constructed of 1/4-inch

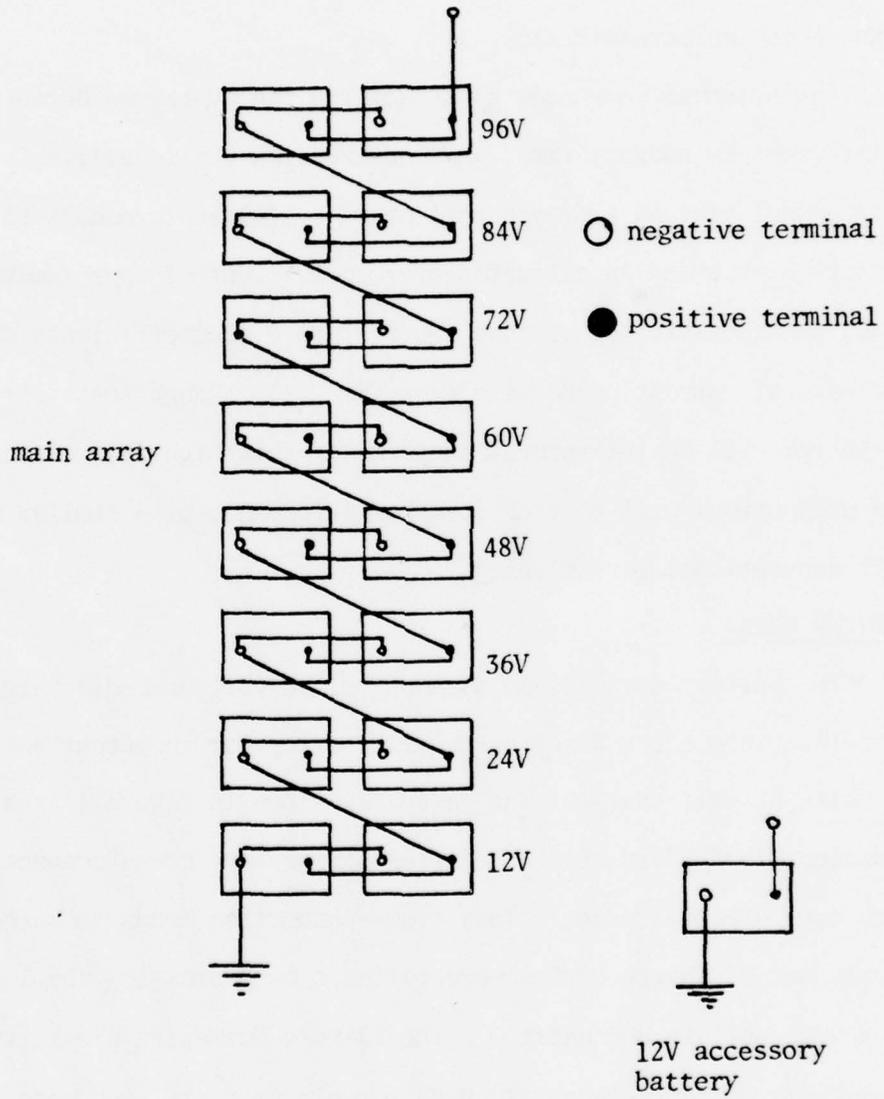
plywood bolted to the skeleton provided by the welded steel members. The windows will be of 1/4 inch plexiglass, except for the windshield, which will be a flat piece of safety plate glass. The corners of the body will be formed of wood moulding which provides for flush mounting of the plywood panels as well as a 1-inch radius on all corners for aerodynamic flow.

Few attempts were made to streamline the prototype because of limitations in budget, time, and construction skills available. A wind tunnel test on a symmetrical pair of 1/10 scale models of the prototype provided an estimated drag coefficient of approximately 0.52, considerably higher than the 0.37 to 0.45 coefficients characteristic of current production cars (Ref. 1). Range tests for the prototype will be interpreted in terms of this high drag coefficient, and projections will be made for the performance of a similar vehicle with conventional streamlining.

BATTERY ARRAY

The battery array is an assembly of 12-volt deep-discharge batteries into a 2 x 8 series-parallel array for an output voltage of 96 volts at full charge. The array, as shown in Figure 1 is a modified "ladder" in that the series strings are cross connected at each equipotential point. This cross connection tends to make array charge and discharge cycles more reliable by decreasing the impact of a weak cell in one battery. The 12-volt batteries are marine deep-cycle batteries normally used for electric trolling motors. They were chosen over 6-volt vehicle batteries because their 12-volt

Fig. 1: BATTERY ARRAY



output allowed the series-parallel connection of the batteries within the constraints of 96-volt operation and a total of 16 batteries. The 12-volt batteries also had a slightly larger energy density than did available 6-volt vehicle batteries.

MOTOR

The motor is a separately-excited DC motor with a 1-hour rating of approximately 8.5 Hp (6340 watts). A 1-Ohm, 10-Kw armature protection resistor limits the armature current to 96 amps until the motor-flywheel speed reaches 2400 rpm, at which point the armature reverse voltage is high enough that the armature can be switched directly across the battery array. Above 2400 rpm, motor speed control is accomplished solely by field weakening with an SCR chopper circuit. Since the motor and flywheel normally operate between 3200 and 5000 rpm during the driving cycle no other speed control is required. This design feature greatly simplifies the motor speed control while simultaneously decreasing cost and power dissipation. The entire field control consists of four integrated circuits and two 6-amp SCRs in a force-commutated chopper circuit.

