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CONTINUOUSLY VARIABLE TRANSMISSIONS: THEORY AND PRACTICE

August 1979

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FOREWORD

This report analyzes transmissison concepts useful for vehicular applications that utilize mechanical energy storage.

Authors Norman H. Beachley and Andrew A. Frank of the University of Wisconsin, Madison, conducted this work as consultants to the Lawrence Livermore Laboratory, Mechanical Energy Storage Project.

The Mechanical Energy Storage Project is funded by the Department of Energy, Division of Energy Storage Systems.

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CONTINUOUSLY VARIABLE TRANSMISSIONS: THEORY AND PRACTICE

Norman H. Beachley

Andrew A. Frank

ABSTRACT

This report examines and compares the five basic principles that can be used in continuously variable transmission (CVT) design: (1) hydrostatic; (2) traction drive (V-belt and rolling contact); (3) overrunning clutch; (4) electric; and (5) multispeed gearbox with slipping clutch.

Appendix A discusses commercially available CVTs suitable for motor vehicles, and Appendix B describes research and development programs for CVTs.

1. INTRODUCTION

This report examines and compares the five basic principles that can be used in continuously variable transmission design (CVT). Appendix A describes commercially available CVTs suitable for motor vehicles.

Basic terms used in this report are defined in this section.

A CVT is a transmission having a speed ratio that can be varied continuously over its allowable range. Its speed ratio may take on any value between its operational limits, i.e., an infinite number of ratios are possible. A gearbox transmission, on the other hand, has a discrete number of fixed speed ratios.

The term continuously variable transmission also usually implies that torque may be controlled independently of speed ratio and vice versa. In other words, the torque converter of the conventional automobile should not be considered a CVT because the speed ratio is set by the torque transmitted.

The term infinitely variable transmission (IVT) means basically the same as CVT, with the added restriction that a speed ratio of zero must be available, i.e., it must be possible to have zero output velocity for any input speed producing an infinite ratio range. A CVT providing negative as well as positive speed ratios would also be considered an IVT since its range passes through a speed ratio of zero.

Even though this definition of IVT is generally accepted, IVT is often used as a synonym for CVT by those not familiar with the difference.

Ratio range is one of the most important parameters of a CVT in terms of characterizing it for possible applications. Ratio range is defined as the numerical ratio of the maximum to the minimum output speeds possible for a given fixed input speed. For example, if a CVT can be controlled to operate between 3000 and 1000 rpm for a given fixed input speed, its ratio range is 3.0. Ratio range is usually more significant than the speed ratios themselves, since the latter can normally be adjusted if necessary by other components in the drive line (e.g., the rear axle ratio of an automobile). The ratio range of an IVT is infinite, since it is calculated as a finite ratio divided by zero.

2. AUTOMOTIVE APPLICATIONS OF CONTINUOUSLY VARIABLE TRANSMISSIONS

2.1 CONVENTIONAL AUTOMOBILES

At any given vehicle speed, and for any needed propulsive force, a certain transmission ratio will provide maximum fuel economy for a given engine. In addition, for any given vehicle speed, one transmission ratio will permit maximum acceleration with that engine. Since a CVT with the proper ratio range can provide the desired transmission ratios, it is obviously attractive for automobiles from both economy and performance points of view. In fact, its use (if its efficiency is high and its ratio range wide enough) can make it possible to have both maximum economy and maximum performance in the same vehicle.

2.2 ELECTRIC AUTOMOBILES

Electric traction motors are even less versatile in terms of efficiency over the typical automobile required torque-speed range than internal combustion engines. An efficient CVT has the potential of improving the average efficiency and, therefore, range of an electric automobile.

2.3 FLYWHEEL AUTOMOBILES

For an automobile using an energy storage flywheel (Fig. 1), a CVT or IVT is not only desirable but essential. The speed of the flywheel cannot be controlled at will, but changes only slowly as energy is added or subtracted. A CVT is required to match the flywheel and vehicle speeds under all possible operating conditions. A typical mode of operation, acceleration, will find the car speed increasing while the flywheel is slowing down. The CVT must match the two speeds in a continuous manner. Furthermore, the driver must be able to control the torque being transmitted in order for the car to be driven in a conventional manner.

To take full advantage of the flywheel concept, regenerative braking must be used, i.e., the system must allow kinetic energy of the car to be converted to flywheel kinetic energy. This kind of braking requires a CVT that can transmit power in both directions--to or from the flywheel.

3. DESIGN CATEGORIES OF CONTINUOUSLY VARIABLE TRANSMISSIONS

Many CVT designs have been proposed, and quite a number have been built, either as prototypes or as production versions. Some designs are so sophisticated it is difficult to determine how they operate from drawings or written descriptions. It is very useful, therefore, to describe and discuss the different categories into which the various CVTs fall. A few well-defined principles form the basis of all known CVT designs, and knowing the basic advantages and limitations of each principle will aid in the preliminary evaluation of any proposed CVT design.

The following basic types of CVT are meant to cover all generic possibilities although it is possible that there are inventions unknown to us that use some entirely different principle. If one can find the proper category for any particular CVT, he can understand certain of its characteristics and features without a complete understanding of the mechanical details.

3.1 HYDROSTATIC TRANSMISSIONS

Hydrostatic transmissions transmit power through the use of high-pressure oil, typically at pressures up to about 5000 psi. A hydrostatic transmission (Fig. 2) consists of a hydraulic pump and hydraulic motor connected together by two hydraulic lines and with the other required hydraulic components (such

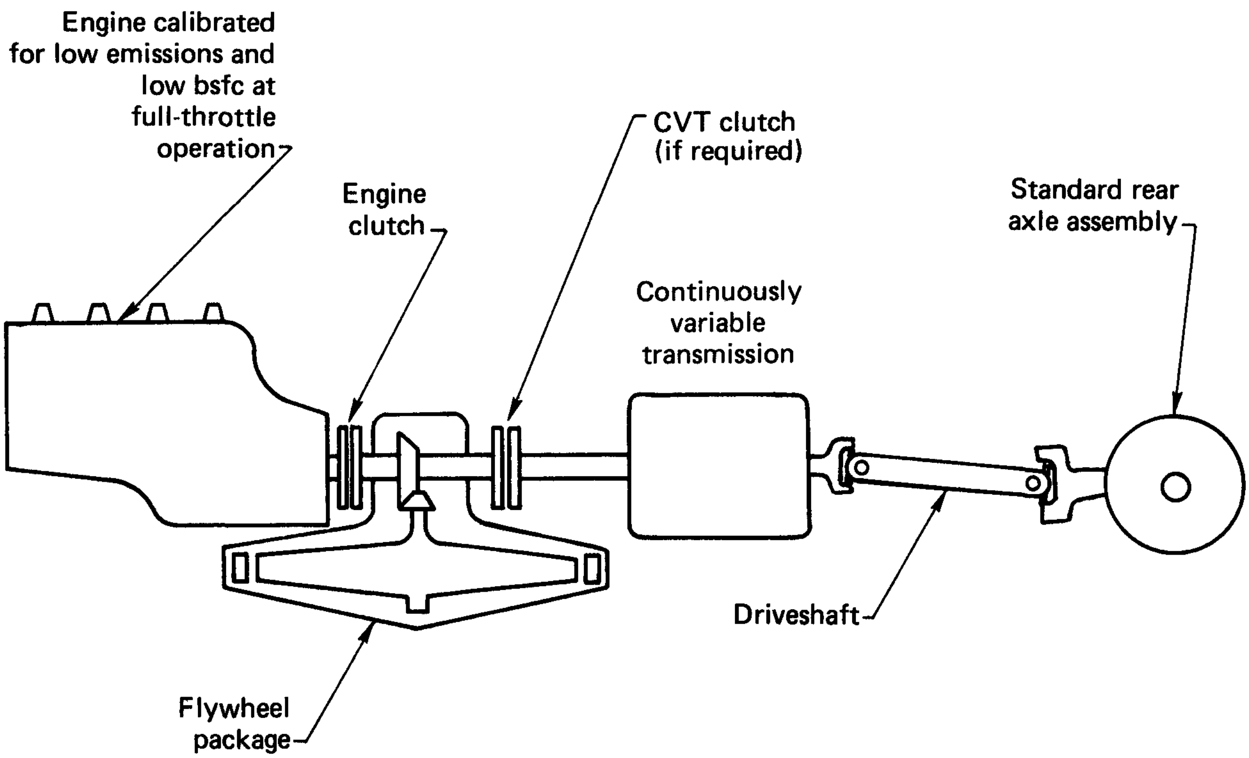

FIG. 1. Schematic diagram of a flywheel automobile. (bsfc is brake specific fuel consumption.)

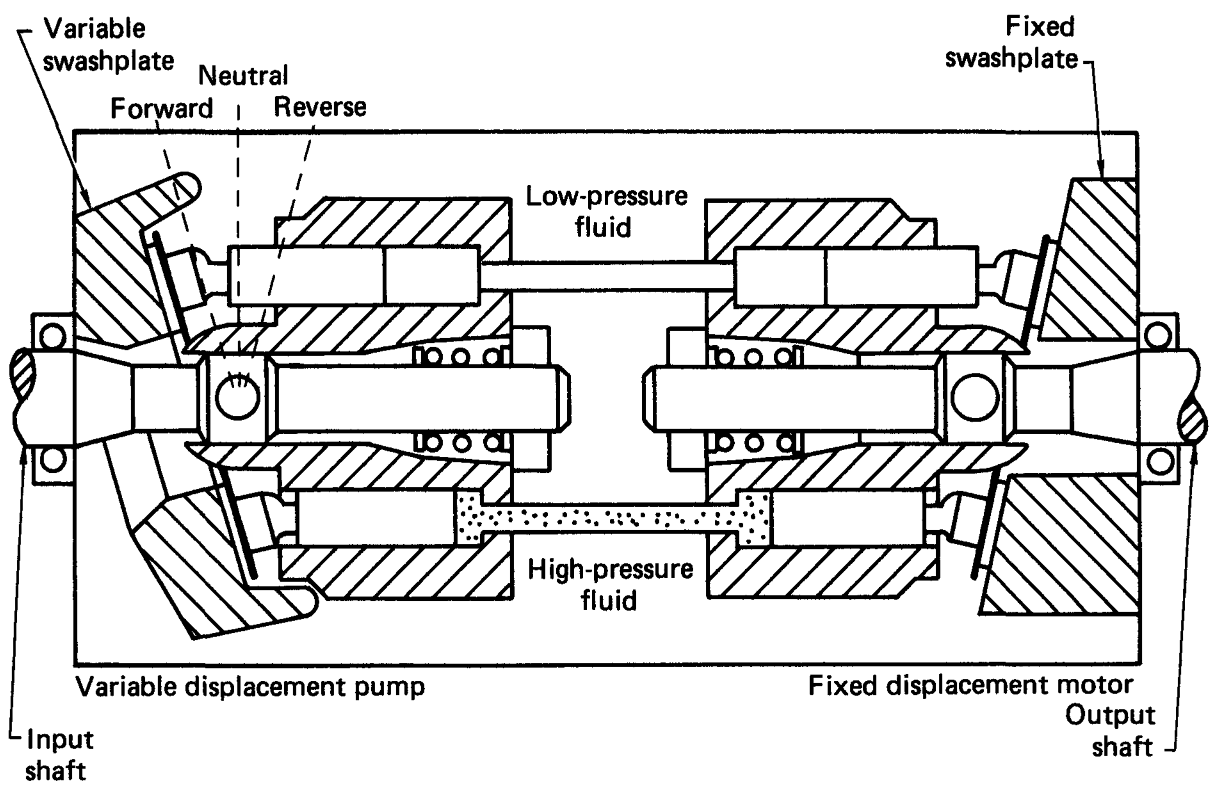

FIG. 2. Typical hydrostatic transmission.

as reservoir, check valves, and relief valves). The pump creates the hydraulic power (pressure and flow rate), and the motor converts the hydraulic power to mechanical power (torque and speed). The basic system is a CVT if the pump is designed to have a displacement ($in.^3$/revolution) that can be varied. (Sometimes the motor is also given a variable displacement to give additional versatility.)