FLYWHEEL

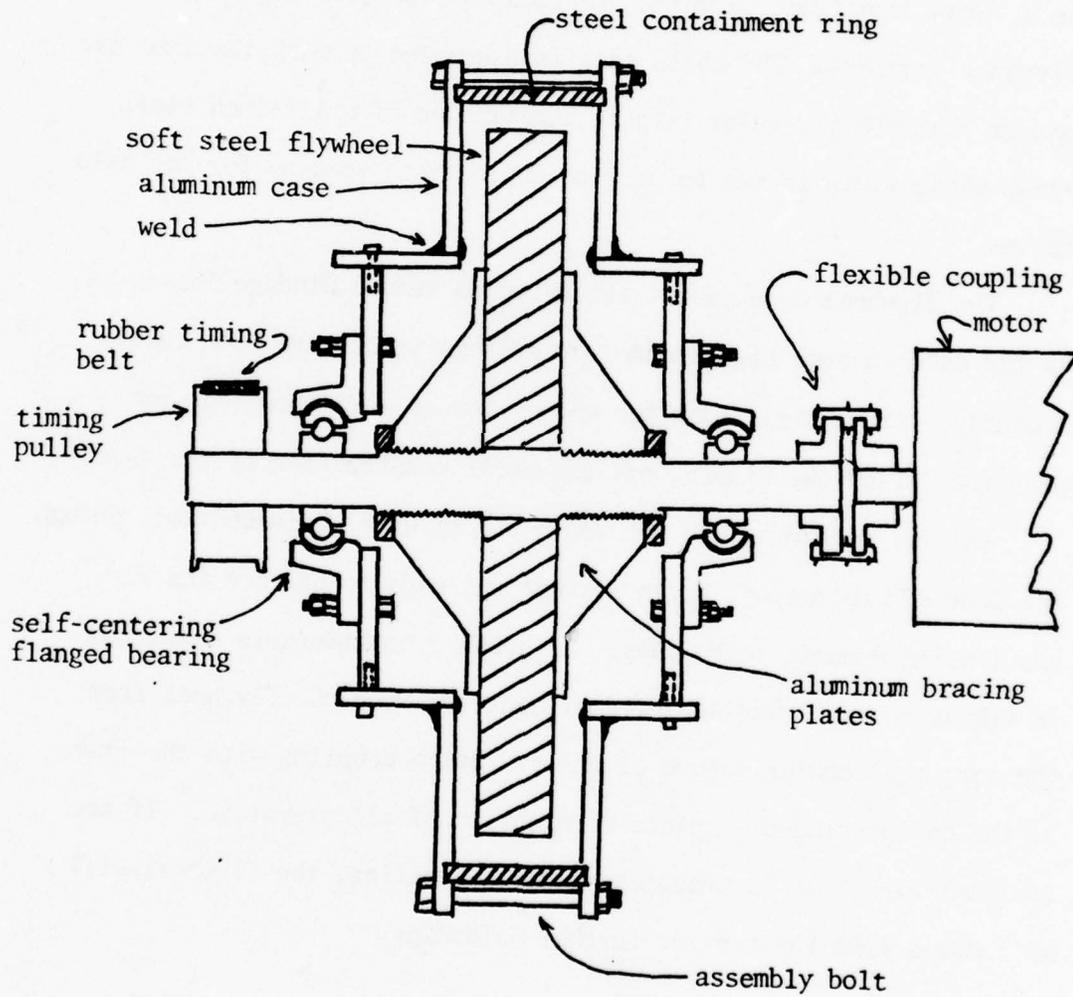
The flywheel assembly for the USAFA prototype has a very simple structure in keeping with the low-technology approach to the overall vehicle. It is a simple disk of hot-rolled steel about 5 cm. (2 in.) in thickness and 54 cm. (21.3 in.) in diameter. A 21.5-inch disk was flame-cut from standard 2-inch plate and a center hole was bored approximately 0.001 inch undersize for a hardened steel shaft which

had been previously machined. (see Figure 2). The disk was heat shrunk onto the shaft and additionally supported by side plates threaded onto the shaft. These plates serve to prevent the center hole from enlarging under the influence of gyroscopic torques during the operation of the car. The shaft was center-drilled and finished on its ends for 1.5-inch bearings. The aluminum side plates are kept from loosening by steel locknuts which are fixed to the shaft with set screws. The flywheel was then turned to finished dimensions between centers on a large lathe. The maximum swing of the lathe determined the diameter of the USAFA flywheel. Although it was desirable to lighten the flywheel from the standards of energy storage density, no material was removed from the hub area of the flywheel since the designers were not expert in metal fatigue analysis. Calculations indicate that at 5000 rpm the combined stresses on the flywheel are less than 15% of yield strength. Needless to say, considerable weight can be saved with a less conservative flywheel design. The total rotating weight of the flywheel is approximately 100 Kg (220 lb). The energy stored at 5000 rpm is 0.5×10^6 Joules.

The bearings used to support the flywheel are 1.5-inch, medium duty industrial ball bearings. The bearings are mounted through self-centering spherical surfaces machined into cast-iron flanges with four bolt holes. This type of bearing was chosen to make the flywheel case simple to construct.

The case for the flywheel is constructed of 3/8-inch aluminum plate and 12-inch-diameter, 1/2-inch-wall tubing. The components

Fig. 2 FLYWHEEL ASSEMBLY
AND CASE



were assembled with a combination of machine screws and inert gas arc welding. A containment ring for the flywheel is set into a 1/8-inch-deep groove machined around the periphery of the end plates. This ring was rolled from 3/8-inch mild steel strap and end welded. A series of bolts around the edge of the end caps assembles the case in a "drum" construction which provides considerable rigidity for the flywheel bearings. The chain case is assembled in much the same way except that the irregular ring is constructed of a 1/8-inch steel strap whose width is set to provide appropriate spacing for the axle halves.

The flywheel case is not evacuated to reduce windage losses as is the case in some high-technology systems which have been built recently. It was felt that the energy losses were more than compensated for by the simple, off-the-shelf construction of the case.

Initial machining did not leave the flywheel balanced well enough for 5000 RPM operation, so an attempt was made to balance the flywheel using dynamic techniques. Although a considerable reduction in vibration level was achieved without removing the flywheel from the car, the complex nature of the vibration coupling with the frame of the car precluded complete elimination of all vibration. If the residual vibration is troublesome during testing, the flywheel will be removed from the car for further balancing.

TRANSMISSION

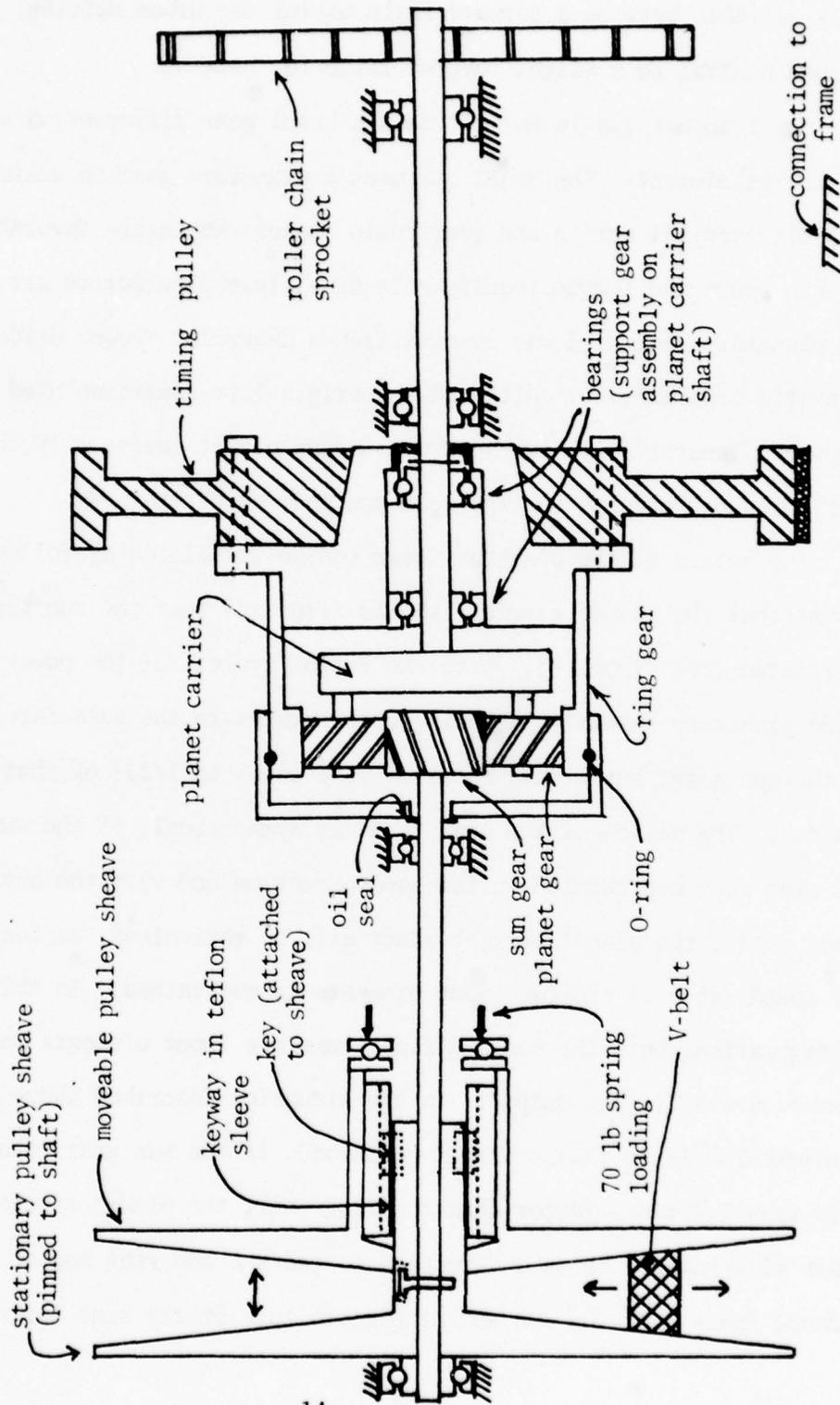
The transmission of the USAFA car is a modification of a differential-draw transmission described in Ref. 2. It is continu-

ously variable between a forward ratio useful for urban driving through neutral to a slight reverse ratio for backing.

The transmission in Ref. 2, uses a bevel gear differential as the active element. The USAFA car uses a planetary gear to achieve both differential action and gear ratio changes which are favorable for the speed and torque requirements of a flywheel-electric car. The planetary gear used was removed from a Chevrolet "Power Glide" automatic transmission. Although the original transmission used a compound planetary with two sets of sun and planet gears, only the rear, or short planets and the rear sun gear were retained.

The action of the planetary gear can be visualized as follows: Assume that the planet carrier is held fixed and that the sun gear is rotated (see Figure 3). With the ratios typical of the power-glide planetary assembly, the ring gear rotates in the same direction as the sun gear, but with a rotation rate equal to $1/2.7$ of that of the sun. The action of the gear train is symmetrical; if the sun gear and ring gear are rotated in the same direction and with the above speed ratio, the planet carrier shaft will be motionless, as long as the speed ratio of the two input elements is maintained. In this configuration, both the sun and ring gears are input elements and the planet carrier is the output. In the situation described above, the transmission is in the "neutral" position. If the sun gear rotates less than 2.7 times faster than the ring gear, the planet carrier shaft will rotate the same direction as the sun and ring and at a reduced speed. If the sun and ring gears turn at the same forward

Fig. 3: PLANETARY GEAR ASSEMBLY



rate, then the planet carrier shaft will turn in the same direction and at the same rate as the input gears. If the sun gear turns at more than 2.7 times faster than the ring gear, the planet carrier shaft will counterrotate with respect to the sun and ring at a low speed. This constitutes the reverse drive situation.

Note that both the flywheel speed and the ratio between sun and ring gear speeds affect the output speed except in neutral. Speed control of the car would be difficult if there were not a unique flywheel speed for each driving speed. This speed relation is simplified considerably by sizing the flywheel so that it contains roughly enough energy to accelerate the car to its design top speed once on level ground. In this way the transmission can be shifted to an intermediate ratio leaving the car near the desired speed at the end of the shift so that the motor need only maintain the speed. Although it may not be apparent at this point, this flywheel size results in a unique flywheel speed for each desired speed of the car. This reduces the motor speed control for the car to a simple servo-controlled chopper with no requirement for an "intelligent" controller such as a microprocessor.

It should be noted that although the speed ratio is variable in this transmission, the torque multiplication from the motor to the rear axle is essentially constant at about 5:1. This limits the torque available for driving on a grade, but does not affect acceleration which is provided by the flywheel.

The transmission was designed to be built by cadets and faculty members who were not experts in machining or welding. For this reason, a timing belt drive system was used, even though it contributed considerable weight and bulk to the transmission. The belt drive allowed the use of bolt-on flanged bearings rather than the precision press-in bearings which would have been required by a gear drive. The efficiency penalty was slight, while benefits from increased involvement from cadet and faculty involvement in the construction were significant.

The relation between flywheel speed and vehicle speed is made somewhat more complex by the fact that stored flywheel energy and vehicle kinetic energy are related to rotation rate and vehicle speed, respectively, by non-compensating square laws. Note that the flywheel liberates more energy per RPM near 5000 RPM than it does at 3200 RPM (the top speed of the car). At the same time, it takes more energy to accelerate the car from 40 to 45 MPH than it does to accelerate it from 0 to 5 MPH. Unfortunately, rather than cancelling, these non-linearities reinforce each other. The relation between these quantities is discussed in Appendix A, where it should be apparent that the non-linearity is actually not serious and that it does not greatly complicate the control loops for the power train.