Straight hydrostatic transmissions (the power-split version will be discussed later) will almost always have a ratio range of infinity, i.e., be IVTs. (Since the stroke of the pump can be set to zero, the output speed of the motor will vary from zero to its maximum value.) The stroke of the pump can usually be reversed so that the hydraulic motor rotation can be either positive or negative. The torque of the hydrostatic transmission can be reversed (the high-pressure line changing to the low-pressure line and vice versa), with the "pump" then acting as a motor and the "motor" as a pump.

The hydrostatic transmission is thus quite versatile, and has a number of features desirable for an automobile transmission. There are many commercially available units in sizes appropriate for automobiles. The major disadvantages are size, weight, and relative inefficiency (especially when compared to gears) of the straight hydrostatic transmission over a wide speed and torque range.

3.2 TRACTION DRIVE

Traction drive is a term applied to any device which transmits power through adhesive friction between two objects loaded against each other. A V-belt is one example; another is the use of metal elements rolling on one another. The concept is in contrast to the use of gears or chains, in which the coefficient of friction serves no useful purpose. Traction drive CVTs fall into two basic categories, V-belt drives and rolling contact drives, and it is useful to discuss the two separately.

3.2.1 V-Belt Traction Drives

A rubber V-belt drive with pulleys (sheaves) whose diameters may be varied is a CVT (Fig. 3) that can transmit power in either direction of rotation. If both pulleys are made variable, a ratio range of about 3.5 is

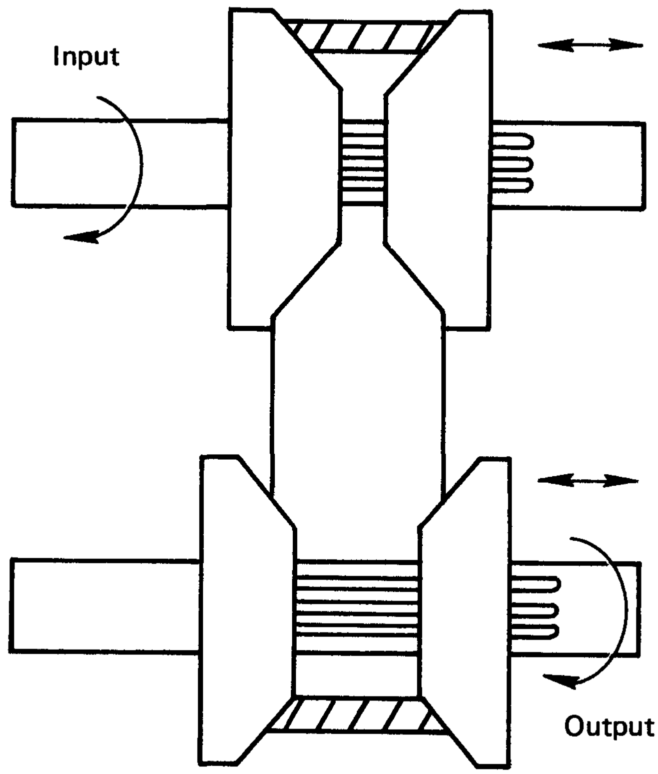

FIG. 3. Variable-diameter pulley V-belt continuously variable transmission.

typically achieved. Such drives are common for machine tools. In recent years they have been the most common type of transmission for snowmobiles, where they may transmit up to 50 hp or more. The DAF automobile, built in Holland (and currently owned by Volvo of Sweden), has used a rubber V-belt CVT for many years.

The pulley diameters may be varied in various ways, depending on the ratio range desired and the type of control needed. A common scheme for machine tools is to have both pulleys variable with a fixed center distance, one pulley having its effective diameter set by a mechanical linkage, and the other one spring-loaded to provide automatic correspondence. Typical mobile applications set the ratio range as a function of demanded torque and speed, using mechanical control system devices to provide the desired relationships.

A recent development is the Transmatic transmission based on a V-belt made of steel blocks joined by steel bands (Fig. 4). (This transmission is produced by van Doorne of Holland.)

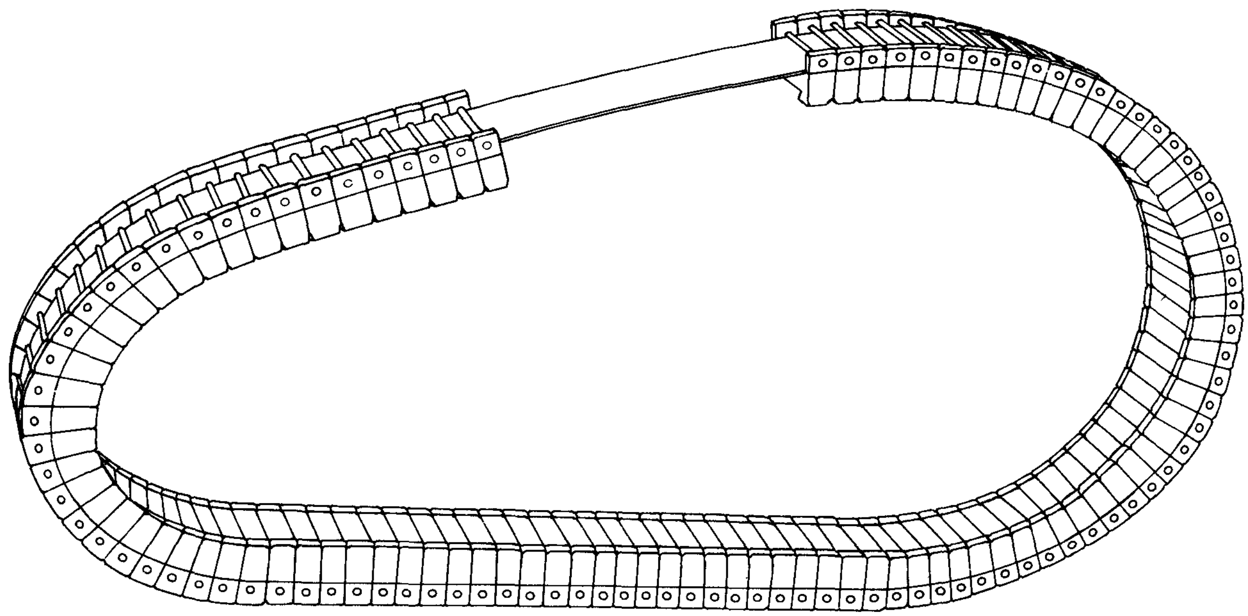

FIG. 4. Steel-block belt as used in the van Doorne Transmatic continuously variable transmission.

3.2.2 Rolling Contact Traction Drives

A number of CVT configurations work on the principle of rolling contact, usually two metal surfaces rolling on one another while lubricated with a special type of oil. By changing the effective radius of one or both surfaces, the speed ratio is varied in a continuous fashion.

Several transmissions in this category are illustrated in Fig. 5. The simple concept shown in Fig. 5(a) was actually used in several early makes of automobiles (e.g., the 1909 Cartercar, the 1909 Sears Motor Buggy, and the 1909 Orient Model BB Buckboard). The output wheel is moved on a splined shaft to different diameters on the input disk to set the desired speed ratio. The design is still in use on some makes of garden tractors.

For the CVT of Fig. 5(b), a ring is moved back and forth to vary the speed ratio. The ring must be kept at the same angle so that the points of tangency will be the same distance apart.

In the CVT of Fig. 5(c), a ball is used to transmit torque between the input and output disks. The ball can be moved as shown to increase the radius of contact on one disk while at the same time decreasing the radius on the other. In practice, a number of balls are used, located in a cage that is positioned to set the CVT ratio. The cage itself must be free to rotate about

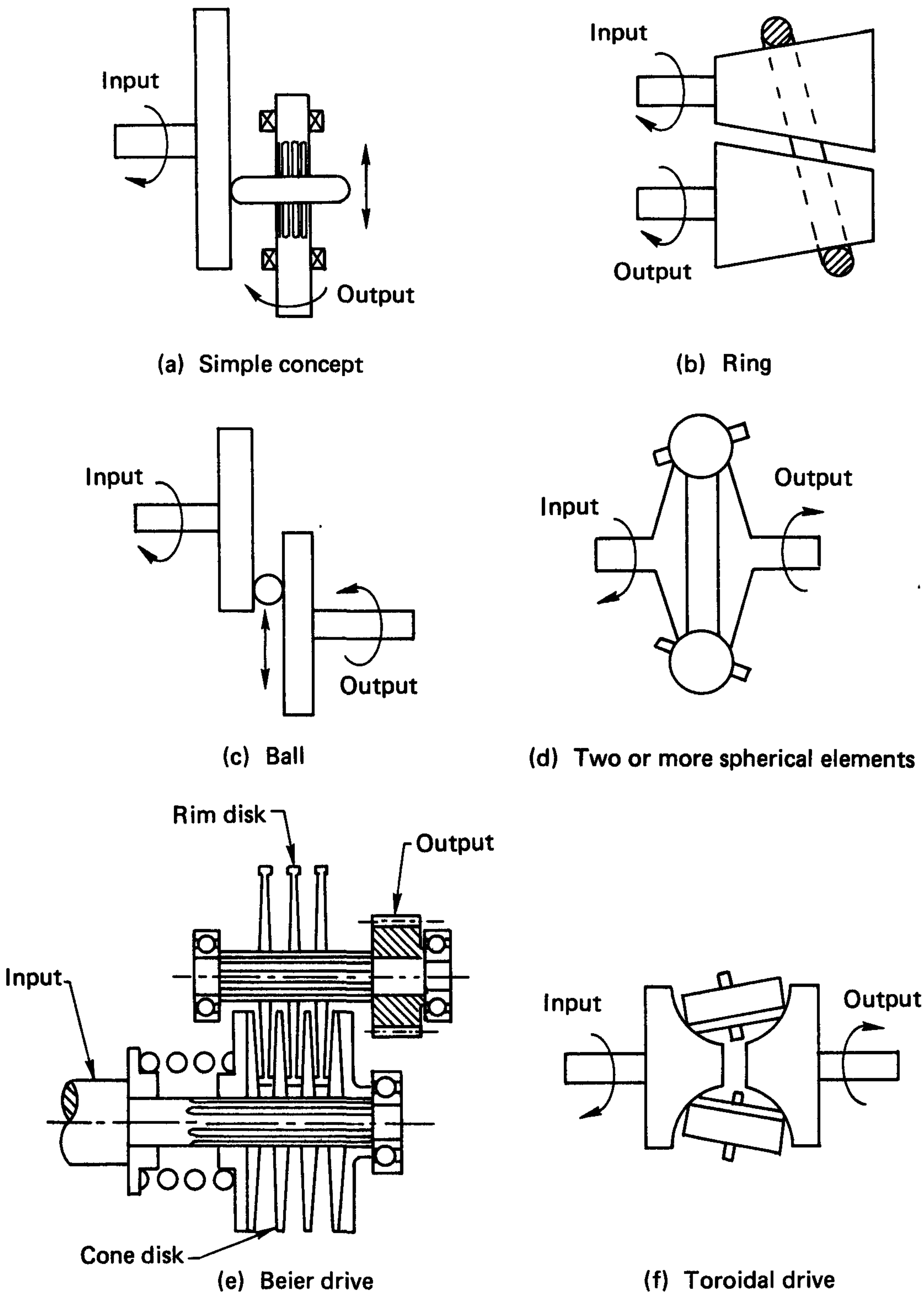

FIG. 5. Rolling contact traction drive continuously variable transmissions.

its centerline, to allow for the fact that the balls in this case will be at different radii. (Although it is not obvious by any means, a kinematic analysis will prove that all balls can transmit torque by a pure rolling action with no sliding required.)