The overall transmission design is shown in Figure 4. A 50 mm wide, sinusoidal-tooth timing belt transfers power from the flywheel output pulley to the ring gear and to an idler shaft. A variable V-belt pulley system constructed from modified snowmobile power

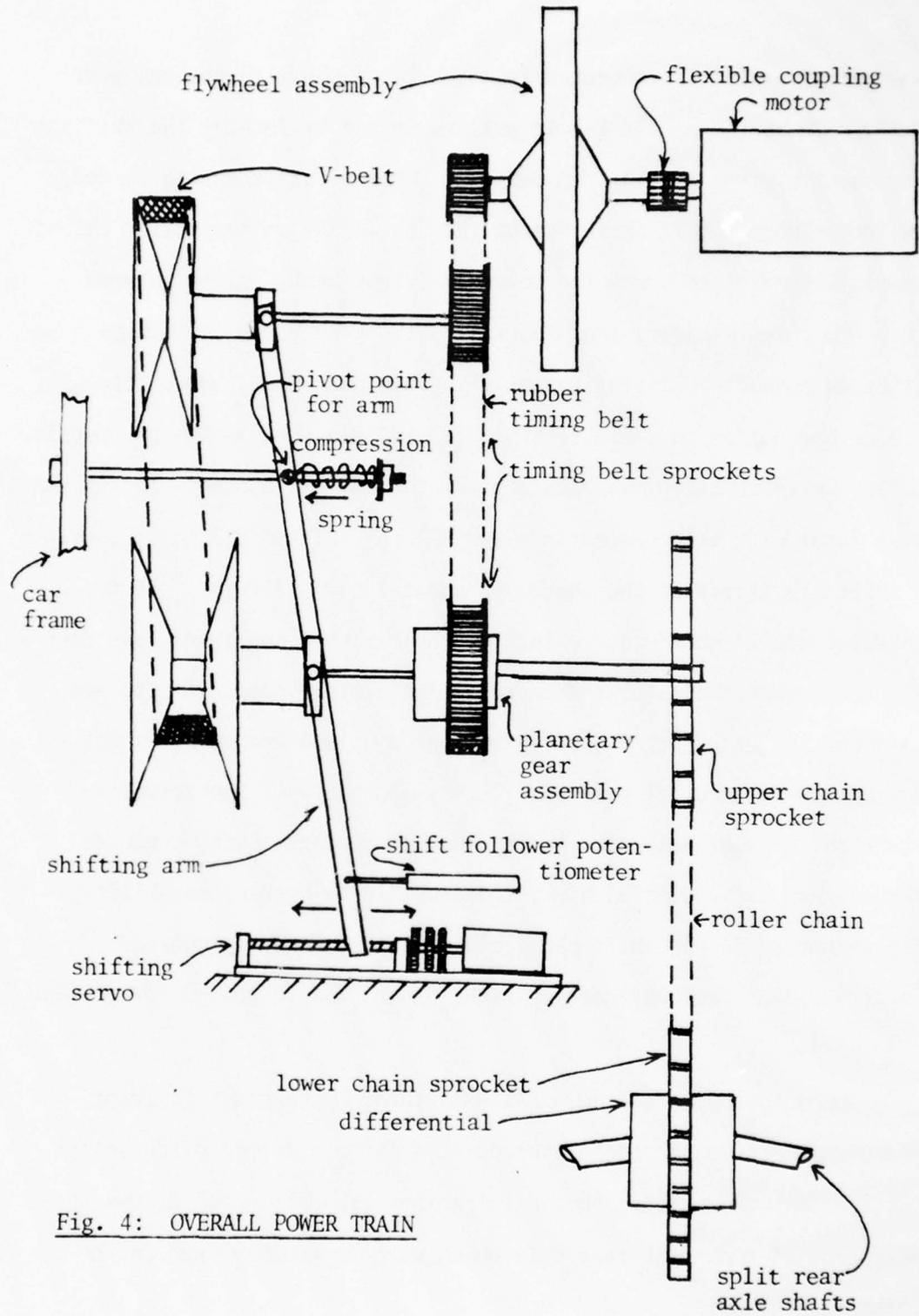


Fig. 4: OVERALL POWER TRAIN

power train parts is connected from the idler shaft to the sun gear shaft. The ratio of the V-belt pulleys is set by rocking the shifting arm about a pivot between the pulleys. This pivot is spring loaded in such a way that it exerts about 150 lbs (667N) on the pulley thrust bearings tending to force the moveable (right-hand) pulley sheaves into the fixed sheaves, thus tensioning the V-belt and providing friction contact. Tilting the shifting arm away from the vertical causes one pulley to increase its effective diameter while the opposite pulley is effectively made smaller. The total ratio change to the sun gear input with this system in the USAFA car is from 2:1 to 1:2, with a shift arm travel at the bottom of about 7.6 cm (3.5 in). If the shifting arm is moved to the left of the car, the sun gear slows down and the output shaft turns forward at increasing speed. If the arm is moved to the right, the sun gear speeds up and the output shaft approaches the neutral position. After about 50% of the travel to the right, the transmission is in neutral; further shifting causes the output shaft to move in reverse providing a backing capability. The asymmetry in the shift pattern is provided because required forward speeds are considerably higher than those required for reverse operation.

The output of the transmission is through the planet carrier shaft which is connected to a sprocket driving a 1-inch-pitch roller chain. This chain is connected to another sprocket which drives the differential and split rear axle which were originally used in the Volkswagen chassis.

SHIFTING SERVO

The shifting arm described above has a total travel of about 7.6 cm (3.5 in) at its lower end. When the motor and flywheel are turning at their normal operating speed, only about 44 Nt (10 lbf) is required to shift the arm. This shifting is accomplished by a servo follower with a feedback circuit which matches its motion to that of the driver foot control. The arm motion is generated by a rotary-to-linear motion converter consisting of a traveling nut with roller bearing contact with a linear worm screw. The worm screw is driven by a small separately excited motor operating through a 28:1 gear reduction train. Motor rotation rate is set by a power transistor controlling the armature current, while shift direction is controlled by a two-transistor switch which reverses the motor field current.