In the CVT of Fig. 5(d), two or more spherical elements are used to transmit torque between the input and output disks. Tilting the axles of the spheres will produce different rolling radii for the input and output contact points.

The Beier drive, Fig. 5(e), is based on rim disks with outer rims that make contact with cone disks at a variable radius. The distance between the input and output shafts is varied to make contact.

Industrial CVTs with small horsepower capacities are available with designs based on Figs. 5(a) through 5(e) as well as other similar principles. The toroidal drive, Fig. 5(f), however, may be more nearly developed to the point of being practical for automobiles. Early work was done by General Motors in the 1920's and 30's, with the concept apparently losing out to the torque converter type of automatic transmission that is now virtually standard. In England, the toroidal drive is known as the Perbury Drive, apparently named after the man who invented or designed that particular version. At least two U.S. companies are now actively engaged in research and development of this particular concept: (1) Excelermatic, Inc., of Austin, Texas and (2) AiResearch Manufacturing Company, Garrett Corporation, Torrance, California. Various companies and private individuals are developing and promoting other rolling contact traction drive concepts.

3.3 OVERRUNNING CLUTCH DESIGNS

An overrunning clutch is a device that allows torque to be transmitted in one direction, but which overruns or freewheels if an attempt is made to apply torque in the opposite direction. A common example is the bicycle coaster brake (or corresponding freewheel of a 10-speed bike). Some CVTs use a combination of overrunning clutches and kinematic linkages.

One of the simpler examples of this class of CVT, and one which is available commercially in smaller power ranges, is the Zero-Max. Figure 6 illustrates the operating principle of a single linkage with four to eight such linkages normally being used. The rotating shaft at the left has an

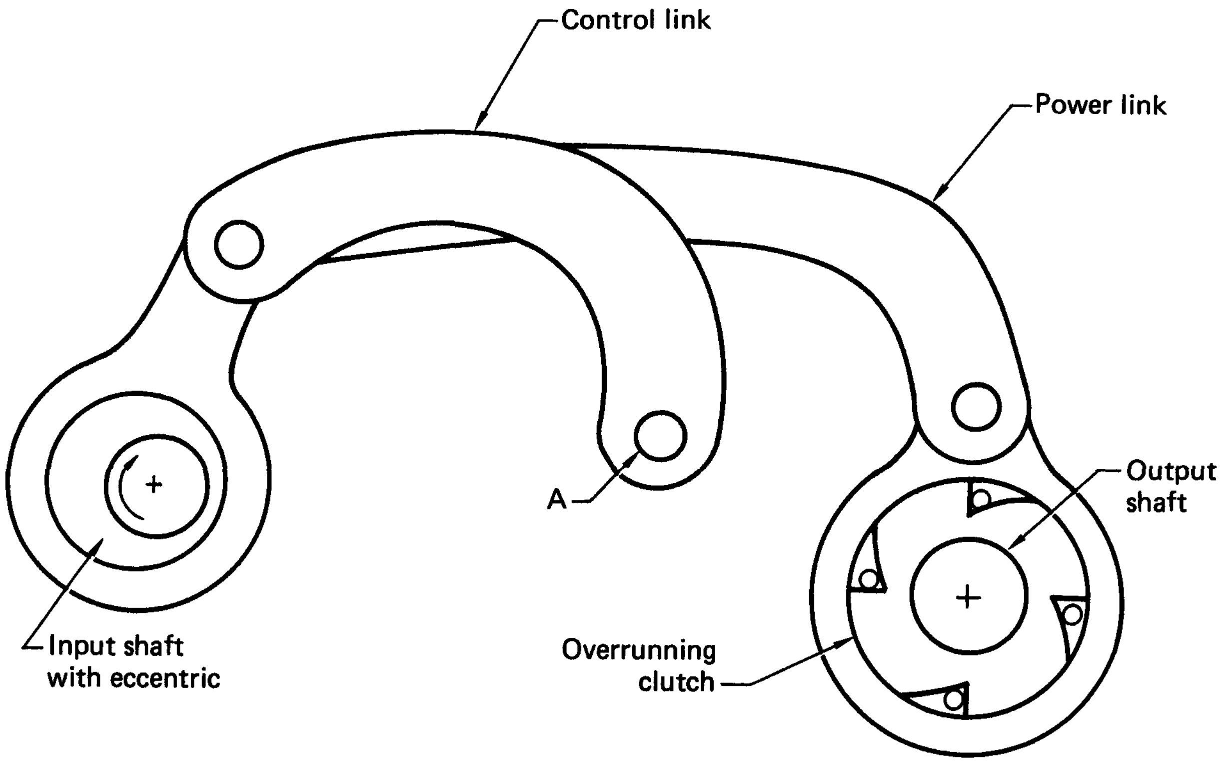

FIG. 6. Single linkage of the zero-max continuously variable transmission.

eccentric for each linkage. This arrangement causes the power link to oscillate. With overrunning clutches (or ratchets), a one-directional rotation of the output shaft on the right is obtained. With multiple linkages, the resultant output motion, equal at any instant of time to the motion of the overrunning clutch that is rotating the fastest and therefore driving, is nearly uniform. The speed ratio is changed by moving point A of the control link.

Other more sophisticated transmissions based on the same basic principle, but in sizes suitable for automobiles, have been proposed. Insufficient experimental data are available to adequately evaluate them.

One important disadvantage of the ratchet type CVT is that it does not allow reverse torque; therefore a single such CVT cannot allow regenerative braking for a flywheel car. The only way to get regenerative braking is to put two such CVTs in parallel, but reversed with respect to each other. One would then be used for positive torque and the other for regenerative braking.

3.4 ELECTRIC CONTINUOUSLY VARIABLE TRANSMISSIONS

An electric generator motor combination makes a CVT (Fig. 7) that is in many respects analogous to the hydrostatic transmission. The generator converts mechanical power (torque and speed) to electrical power (voltage and current). The electric power is then fed to the motor, which converts it back to mechanical power. The continuously variable feature is achieved because of the lack of any rigid requirement on the relative speeds of the two electric machines and because the torque of the motor can be controlled by varying the voltage and/or the current of the generator. With proper component characteristics, the system will be an IVT, i.e., the motor can supply torque while motionless. Such a system can be based on either ac or dc power.

The concept is attractive because of the versatility of electric motors in terms of torque and speed. Currently available electric machines capable of automobile level power are quite large and heavy, however. Efficiency drops off when they are operated at conditions far removed from the design point. Another consideration is the complexity and efficiency of a controller that would allow the driver to control torque independently of vehicle speed. Research in the electric drive field is being conducted with these factors in mind.

The electric CVT is readily adaptable to the power-split principle (Section 4.1).

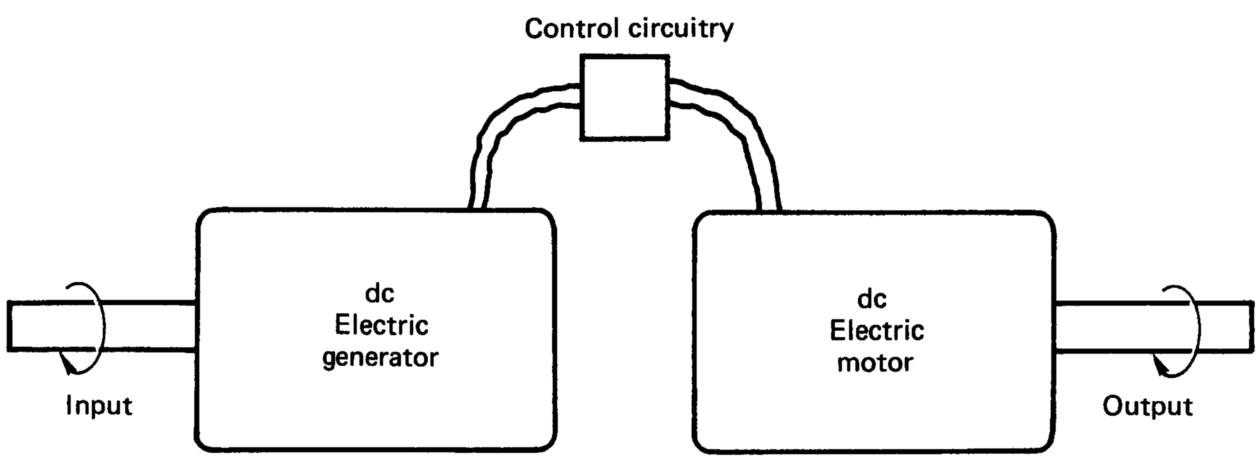

FIG. 7. Simple electric transmission.

3.5 MULTISPEED GEARBOX WITH SLIPPING CLUTCH CONTINUOUSLY VARIABLE TRANSMISSION

A gearbox can operate only at discrete speed ratios. If a clutch is placed in series with the gearbox, however, its slippage can allow any speed ratio to be available, and the system can be considered to be a form of CVT (Fig. 8) because the torque can be controlled independently of the ratio. If enough gear ratios are available, the energy loss due to slippage is minimal. For example, if we ignore such things as bearing friction, a clutch that has 15 percent slippage is 85 percent efficient.

One major advantage of the slipping clutch concept is that it could be designed and developed in a straightforward manner with current technology. Some early experimental flywheel vehicles have operated on this principle. Some disadvantages are the high frequency of shifting required and the somewhat unknown factor of clutch wear. It is possible, however, to use a device that acts as a clutch (e.g., a hydrostatic pump with a controllable orifice between it and the reservoir) that would have virtually no wear.

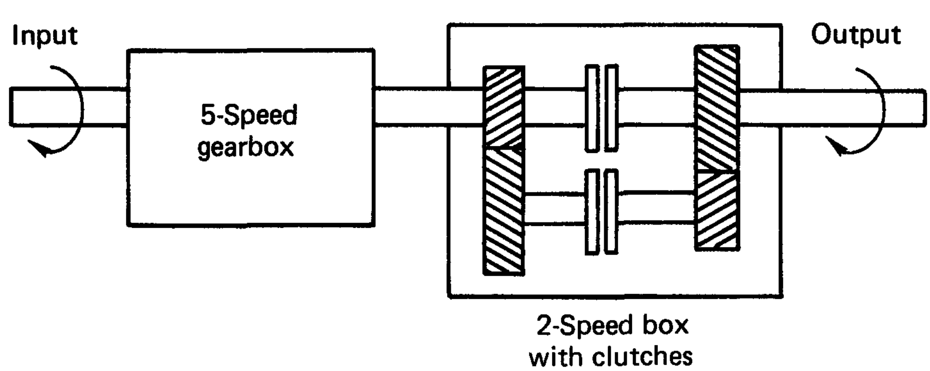

FIG. 8. Schematic diagram of a multispeed gearbox with slipping clutch continuously variable transmission.

4. POWER-SPLIT AND INVERSE POWER-SPLIT PRINCIPLES

4.1 POWER-SPLIT PRINCIPLE

The power-split principle was developed to partially overcome the poor efficiency characteristics of certain CVTs. The basic idea is to send only part of the power through the continuously variable unit (CVU),* with the remainder of the power going through a straight mechanical path (with higher efficiency). The two components of power are then added in a mechanical gear differential at the output of the power-split CVT. Figure 9 illustrates the basic concept.

For a given input speed (ω_{in}), we are essentially adding two velocities at the mechanical differential. With one of these fixed and the other variable, the output speed (ω_{out}) is variable and the overall system of Fig. 9 is a CVT. As is usually the case, however, we don't get something for nothing. In gaining higher efficiency, we suffer a reduction in ratio range.

Figure 10 is another schematic of a power-split CVT, one which shows a little more detail. The mechanical differential is drawn as a bevel gear type (exactly the same principle as used in the drive axle differentials of automobiles) for ease of illustration, but a planetary or a spur gear type of

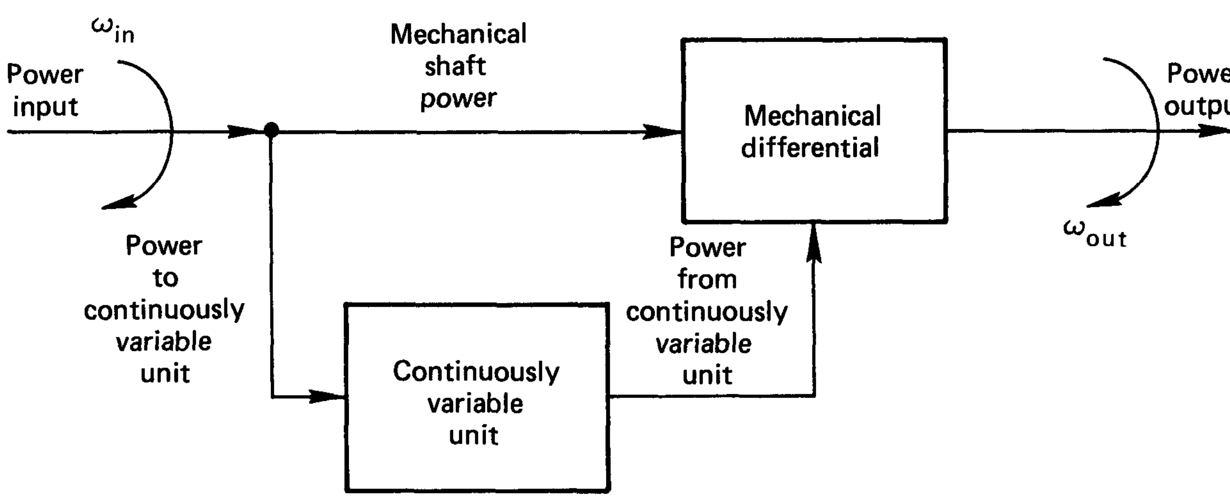

FIG. 9. Illustration of the power-split continuously variable transmission principle.

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*Where a basic CVT unit is used as part of a more complex CVT system it will be called a <u>continuously variable unit</u> in an attempt to avoid confusion.

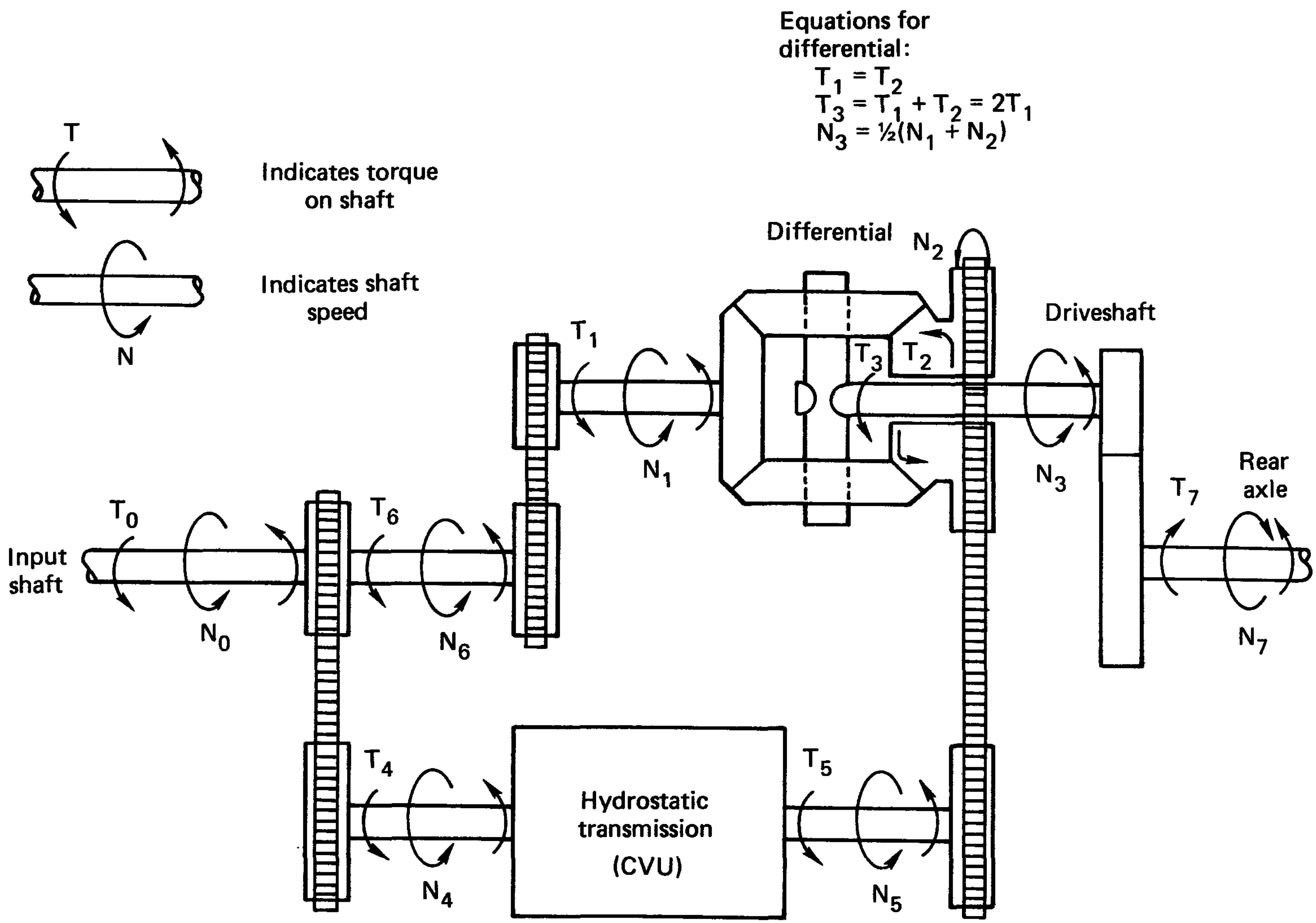


FIG. 10. Schematic diagram of a hydrostatic power-split continuously variable transmission.

differential is a more logical choice for a practical design. (Planetary gearing is used in the Sundstrand and Orshansky power-split CVTs.) Note that Fig. 10 shows a gear ratio between the input shaft and the input to the CVU and also between the output of the CVU and the gear differential.

To reduce the fraction of power going through the CVU (and thereby raise overall efficiency), we reduce its torque (which also allows its size to be reduced). But to satisfy the torque balance of the differential ($T_1 = T_2$), a relatively large gear ratio (N_5/N_2) is needed. As this gear ratio increases, the effect of a given change in CVU output speed upon N_3 decreases, resulting in a lower ratio range. (This explanation is based on the assumption that the speed characteristics of the CVU do not change appreciably with a change in size.)

It is interesting to consider the type of application for which a power-split CVT is ideally suited. This would be an application where a device is to be run at a speed that is almost, but not quite, constant, and where the small speed changes must be made in a continuous manner. Certain components of paper-making machinery (e.g., large rolls) fit this category, since small speed adjustments are required to keep the proper tension in the paper as it runs through. The CVT ratio range may be reduced to 1.1 or less for such an application, meaning that only a small fraction of the power is transmitted by the CVU and the rest by mechanical shafts and gears.

For an automobile, the loss in ratio range caused by using the power-split principle can be compensated by having a gearbox (or something comparable) in series. The gearbox-CVT then becomes a <u>wide range continuous transmission system</u>, with the CVT filling in the ratio gaps between gears. As an example, suppose we want to have an overall ratio range of 10.4 to 1, and we wish to accomplish this using a 4-speed gearbox and a power-split CVT in series. Then we find that $\sqrt[4]{10.4} = 1.8$; therefore, each gear ratio of the fixed ratio transmission should vary from the adjacent one by a factor of 1.8; i.e., first gear will be 5.83, second gear will be 3.24, third gear will be 1.8, and fourth gear will be 1.0. The CVT must also have a ratio range of 1.8. The overall transmission system ratio is then the CVT ratio multiplied by the fixed transmission ratio. Thus, in first gear the overall speed ratio varies from 10.4 to 5.83 with the CVT varying from 1.8 to 1, at which time the fixed transmission is shifted and the CVT set again to 1.8. The gear ratio in second gear then varies continuously from 5.83 to 3.24. Thus by changing gears in the fixed ratio transmission and letting the CVT vary back and forth the overall transmission system can vary continuously from 10.4 to 1.0 to 1. It is important to realize that this shifting and control can be automated very easily if the proper control philosophy is chosen. It can also be rather complex if not done cleverly.

As long as the CVU is reversible, that is, can transmit power equally well in either direction (or, more specifically, can have positive or negative torque for either direction of rotation), regenerative braking can be satisfactorily handled by a power-split CVT. The level of braking that can be handled regeneratively depends on the torque capacity of the CVT.

4.2 INVERSE POWER-SPLIT PRINCIPLE

The regular power-split principle sacrifices ratio range to improve efficiency. The inverse power-split configuration does just the opposite, sacrificing efficiency to improve the ratio range. This behavior is attractive for CVTs that have good efficiency but limited ratio range since a small decrease in overall efficiency may allow a great improvement in the ratio range.

Figure 11 illustrates the fundamental principle involved. The only significant difference between Fig. 9 and Fig. 11 is the direction of power flow. The regenerative gearing is a simple gear differential, virtually the same as for the regular power split but connected to the other elements in a slightly different manner. Ignoring for the moment the details of the gearing and concentrating on the directions of power flow, we see that, in the direct mechanical path, power flows "backwards" from the differential to the input shaft. This causes the power going through the CVU to be greater than if it were used alone.* By carrying more power and being a larger unit in order to do so, it will operate at a lower efficiency, producing a greater energy

*An example may help clarify what is occurring. Assuming 100 percent efficiency of all components for simplicity, typical operation may find 100 hp at the input. To this may be added 20 hp from the mechanical path, causing 120 hp to pass through the CVU. At the differential, 20 hp is taken off by the mechanical path, leaving 100 hp at the output.