Signals for control of these transistors are generated by the servo amplifier train shown in Figure 5. A differential amplifier (board #1) composed of two voltage follower amplifiers senses the voltage difference, or error, between the foot control and servo follower potentiometer sliders. A single-stage differential amplifier (board #2) rejects the common mode signal and amplifies the error signal to a level useful for driving the 2N2222/2N2907 complimentary transistor pair, which then drives the 3055/2955 pair acting as a SPDT reversing switch for field current. Another differential amplifier followed by an absolute value amplifier (board #3) provides a signal proportional to error to a 2N2222 transistor driving a 3055 transistor which controls the armature current of the motor. The

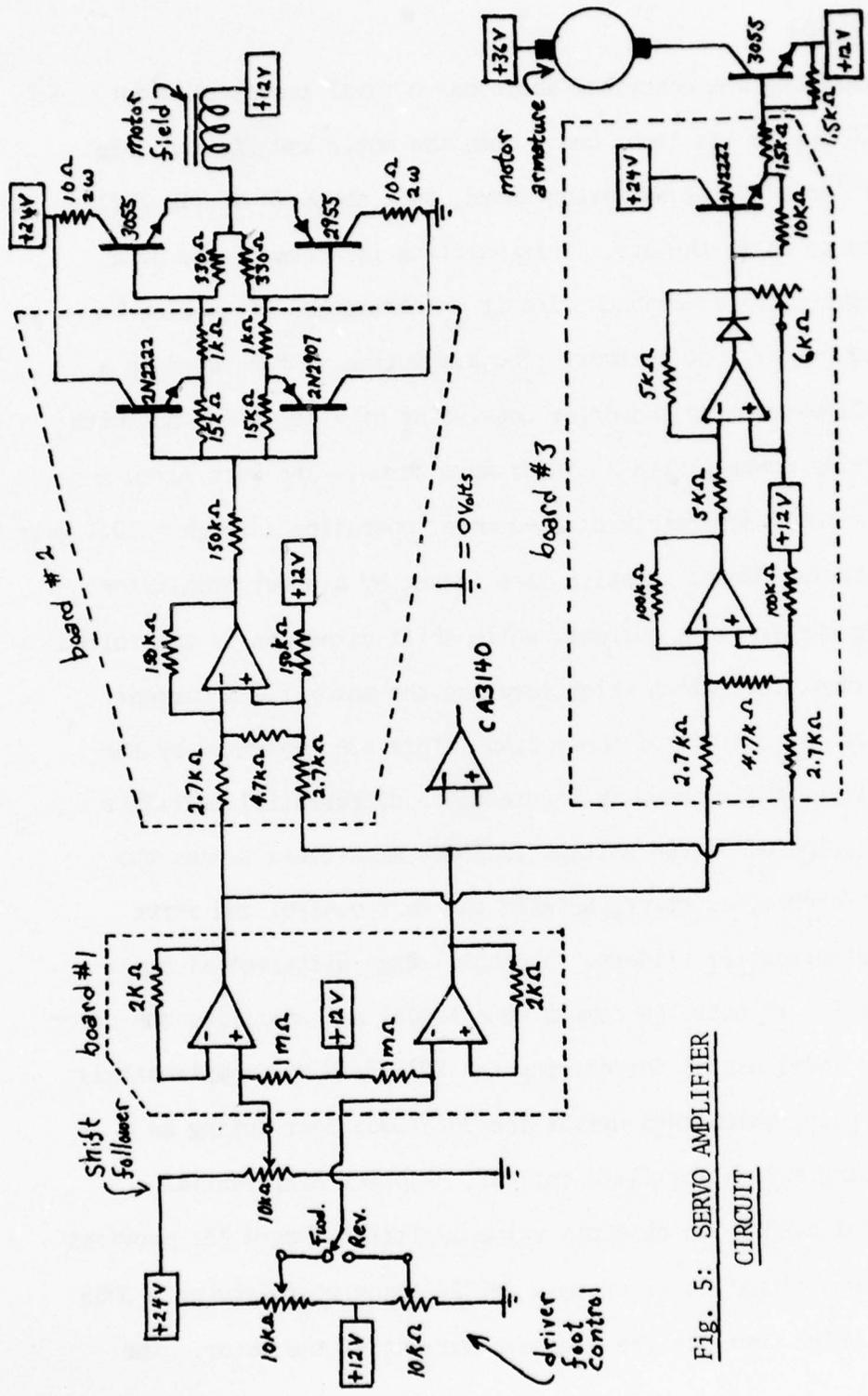


Fig. 5: SERVO AMPLIFIER
CIRCUIT

servo shifter is inherently rate limited by the rotation rate of the motor with full field and armature voltage applied. This rate limiting is an important safety feature since the shift rate is the only parameter limiting the maximum shaft horsepower which is extracted from the flywheel shaft under acceleration and deceleration. If the shift rate caused a shaft horsepower greater than about 45 Kw (60 HP), the transmission on the USAFA car would slip and possibly suffer mechanical damage.

BENEFITS DUE TO THE TRANSMISSION DESIGN

NARROW MOTOR SPEED RANGE

The transmission allows the motor and flywheel to operate between 3200 rpm when the car is moving at 45 mph and 5000 rpm when the car is stopped. Thus, the motor speed drops below 3200 rpm only at the beginning and end of a driving cycle. The significance of this feature lies in the fact that the motor has a high back EMF during the entire trip, as long as the motor field is maintained. There is adequate EMF above 2400 RPM to overcome the maximum battery array voltage (96 VDC) so that motor speed control can be accomplished solely by field control. The armature can thus be switched directly across the battery array at the start of the trip and left there until the trip is over. During start-up, an armature protection resistor limits the current until 2400 RPM is reached. Two advantages result from this configuration.

The first advantage is apparent in the motor speed control. The armature current can be well over 100 amperes and is bi-directional

if electrical energy regeneration is desired. This electrical regeneration feature is very desirable on downgrades because not only is energy recovered, but an automatic speed holding influence is exerted on the car due to the drag of the traction motor acting as a generator. If the motor stops during normal operation of the car, as it does in the operation of most electric cars, the armature current must be directly controlled. The control function is usually performed by SCRs (silicon controlled rectifiers) or power transistors. The requirement for bidirectional control of over 100 amperes results in an expensive control device with a large power dissipation and high weight factor. If speed control can be performed by field control (i.e. by control of the back EMF of the motor) only about 4 amperes need be controlled in the motor used in the USAFA prototype. See Figure 6 for a description of a proposed field chopper for the car.