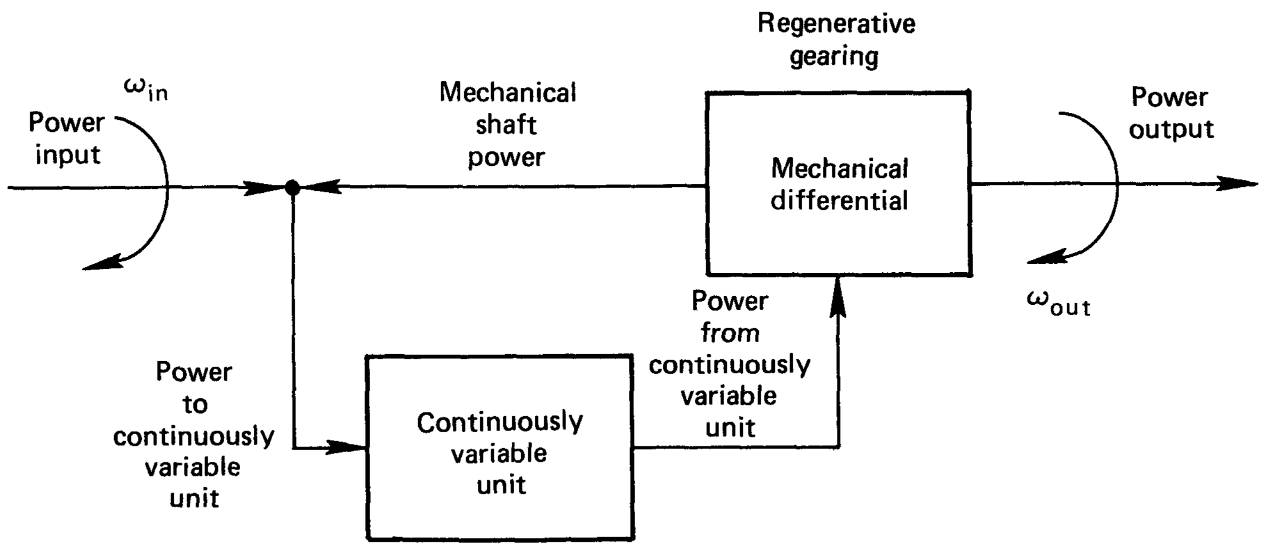
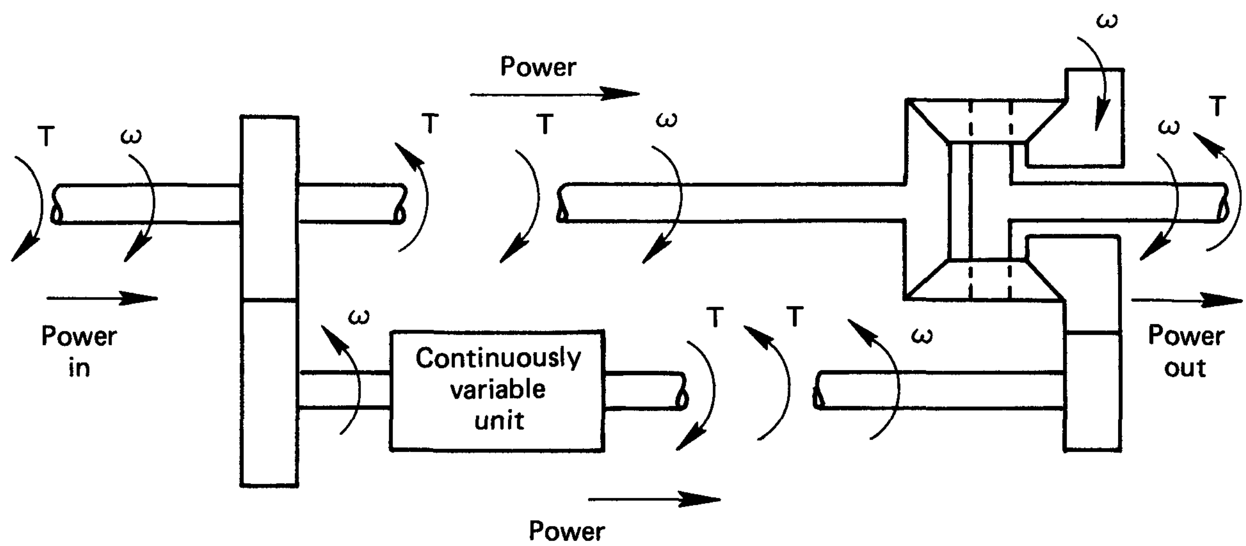


FIG. 11. Illustration of the inverse power-split continuously variable transmission principle.

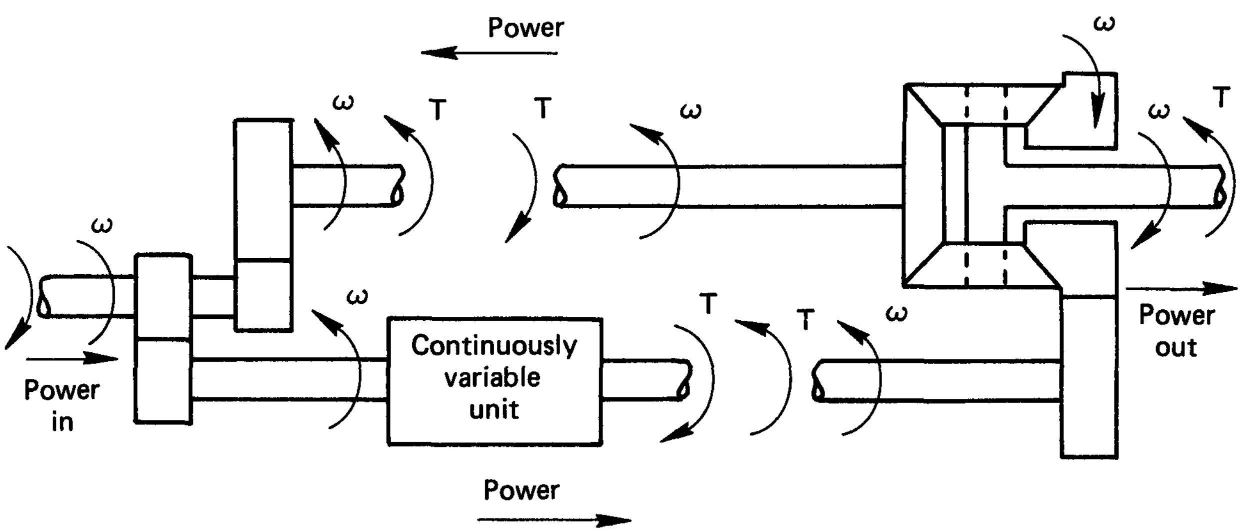
loss and a resultant lower efficiency for the overall system. (With a good design and a small amount of power recirculation, the efficiency reduction may be quite small, however.) An example of its use would be to extend the ratio range of a V-belt CVT from a finite value to infinity, thereby producing an IVT.

At this time, we can focus on the mechanical design details to explain the differences that cause either a regular power-split or an inverse power-split situation to occur. Figure 12 shows two configurations that are identical except for one item: the extra gear pair of the second version. Figure 12(a) is a regular power-split CVT, and Fig. 12(b) is an inverse power-split CVT. Included in Fig. 12 are arrows that show the directions of the shaft rotations as well as torques acting on the various shafts. (Note that the schematics and corresponding explanation are based on a CVU that has its input and output directions of rotation the same.)

For the regular power-split [Fig. 12(a)], the torque and direction of rotation of the mechanical path shaft are such that its power is transmitted into the differential. For the inverse [Fig. 12(b)], the extra gear pair (which incidentally should have a large reduction ratio) reverses the direction of rotation of the mechanical path shaft. The torque balance



(a) Normal power-split configuration.



(b) Inverse power-split configuration.

FIG. 12. Diagrams of regular and inverse power-split continuously variable transmissions, showing directions of rotation and of torque (based on a continually variable unit configuration that has identical input and output directions of rotation).

requirement of the differential, however, constrains the torque on that shaft to have the same sign as the other case, resulting in power being taken from the differential and transmitted back to the input.

Again, it should be emphasized that both the power-split and inverse power-split principles are useful. They both involve trade-offs between efficiency and ratio range, and both are useful depending on the applications and the characteristics of the CVUs. It is also possible to design and build a CVT that can be used alternately as a power-split or inverse power-split device by a gear shifting arrangement at the input that would allow either direction of the rotation for the mechanical-path shaft. If the input and output are interchanged (i.e., the differential is at the side of the input), the operation is slightly different, but the basic principles still apply.

4.3 POWER RECIRCULATION MODE IN REGULAR POWER-SPLIT CONTINUOUSLY VARIABLE TRANSMISSION

Tending to confuse the issue is the fact that some regular power-split CVTs may be operated in a mode giving power recirculation that is somewhat similar to that of the inverse power-split configuration.* Figure 13 shows schematically what occurs in such a situation. Comparing this schematic with Fig. 12(b), shows that the significant difference is that the power recirculation in Fig. 13 takes place through the CVU path rather than the mechanical path. The mechanical path is the one then that is overloaded (carrying more than the system input).

To explain how this type of power recirculation can occur, let us consider a power-split system in which the CVU is a hydrostatic transmission (Fig. 10), with a fixed displacement motor but a variable displacement pump that has a fully reversible stroke. To achieve the maximum ratio range possible with this system, we would plan to vary the pump stroke from one extreme to the other. When the stroke of the pump becomes negative, however, the hydraulic motor will rotate in the negative direction. To maintain the same direction of output torque, the motor torque cannot change. With a

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*This can occur only if the CVU is an IVT, which, for a given direction of input rotation, can have either positive or negative output rotation. The basic hydrostatic transmission is such a CVU.

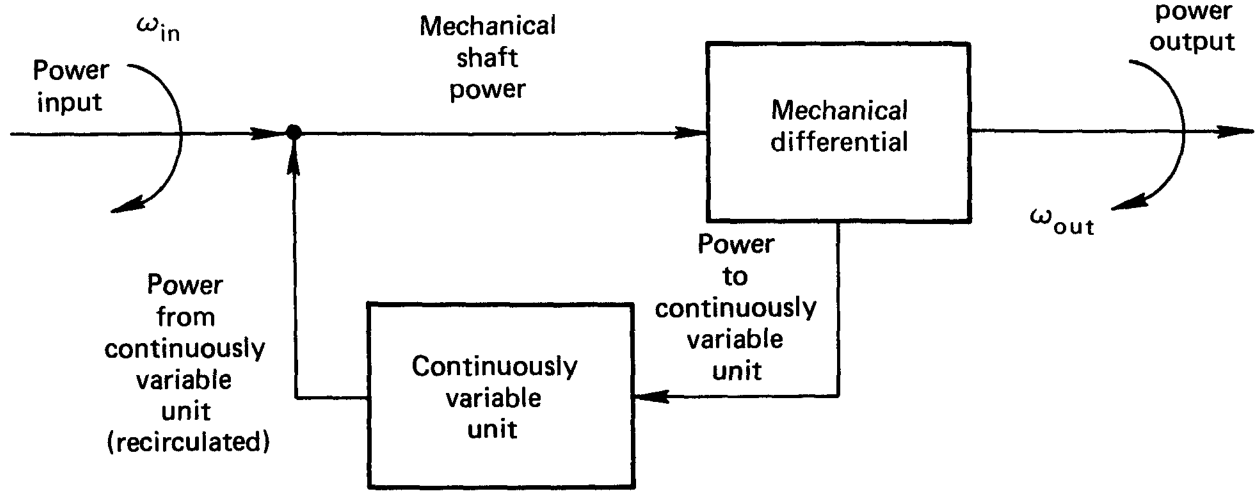

FIG. 13. Schematic diagram of a regular power-split continuously variable transmission when operating in the power recirculation mode.

change in direction of rotation but no change in direction of torque, the motor in actuality becomes a pump, and, from similar reasoning, the variable-displacement pump is in actuality now a motor. Power therefore flows backwards, giving what is known as power recirculation.

In practice, it is usually not desirable to allow very much power recirculation, that is, the pump is usually allowed to use only a part of its negative stroke. The use of maximum possible power recirculation can sometimes result in an extreme situation where the power being recirculated is actually several times the input power. To allow for the extra power in the internal loop would require larger bearings, gears, and the like. In addition, most losses are proportional to the amount of power being transmitted. Therefore, a power-split CVT designed to operate with significant power recirculation would have poor efficiency.

5. CONTROLS

To be useful, a CVT must be controllable, that is the operator must be able to set the speed ratio at a desired value either automatically or by a manual input. For most light commercial application, the CVT is controlled by a simple manual adjustment. A crank may be turned by the operator to change the speed ratio in a more-or-less continuous manner. For example, the crank may turn a threaded rod which moves a nut axially to change the effective diameter of a variable V-belt pulley, with the mating pulley spring-loaded to allow its diameter to automatically match (Fig. 14). For a manually controlled hydrostatic CVT, the operator may move a control lever back and forth which controls directly the stroke of the variable-displacement hydrostatic pump (Fig. 15). This is the method used on garden tractors, where the operator can set the pump displacement at full positive, full negative (for backing up), or anything in between, including zero. He therefore has direct control over the CVT ratio.

For heavy-duty industrial applications (as well as some light-duty ones), manual control may not be desirable or even feasible. The forces involved in setting and holding a given speed ratio may be too great and/or the required accuracy of control, speed of response, and the necessity of continual adjustment may rule out human control.

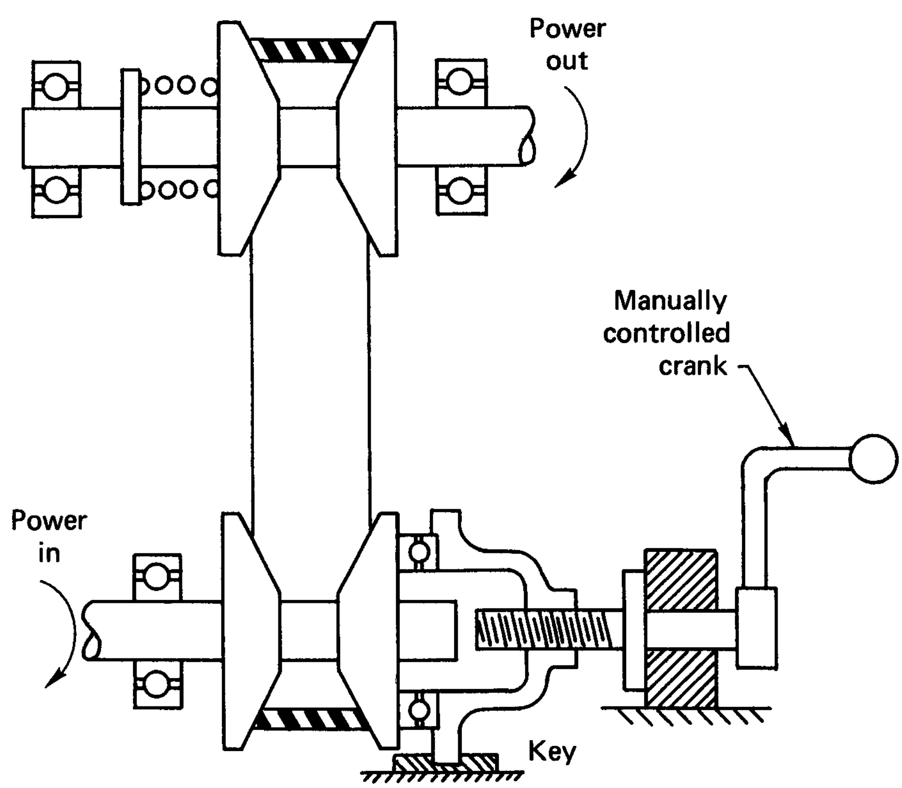

FIG. 14. Simple manual system to control the speed ratio of a variable V-belt continuously variable transmission.

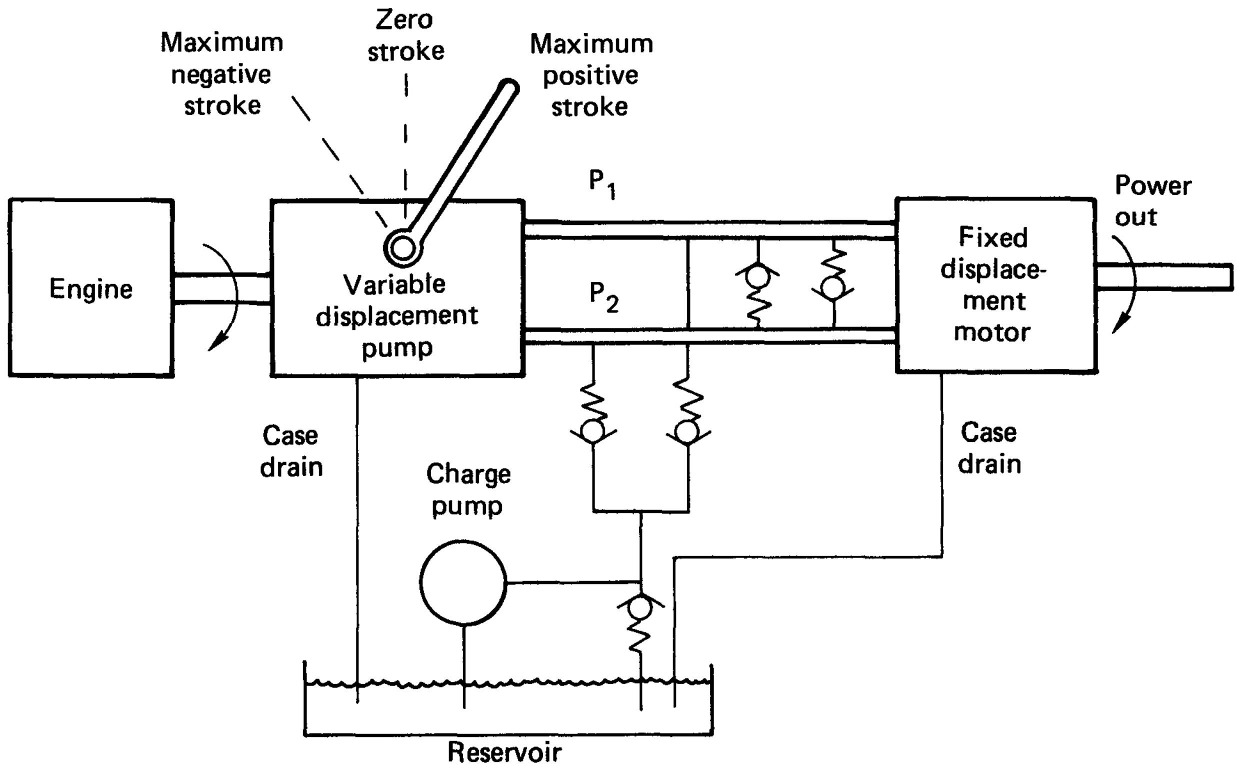

FIG. 15. Schematic diagram of a hydrostatic transmission showing a manually controlled lever that gives direct speed ratio control.

5.1 CONTINUOUSLY VARIABLE TRANSMISSIONS IN AUTOMOBILES

Let us now consider the special problems associated with control of an automobile CVT. The driver must have control over what the vehicle does. He basically needs to be able to control torque (torque at the drive wheels or driveshaft torque). In a conventional car, the torque produced at the driveshaft can be considered as basically proportional to accelerator or engine throttle position. The relationship is far from perfect, however, since the driveshaft torque depends not only on accelerator position, but also on engine speed and what gear the car is in. The driver quickly learns to adequately control any particular car with the accelerator pedal, regardless of the details of its characteristics, because he knows that he can get more torque by depressing it further, and vice versa.

In considering the controls for an automobile CVT, we must differentiate between one used in an otherwise conventional car and one used with an energy-storage flywheel, since the control requirements are quite different.

5.1.1. Continuously Variable Transmissions in the Conventional Car

For a CVT in a conventional car, the driveshaft torque is essentially equal to the product of the engine torque and the CVT ratio. The CVT needs to be controlled so that the desired driveshaft torque is obtained with the engine operating at the most efficient condition that will produce that output torque. This implies that a specific CVT ratio is required for a given combination of desired driveshaft speed and torque. The control at the CVT is therefore ratio control, but a control system (e.g., a microprocessor) with transducers is also required to choose the proper CVT ratio on a continuous basis since the engine efficiency characteristics are not necessarily simple relationships.

To summarize the driving of such a car, the driver chooses the torque he wants by moving the accelerator pedal, which is connected to the transmission control box by a direct mechanical linkage. The controller then sets the engine throttle position and the CVT ratio based on the driveshaft speed, the desired torque, and stored data.*

Ratio control systems have been developed by Sundstrand for their truck CVT (the Responder) and by Orshansky for their developmental automobile CVT (both hydrostatic power-split designs).

5.1.2. Continuously Variable Transmissions for the Flywheel Hybrid Car

For a flywheel car, the situation is quite different. The flywheel effectively isolates the engine from the driveshaft, so that there is no direct relationship between engine torque and driveshaft torque. In this case, only a single variable need be controlled to control driveshaft torque--the rate of change of the CVT ratio. The speed of the high-inertia flywheel cannot be readily changed at will. At any instant of time, therefore, there

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*Variations of this control scheme are possible, and some may be implemented so as not to require the complexity of a computer. In all cases, however, the output signals from the controller should be a required CVT speed ratio and engine throttle position.

is only a single CVT ratio that will match the flywheel and driveshaft speeds, and the driveshaft torque is proportional to the deceleration of the flywheel, which is controlled by the rate-of-change of the CVT ratio.

If one should try to determine the proper CVT ratio and the required rate-of-change of that ratio in accordance with the driver's commands, the required system would be quite complex with a good chance of instability because of the two large effective inertias (vehicle and flywheel) connected through the CVT. Note, however, that it is not necessary to actually choose and control the CVT ratio and its rate-of-change, as these are resultant rather than primary variables. Since we desire to control torque, we would prefer a control system that will manipulate the CVT in whatever manner is required to produce the commanded value of torque. Happily, such a torque control system is quite easy to implement for most CVTs.

The torque control system used on the University of Wisconsin flywheel car is illustrated in Fig. 16. The engine operates on-off in a manner that is not directly related to the driving details. The accelerator pedal is connected directly to the CVT, and its position is translated directly to the position of a lever on a pressure control valve manufactured by Sundstrand. This valve, which includes a pressure feedback loop, sets the hydrostatic system pressure at a value directly proportional to the valve lever position. Since torque transmitted by the CVT (i.e., driveshaft torque) is directly proportional to this pressure, the system provides torque control directly. The proper CVT ratio and its rate of change occur automatically as a by-product of the torque and do not even need to be known.

For regenerative braking, the valve lever is merely moved to a negative position which reverses the high and low pressure sides of the hydrostatic units to reverse the direction of the driveshaft torque.

Although other control principles might be made to work in some cases (with reduced efficency and/or unusual control characteristics as seen by the driver), a torque control system is the proper way to control any CVT used with a flywheel. The implementation is known to be fairly straightforward for all hydrostatic CVTs, electric CVTs, rolling contact traction drives, and slipping clutch CVTs. For V-belt drives and overrunning clutch types of CVT, the exact design principles for torque control are not currently available, but it is felt that the details could probably be developed with straightforward mechanical design.