A second benefit is the simplicity of electrical energy regeneration. The transition from motor to generator action is very simply accomplished by field current control of the back EMF of the motor at a given speed. An EMF less than the battery array voltage allows current to flow through the armature and motor operation occurs. If the back EMF is equal to the array voltage, no current flows and the car coasts. If the EMF is greater than the array voltage, generator action drives current backwards through the batteries, charging them while exerting a drag on the car which helps

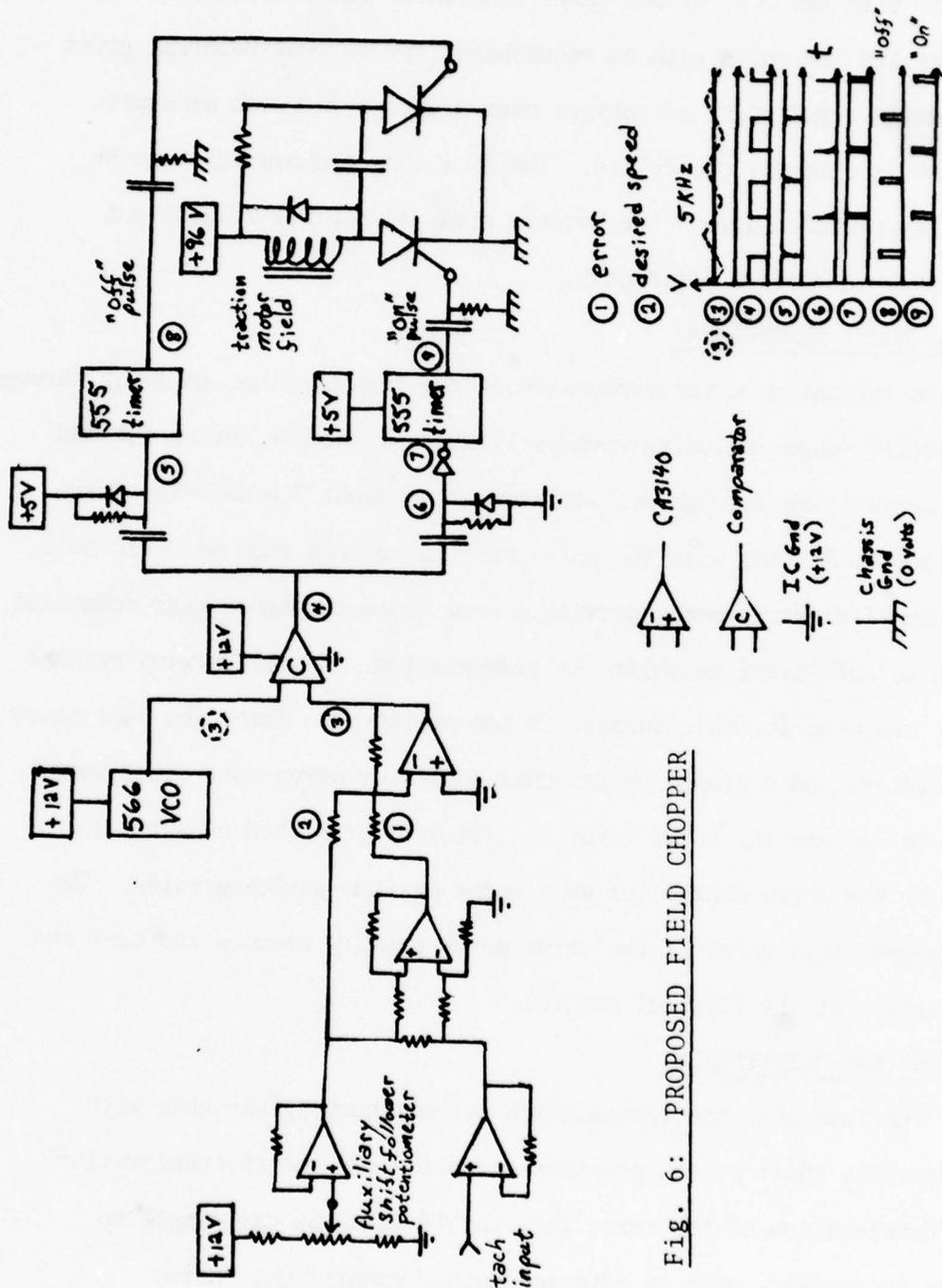


Fig. 6: PROPOSED FIELD CHOPPER

keep it from accelerating downhill. The fact that this can be accomplished with two SCRs or one power transistor rated at about 6 amperes and 120 volts with no requirement for current reversal gives the design significant advantages over a design in which armature current is directly controlled. The fact that the armature can be directly switched across the battery array also gives it a slight advantage in overall efficiency.

SIMPLE SHIFT ARRANGEMENT

As indicated in the discussion of the transmission, shifting through the entire range-including reverse-is accomplished by moving the end of a control arm through a displacement of about 7.6 cm. The force required to do this with the motor running is less than 44 N (10 lbf), so a small electric motor driving a worm screw through a gear reduction train is sufficient to shift the transmission. A small sewing machine motor was used for this purpose in the prototype. Three low cost power transistors and a simple operational amplifier servo-controller were used to operate the shift lever. A total of less than 60 watts is used by the servo controller even under maximum shifting rates. The low power requirement of the servo motor greatly reduces the cost and complexity of the flywheel control.

DRIVING AND MAINTENANCE

The fact that the transmission is continuously variable with no discrete shift points provides exceptionally smooth acceleration and deceleration of the car. This should make the car simple to drive in traffic, even in adverse weather conditions. Servo

modifications such as a shift rate limiter control on the dashboard will also allow the driver to adjust the "feel" of the car to the driving situation. A further benefit of the design of the transmission and servomechanisms is that the complexity of driving a flywheel vehicle is taken care of in the design; the USAFA flywheel-electric car would be essentially identical to an automatic transmission car in its requirements for driver training.

The simplicity of the mechanical parts of the transmission will make owner repairs considerably simpler than on currently available transmissions. The main item which will require attention is the V-belt in the variable drive. Since the adjustments on this drive are relatively non-critical, owner replacement of this drive belt is quite feasible.

A final benefit of the transmission design is efficiency. The transmission should be somewhat more efficient than a conventional automatic transmission with a torque converter, especially under hard acceleration. Due to the power splitting which takes place in a differential, only about one-quarter of the power from the motor and flywheel go through the V-belt at driving speeds. The V-belt has an efficiency of about 75%. Three-quarters of the power is transmitted to the planetary ring gear by the timing belt, which has a characteristic efficiency of about 95%.

FLYWHEEL SIZING

As indicated in the flywheel section, the flywheel was sized specifically to provide the energy for a single acceleration to 45 MPH. The reasons for this choice may not be immediately apparent, but they result in a very significant simplification of the speed control philosophy for the car. When the flywheel is chosen this way, there is a uniquely determined flywheel-motor speed and transmission shift point for each speed of the car. The flywheel is constantly maintained at such a speed that it can absorb enough energy to stop the car on level ground and to liberate enough energy to accelerate the car to 45 MPH, the designed top speed of the car. The driver selects the desired speed input to the control servo which then sets both the transmission shift point and the motor-flywheel speed. Due to the tachometer feedback from the flywheel which is required to do this, the car will inherently hold a desired speed on small up and down grades. In addition, a full cruise control can be added to the car for under \$10. The entire transmission shifting servo and motor speed control can be built with about nine operational amplifiers, two integrated circuit timers, six low-cost transistors and two small SCRs for a parts cost of under \$100. (See Figures 5 and 6)

SLOW FLYWHEEL ROTATION

The simple steel flywheel selected for the design has a very low energy-mass ratio compared to composite flywheels currently being designed. Cycling between 3200 and 5000 RPM it releases or stores about 3×10^5 Joules with a rotating mass of about 100 Kg. Energy

densities of up to ten times this figure are available with high-technology systems operating at 10,000 RPM and above. The disadvantages of this heavy flywheel are moderated, however, by the fact that it can be made by conventional machining techniques out of low-cost hot-rolled steel stock and run in a non-evacuated case without severe windage losses and without the requirement for vacuum-sealed bearings which can operate above 10,000 RPM. These advantages not only result in a less expensive car, but also allow the construction of such a car immediately, without lead time for research or development of any of the required materials or parts.