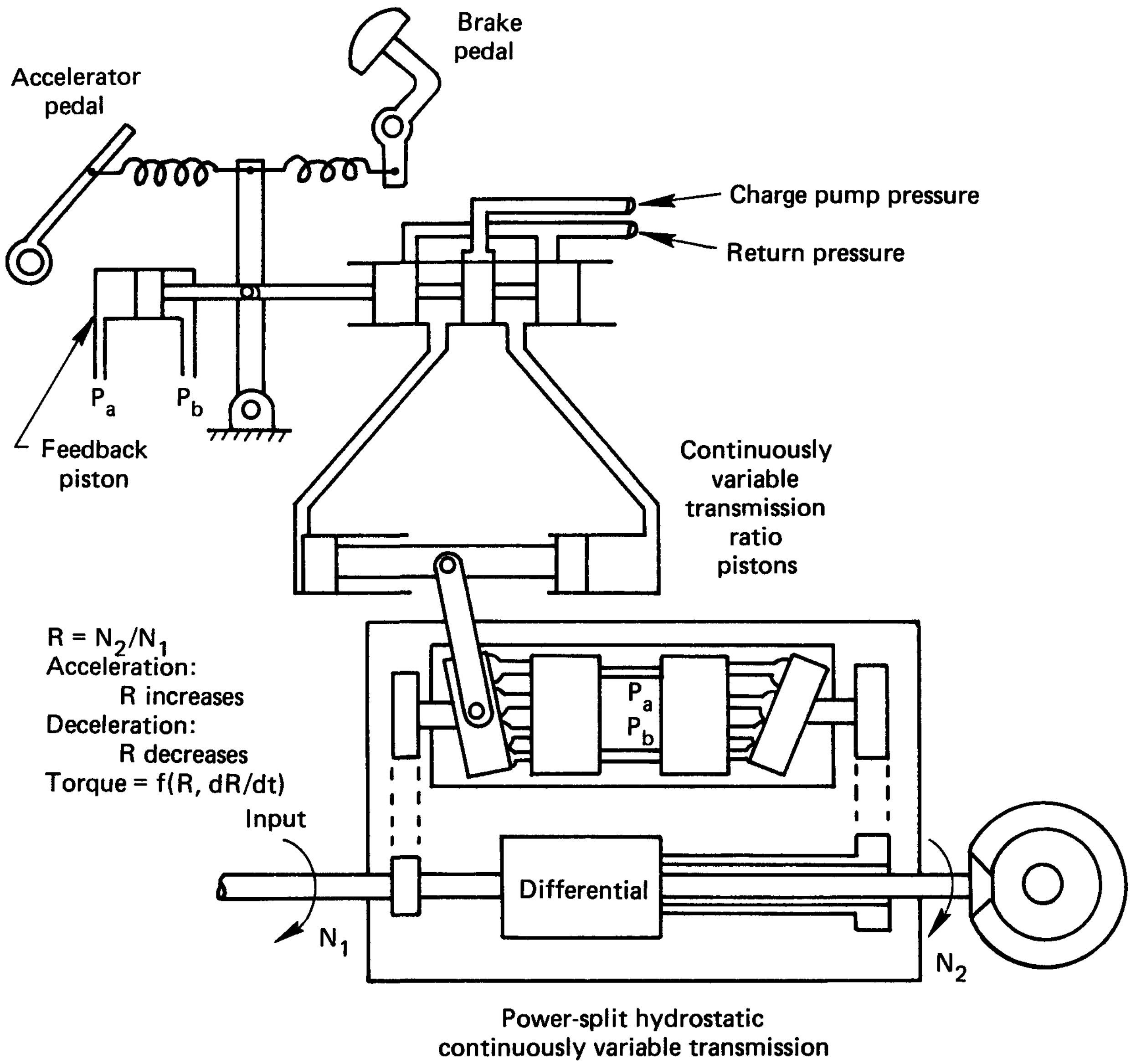

FIG. 16. Schematic diagram of the torque control system used in the University of Wisconsin flywheel automobile.

6. SUMMARY

A number of CVT terms have been presented along with generally accepted definitions. The five basic mechanical principles that can be used in a CVT design have been listed and discussed in detail.

To improve CVT efficiency, the power-split principle may be used, sending only part of the power through the continuously variable unit and the rest through a straight mechanical path. Higher efficiency is gained only at the expense of a reduced ratio range, however. The opposite approach, an inverse power-split configuration, is often useful. In this case, ratio range is increased at the expense of a slight decrease in overall efficiency.

CVTs are commonly used for machine tool drives and other industrial applications. They have the potential of being useful in automobiles, both conventional versions and those utilizing an energy storage flywheel.

For conventional cars, a CVT allows the engine operating condition to be chosen for best economy on a continuous basis. A practical and attractive CVT must have efficiency approaching that of a gear transmission, good reliability and life, and a satisfactory control system that allows the speed ratio to be set based on a signal from the system controller. Except for rubber V-belt systems (e.g., that of the DAF/Volvo automobile), no production CVTs are suitable for otherwise conventional automobiles.

For flywheel cars, a CVT is essential. A satisfactory CVT must have high efficiency under the unique operating condition of the flywheel vehicle, as well as good reliability and life. It must be able to transmit power in both directions to permit regenerative braking. Finally it must be torque-controllable. At present, no production CVTs are suitable for flywheel cars, and the few experimental CVTs specially built for this application are only marginal. A significant amount of additional research and development work is therefore needed. One current problem is that there is a lack of full range friction loss data on components that might be used in a CVT for a flywheel car.

Major CVT research and development programs are described in Appendix B.

APPENDIX A: COMMERCIALLY AVAILABLE CONTINUOUSLY VARIABLE TRANSMISSIONS SUITABLE FOR MOTOR VEHICLES

Very few commercially available CVTs are really suitable for motor vehicles. Many have the proper power range that might conceivably be used, but their excess weight and/or poor efficiency make them unattractive. Many straight hydrostatic transmissions fall into this category.

Below are listed some commercially available CVTs that may be of interest to motor vehicle designers. They are units that might conceivably be adaptable, or whose design features might be used as the basis of new designs:

A.1 Sundstrand Hydro-Transmission
2800 East 13th St.
Ames, Iowa 50010

Sundstrand is manufacturing the Responder hydromechanical transmission for use in large trucks. It is designed as a replacement for the normally used 10-speed manual gearbox. The transmission is most useful for in-city and construction work service where slower stop-and-go driving makes an automatic transmission attractive.

The Responder is capable of handling 250 hp, and weighs about 725 pounds. It has two modes of operation: (1) a straight hydrostatic mode for low speeds, and (2) a power-split mode for higher speeds. (At the lower end of the power-split mode, there is power recirculation through the hydrostatic path.) Full-power efficiency varies from about 70 to 93 percent.

For additional information, contact Sundstrand Hydro-Transmission for sales literature or refer to the following papers:

1. P. E. Troin and V. G. Gostomski, "Application Considerations with the Cummins Sundstrand DMT-25 Hydromechanical Transmission," SAE Paper 750732, 1975.
2. W. A. Ross, "Designing a Hydromechanical Transmission for Heavy Duty Trucks," SAE Paper 720725, 1972.

A.2 Volvo Car B.V. (DAF Division)
Eindhoven, Netherlands

The DAF automobile (DAF is a Dutch company now owned by Volvo) has used a rubber V-belt drive with variable pulleys for many years. Most versions use two belts with engines up to about 60 hp; however, one 34-hp version uses a single V-belt. The DAF automobiles are not currently being imported into the United States.

For additional information, refer to D. Scott, "DAF Simplifies Belt-Drive Automatic," Automotive Engineering (March, 1975) p. 14.

A.3 Various snowmobile manufacturers

In the same category as the DAF/Volvo 343 rubber V-belt transmissions are the very similar units used for snowmobiles. They are by far the most commonly used snowmobile transmissions. They could be readily adapted to conventional automobiles, and the control system would work reasonably well although it would probably not produce maximum fuel economy. To use them effectively with a flywheel car, however, a torque control system would need to be developed.

Information on snowmobile rubber V-belt CVTs is available at dealerships and in service manuals.

A.4 van Doorne's Transmissie B.V.
Dr. Hub van Dooreweg 120
Postbus 500 Tilburg
Netherlands

Van Doorne has developed a steel V-belt that works with variable-diameter pulleys as a CVT. The belt is constructed of small steel blocks joined by a set of steel bands, and transmits power through compression rather than tension (Fig. 4). The system is called Transmatic.

Industrial units are available as production items, with torque capacities up to 130 N•m. The ratio range is 4. The belt design is the same as that being used in their automobile CVT research and development program.

For additional information, contact van Doorne for sales literature, or refer to the references listed later in the van Doorne automobile CVT writeup.

A.5 Jean E. Kopp Variators
CH-3280 Meyriez/Murten
Switzerland

Kopp manufactures the K Type Variator. It is of special interest because it can transmit up to 100 hp in the larger versions. It is the largest power capability of any commercially available rolling contact traction drive known to us. Units are available in eight sizes, with maximum power ratings that vary from 1 to 100 hp. However, they are much too heavy to consider for use in automobiles without significant modification.

The design is based on the use of a number of double conical rollers that are arranged in a roller carrier. A drive disk contacts one face of the rollers. The other face drives a ring which is connected to the output shaft. The speed ratio is varied by moving the roller carrier axially to change the rotating diameters of the rollers. Torque responsive mechanisms are incorporated on both the input and output sides to provide normal loading on the rollers proportional to the torque transmitted through the drive, thereby reducing losses at the lower torque conditions. A ratio range of 12 is provided. Over the middle speed range the efficiency exceeds 90 percent at rated load, and it is greater than 80 percent at all speed ratios.

For additional information, obtain sales literature from Jean E. Kopp.

APPENDIX B: RESEARCH AND DEVELOPMENT PROGRAMS FOR CONTINUOUSLY VARIABLE TRANSMISSIONS

This appendix briefly describes the major research and development activities on CVTs, both in the United States and abroad. The emphasis is on CVTs that would be applicable to automobiles, both conventional ones and those utilizing an energy-storage flywheel.

The CVT programs have been separated according to the basic principles involved in their operation, with the following categories being used: (1) hydrostatic transmissions; (2) traction drives (including V-belt and rolling contact traction drives); (3) overrunning clutch drives; (4) electric CVTs; and (5) slipping clutch drives.

The basic principles of each CVT category have been already covered. Power-split and inverse power-split versions are considered in the category that properly describes the principle involved in the continuously variable unit.

There are a number of active CVT programs, and some that have been active but are now dormant. These range from efforts that have been well-funded for a number of years to "shoestring" operations of private inventors working alone in their spare time. This list given here is meant to cover the most significant CVT programs regardless of the level of funding. There is undoubtedly some significant research, however, with which we are unfamiliar.

B.1 HYDROSTATIC CONTINUOUSLY VARIABLE TRANSMISSIONS

B.1.1 Orshansky Transmission Corporation

5141 Santa Fe Street
San Diego, California 92109

Orshansky has been involved in CVT research and development for the last several years, being funded by ERDA and DOE. They have built a two-mode power-split hydrostatic CVT for an otherwise conventional automobile, installing it in a production automobile and conducting performance and economy tests. The results have been quite favorable. They have designed a new lightweight version that has three power-split modes and weighs essentially the same as the automatic transmission it would replace. Only the hydrostatic module (pump and motor and valving) has been constructed, due to a discontinuation of funding.

For further information, refer to the following documents:

1. E. Orshansky et al., "Automobile Fuel Economy with Hydromechanical Transmission by Simulation Studies," SAE Paper 740308, 1974.
2. W. E. Weseloh and P. Huntley, "Design Factors of Hydromechanical Transmissions for Passenger Cars," Proc. Fourth International Symposium on Automotive Propulsion Systems, April, 1977.

B.1.2 Scientific Research Foundation
Jerusalem, Israel

The Scientific Research Foundation has developed an experimental flywheel-electric vehicle, a 7000-pound van suitable for city applications. As part of the project, they have designed and constructed a power-split hydrostatic CVT. The unit has a ratio range of 16, with a full load efficiency varying from 86 to 91 percent over that range. It is completely reversible, allowing regenerative braking with the same efficiency characteristics. Two ranges are achieved by a synchronous gear change, causing the basic power-split ratio range of 4 to be increased to 16. The concept is essentially the same as that of the Orshansky two-mode CVT.

For further information, refer to D. Locker and M. L. Miller, "Flywheel-Electric Hybrid Vehicle," Proc. Fourth International Electric Vehicle Symposium, Dusseldorf, Germany, Aug. 31 - Sept. 2, 1976.

B.1.3 General Electric Company
Ordnance Department
Pittsfield, Massachusetts 01201

During the 1960's, General Electric did research and development work on hydrostatic power-split CVTs suitable for otherwise conventional trucks and army tanks. Designs were made for a family of such transmissions. On the HMT-250 model, capable of about 110 hp, a single range is used, and it gives an IVT having a speed reduction varying from 4:1 in reverse to 0.75:1 forward. The hydraulic circuit carries 60 percent of the torque. At lower output speeds (and reverse), torque is "regenerated" through the hydraulic path, so that the mechanical path carries more than the engine input. Other models used two or more ranges.