In summary, the heavy steel flywheel imposes a weight penalty of about 50 Kg on the car while providing simplicity, long life, low life cycle cost, and immediate availability without precision machining. In a near-term vehicle the advantages appear to outweigh the increased weight penalty.

DISADVANTAGES OF THE DESIGN

FLYWHEEL

As mentioned in the last section, the flywheel is rather heavy. The total assembly adds about 150 Kg to the weight of the prototype. Even in a production car, the weight would probably be about 100 Kg. (Note however the possibility of combining the motor and flywheel into a single unit mentioned in the section of opportunities for further improvement.) This is equivalent to the weight of adding an additional 4 batteries to the array, an increase of 25%. Under certain conditions, it might be better to add this weight in

batteries rather than in the flywheel assembly. One specific example is in a vehicle designed to operate in an area with many hills.

TRANSMISSION

The primary disadvantage of any differential transmission is that it does not multiply torque at low output speeds as do both manual and automatic transmissions of conventional design. This disadvantage is felt most if operation on grades of over about 3% is desired routinely. The transmission as it exists in the prototype is essentially a constant-torque drive with a total torque multiplication of about 5:1 from the motor shaft to the rear axle. An auxiliary low range such as that described in the "opportunities" section would probably be required for routine operation in an area with grades over 3%.

A second disadvantage is the inherent efficiency limit of the V-belt in the transmission to about 70-75%. This deficiency is moderated by the fact that the torque converter efficiency of a conventional automatic transmission is often even lower under acceleration. Another moderating factor is that under steady driving conditions at or above about 30 MPH, less than 30% of the transmitted power goes through this belt.

MOTOR

There are two basic disadvantages of the motor design used. First the motor and flywheel are not integrated, so there is a weight penalty of at least 50 Kg imposed on the vehicle over the weight of

an integrated unit. It should be relatively simple for a motor manufacturer to design a high-inertia motor whose armature provided the function of energy storage.

A second disadvantage results from the lack of an armature current control system. A very large starting resistor (1 ohm, 10 Kw) is required to limit current in the armature until a speed of about 2400 RPM is reached and the armature can be switched directly across the battery array. Although the resistor is not necessarily expensive, it tends to be rather bulky due to heat dissipation requirements. Since the resistor is needed only for about one minute on any one trip, the power loss due to the resistance is not significant in the driving cycle.

OPPORTUNITIES FOR FURTHER IMPROVEMENT

MOTOR-FLYWHEEL COMBINATION

Perhaps the most significant improvement which can be made in the power train design over that in the prototype is to combine the functions of motor and flywheel. A 22" diameter separately excited motor with an armature mass of about 100 Kg and a power rating of about 7460 watts mechanical (10 Hp) would supply both the motor and flywheel requirements in a relatively compact space. Although the design would require very secure mounting of the armature coils due to the large diameter, other parameters of the motor such as flux requirements in the armature and field might be relaxed compared to current small-diameter motors. In the event that future developments

in solid-state devices made current control in the 96 Vdc, 100 ampere range simple and inexpensive, the large diameter shape is ideal for an inverter driven induction motor design.

TACHOMETER FEEDBACK TO TRANSMISSION

In the prototype, the flywheel tachometer is a part of the motor speed control loop but not the transmission shifting loop. The transmission feedback comes solely from the shift follower potentiometer (see Figure 4). The disadvantage of this is that it does not compensate for belt wear and potentiometer shift. If a tachometer were added to the sun gear input shaft, the flywheel and sun gear rotation rates could be compared in an analog ratio detector. The voltage output of this ratio would give an unequivocal shift indication regardless of mechanical changes in the shift servomechanism.

Drift or wear in the V-belt speed controller would then have little effect on shift servo performance. The voltage output of the ratio detector would be used instead of the output from the shift potentiometer in the shift feedback loop. Such a ratio detector could be constructed from a single operational amplifier with an analog multiplier in its feedback loop.

TWO-RANGE TORQUE MULTIPLIER

The prototype transmission has the disadvantage of limited torque multiplication, resulting on poor performance on hills. This problem could be alleviated by a two-ratio planetary speed reducer with electrical clutch actuation located at the output of the motor-

flywheel shaft. This speed reducer would provide a multiplication of output torque at the expense of top output speed. The motor speed control electronics could be modified to automatically select this mode when armature current became excessive. The potential benefits of this added performance must be traded off with the increased complexity of the transmission, with greater desirability in terrain with significant grades than on level ground.

CONCLUSION

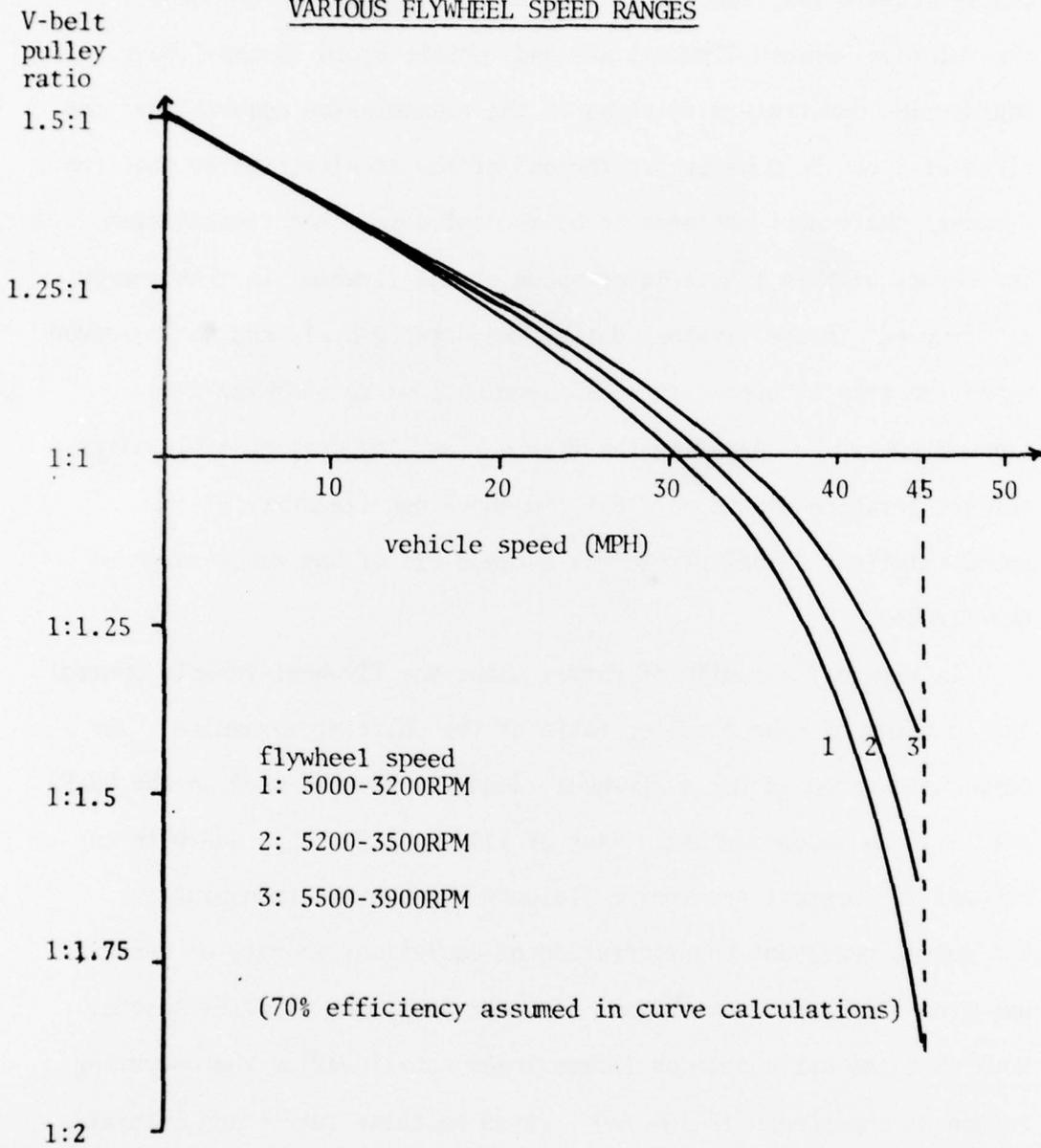
The flywheel-electric car described in the preceding paper was designed to make effective use of commercially available parts and lead-acid batteries. It constitutes an attempt to construct an urban vehicle which can greatly alleviate urban pollution and operate on alternate energy sources during a time when few solutions are available for automobile pollution and declining petroleum fuel supplies. Although the vehicle has not been driven at the time of writing of this preliminary paper, testing of subsystems and wind tunnel testing of models indicates that the car should have a range between 70 and 100 miles on level ground depending on speed. The acceleration performance should be comparable to current compact cars. Driver training for the USAFA flywheel-electric car should be comparable to that required for automatic transmission vehicles. Testing which will soon commence will be reported in a follow-on report.

APPENDIX A: RELATION BETWEEN FLYWHEEL ROTATION RATE AND VEHICLE SPEED

Because the energy of the flywheel and that of the car are non-linear (square law) functions which do not compensate each other, the relation between flywheel RPM and vehicle speed is non-linear. Engineering constraints relating to the transmission require that the flywheel speed be non-zero at the end of the acceleration so that the flywheel shaft does not need to be decoupled from the transmission. The result of this finite lower speed of the flywheel is that energy is "trapped" in the flywheel during the driving cycle and not released until the trip is over. It would seem optimum to minimize this trapped energy by operating the flywheel as slowly as possible after the acceleration of the car, but the above non-linearity of the speed relations actually requires a trade-off of the speed range of the flywheel.

In Figure 7 a family of curves shows the flywheel-vehicle control law in terms of V-belt pulley ratio at the shifting mechanism. The curves are computed for a flywheel identical to that used on the USAFA car, with an assumed vehicle mass of 1140 Kg (2500 lb), and with an assumed 70% overall transfer efficiency through the transmission. The curves represent the liberation of equivalent amounts of energy, but from different combinations of upper and lower flywheel speeds. Note that the curve becomes increasingly non-linear as the operating regime of the speeds is lowered. Based on these curves and initial projections of vehicle mass and control system, a speed range of 3200

Fig. 7: SPEED/RPM CURVES FOR
VARIOUS FLYWHEEL SPEED RANGES



to 5000 RPM was chosen. The future test program will allow an optimization of the parameters involved, at which time some other range will probably be desirable. Note that the main effect that the non-linearity has at a constant shift rate of the control arm is that the acceleration rate will drop between 35 and 45 MPH, the design top speed of the car. A similar drop in the acceleration of a conventional electric car occurs because of power drain on the batteries, so the effect should not be particularly noticeable to someone experienced with electric car operation.

APPENDIX B: ULTRASONIC EXCITATION OF A LEAD-ACID BATTERY

Lead-acid batteries which are discharged in a short period of time (2-4 hours) tend to give up considerably less energy than those which are discharged in a longer period of time (20 hours). The prime factor in this effect is the localized depletion of electrolyte in the region of the plates with insufficient replacement by diffusion. Since ultrasonic vibrations are commonly used to force liquids into porous structures similar to that of the plates of a lead-acid battery, it was of interest to examine the effects of ultrasonic vibrations on a lead-acid battery under a rapid discharge.

The battery used was a 4-ampere-hour lead-acid battery designed for motorcycle use. Several charge-discharge cycles were run at the 4-ampere discharge rate. The battery was kept at constant temperature in a flowing water bath. The battery was then discharged several times at the same rate in the tank of an ultrasonic cleaner, again maintained in temperature with a water bath. In each case the decision to terminate the discharge was based on the battery voltage, and the test was run until the voltage knee was reached.

Since there was no way available with which to control the recharge operation with any degree of repeatability, the results were somewhat variable. There was, however, a definite tendency towards longer discharge cycles with the ultrasonic vibrations present. In some cases, the discharge cycle was extended 30% beyond cases where no vibrations were present.

Although the results are in no way definitive, it appears that there is sufficient justification to do a more involved study which could better simulate a practical system, such as one using small ultrasonic transducers operating at low levels in each cell of the battery. A study of the net gain in released energy (if any) when the power consumed in the ultrasonics is considered would indicate whether there is any engineering feasibility to the method.

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