The hydraulic pump and motor are ball piston units. Both have variable displacement, and they are closely coupled to produce a compact unit, with the mechanical power shaft passing through their centerlines, A planetary gear unit is used for the power-adding differential.

About 1970, work on the smaller models was discontinued, with the continuing effort concentrated on a large 3-mode 500 hp version suitable for driving Army tanks. General Electric currently has a production contract with the Army to manufacture this CVT.

For further information, refer to the following:

1. D. M. Latson et al., "A Hydromechanical Transmission Development," SAE Paper 670932, 1967.

2. D. M. Latson et al., "Hydromechanical Transmission Fares Well in Truck Tests," SAE J. 76, 64-66 (June 1968).

B.1.4 Mechanical Technology, Inc.
968 Albany-Shaker Road
Latham, New York 12110

MTI has been involved in the design and development of a hydrostatic power-split CVT for a number of years. Their recent work has been under a subcontract from Chrysler, which has been funded by the U.S. Department of Energy. The CVT is designed to be suitable for use in an automobile having a single-shaft gas turbine with a maximum power of about 100 hp.

The hydrostatic units are based on a proprietary axial piston design. Both are identical variable displacement units with a maximum displacement of 5.73 in.^{3}/rev, and have demonstrated above average efficiencies, particularly at low speeds and torques.

The CVT operates in two modes, pure hydrostatic and power-split, to cover the range from reverse to top speed (therefore being in the IVT category). At top speed, the displacement of the motor is decreased with the pump displacement fixed to give an overdrive effect. The CVT has a compact in-line configuration, with the mechanical power shaft passing through the center of the hydrostatic units to a planetary power-summing differential at the ouput. A hydro-mechanical control system is used.

For further information contact M.T.I.

B.1.5 College of Engineering
University of Wisconsin
Madison, Wisconsin 53706

An experimental flywheel internal-combustion engine automobile has been constructed and tested at the University of Wisconsin-Madison. As part of the project, a hydrostatic power-split CVT was designed and constructed at the University. The unit uses the Sundstrand Series 20 pump and motor, and an internal spur gear differential. The ratio range is 3.5, but it has been extended to approximately 12 by using an overall transmission system consisting of a 4-speed gearbox in series with the CVT. The system has an output torque capacity of 250 ft-lb, and is controlled by a simple torque control system based on the Sundstrand Variable Pressure Control Valve.

The unit has demonstrated ruggedness, reliability, and ease of control. It was built as an experimental model, as opposed to a prototype, in terms of size and weight.

For additional information, refer to the following:

1. N. H. Beachley and A. A. Frank, "Flywheel Energy Management Systems for Improving the Fuel Economy of Motor Vehicles," Report No. DOT/RSPA/DPB-50/79/1, prepared for U.S. Department of Transportation, Dec. 1978.
2. A. A. Frank and N. H. Beachley, "Evaluation of the Flywheel Drive Concept for Passenger Vehicles," SAE Paper 790049.
3. Tom C. Hausenbauer, "Design Study of a Power Split Hydrostatic Transmission," M.S. Thesis, University of Wisconsin-Madison, 1976.

B.2 TRACTION DRIVES

B.2.1 V-Belt Traction Drives

There are many V-belt drives in production (particularly those used in snowmobiles) that could be adapted to small conventional automobiles. In addition, there is the DAF/Volvo rubber belt automobile system that has been used for many years. This section will, therefore, concentrate on unique designs under development specifically for automobiles.

B.2.1.1 van Doorne's Transmissie B.V.
Dr. Hub van Doorneweg 120
Postbus 500 Tilburg
Netherlands

In addition to their commercially available steel V-belt CVTs mentioned earlier, automotive designs are also under development by van Doorne. The basic belts and sheaves are apparently the same, so that the research and development is focused primarily on the control system necessary for automotive application. In addition to proper continuous adjustment of the CVT ratio to match driving conditions, the control system must provide sheave loading proportional to the torque being transmitted to minimize friction losses. One particularly attractive aspect of the steel V-belt is its compact size and small weight. A ratio range of 4.5 is used in the automotive version.

A development program is under way that involves Borg Warner, Fiat, Van Doorne, and the Dutch government. Production units for otherwise conventional cars are expected to be available by about 1983.

For additional information, refer to the following:

1. Olaf Fersen, "Transmatic," Autocar, 17 Feb., 1979, pp. 42-43.
2. S. C. van der Veen, "Stufenloser Drehmoment/Drehzahlwandler Transmatic," Ant-Antriebstechnik 16, Nr. 4, 217-222 (1977).

B.2.1.2 AiResearch Manufacturing Company
Garrett Corporation
2525 West 190th Street
Torrance, California 90509

AiResearch is currently developing a flywheel energy storage unit for use with the electric postal vans. The program is sponsored by the U.S. Postal Service. Even though the van is powered by an electric motor, the motor is used only to spin up the flywheel, and the flywheel is used to drive the van through a rubber V-belt CVT. The ratio of the CVT is controlled by a pneumatic system based on a combination of torque and power control. The unit has a power capacity of about 50 hp, and has a usable ratio range of 7.5.

For additional information, refer to D. L. Satchwell, "An Advanced Energy Storage Unit for U.S. Postal Services Delivery Vehicle," Proc. 1977 Flywheel Technology Symposium, Sponsored by Lawrence Livermore Laboratory and the U.S. Department of Energy, 1977.

B.2.1.3 Kinergy Research and Development
P.O. Box 1128
Wake Forest, North Carolina 27587

Kinergy has been involved in flywheel automobile research and development for a number of years. They have built several experimental flywheel automobiles, both internal-combustion engine flywheel and electric flywheel models. Most of these models have used some type of V-belt drive.

Kinergy has two basic V-belt CVT designs, with experimental models of each built and installed in flywheel automobiles. One design is a V-belt CVT that is integrated with an energy-storage flywheel to give an attractive compact package. The engine (or motor) input shaft, the flywheel, and the planetary differential are all in line. The transmission is an IVT with reverse capability due to the use of power recirculation under some operating conditions. The V-belt pulleys are loaded in proportion to the torque transmitted to minimize friction losses.

The other design used in their electric flywheel vehicle combines a V-belt CVT with a 2-speed gearbox. The major feature of this design is that power can go directly from the electric motor to the rear wheels without going through the CVT. Only the energy going to and from the flywheel goes through the CVT. This is advantageous for a flywheel-electric car with a small motor that is running almost continuously.

For additional information, refer to literature from Kinergy Research and Development.

B.2.1.4 Fiat Automobile Company
Torino, Italy

Fiat is working on a V-belt CVT drive to replace the gearbox on its conventional cars. The basic concept is quite similar to that used in the DAF/Volvo vehicle. The driven sheave diameter is varied by an electric motor acting through a rack and pinion, with the driving sheave spring loaded. The speed ratio is chosen by a digital computer based on driver command and vehicle operating conditions, with fuel economy as the principal goal. A ratio range of 5•5 is available. Several prototype cars have been built and tested.

For additional information, refer to David Scott, "Belt-Drive Autómatic Programmed for Economy," Automotive Engineering, 86, 98-99 (August 1978).

B.2.1.5 Electric Passenger Cars and Vans, Inc.
7954 Convoy Court
San Diego, California 92111

Electric Passenger Cars is developing a proprietary CVT that incorporates a variable sheave rubber V-belt drive. The design, called the CVIRT (continuously variable infinite range transmission) is an IVT based on the inverse power-split principle. It is being developed for electric car use, and incorporates an automatic ratio control system to maximize vehicle efficiency. It also provides for regenerative braking.

For additional information, contact Electric Passenger Cars and Vans, Inc.

B.2.2 Rolling Contact Traction Drives

Many rolling contact traction drive CVTs are in production for lower power ratings, from fractional hp sizes up to about 5 hp. These CVTs are designed for machine tool speed control and other such industrial uses. Due to the large number of these available, only models that might be applicable to automobiles are considered here.

B.2.2.1 Excelermatic, Inc.
913 Sagebrush Drive
Austin, Texas 78758

Excelermatic has been doing research and development work for a number of years on Cone Roller Toroidal Drive steel-on-steel traction drive units. They have designed units using a single toroid, a double toroid, and a single toroid with regenerative gearing (an inverse power split). The latter is an IVT, while the units without the regenerative gearing have a ratio range of about 12:1.

Units have been built and tested on medium-sized automobiles, as gas turbine transmissions, and as other special purpose drives. One interesting program was the development of an experimental toroidal drive unit for the B-1 airplane program. This was powered by a flywheel and used to raise and lower the landing gear, handling up to 50 hp. A current research and development effort is being carried out in conjunction with one of the "big-three" automobile companies, with the CVT now undergoing extensive testing.

Excelermatic has also developed fixed ratio traction drive speed reduction units with power ratings up to 1000 hp. These are said to provide cheaper and quieter power transmission than gears, with comparable efficiency and life.

For additional information, refer to the following:

1. J. H. Kraus, "The Selection and Optimization of a Continuously-Variable Transmission for Automotive Use," ASME Paper 75-WA/Aut-16, Dec. 1975.
2. J. H. Kraus, "An Automotive CVT," Mechanical Engineering 93, 38-43 (Oct. 1976).

B.2.2.2 AiResearch Manufacturing Company
Garrett Corporation
2525 West 190th Street
Torrance, California 90509

AiResearch Manufacturing Company has designed and built CVTs based on the toroidal drive principle. Part of the research and development program was sponsored by the Navy and part was done as proprietary in-house work. Units of 60 and 100 hp have been built. They employ "regenerative gearing" that puts them in the inverse power-split category and makes them IVTs. The regenerative "gearing" is in actuality a traction drive fixed ratio planetary unit.

Work is continuing on the concept with the goal of using the toroidal drive as the transmission for a flywheel automobile. Current funding of the program is from NASA-Lewis.

For additional information, contact AiResearch Manufacturing Company.

B.2.2.3 Bales-McCoin Research, Inc.
4401 Montana
El Paso, Texas 79976

Bales-McCoin Research, Inc., has developed a unique CVT design based on the rolling contact principle. Regenerative planetary gearing puts it in the inverse power-split category, producing an IVT that has neutral and reverse capability. The regenerative gearing is also designed to cause the CVU (a cone with a roller that contacts it at various radii) to operate at very high speed to allow smaller size and lower contact forces for a given power rating. A set of range gears is included at the output to allow a 10 percent overdrive. One innovative feature under development is an electronic control system that sets the loading between the traction elements based on a condition of optimal slip.

The unit has been designed for automotive use as a replacement for the conventional automatic transmission. It is also considered attractive for use with an energy-storage flywheel, and Bales-McCoin has developed integrated designs that include a flywheel in combination with the IVT. Prototype units have been built and are undergoing evaluation. Current work is being done under a NASA contract, and is for application to electric vehicles.

For additional information, contact Bales-McCoin Research.

B.2.2.4 Vadetec Corporation
2681 Industrial Row
Troy, Michigan 48084

Vadetec is developing a traction drive unit based on the rolling contact principle. Their design has one unique feature that distinguishes it from other CVTs in this category: the rolling contact takes place between a rotating output member and the inside surface of a hollow input cylinder that nutates instead of rotates. The input to the total unit is a rotation, but it imparts nutation to the grounded nutator by eccentrically mounted roller bearings. The speed ratio can approach 1:1 at the upper end of the range and go down to an apparent zero at the lower end.

Prototypes have been built and tested. A design has been made that combines the Vadetec CVT with an energy storage flywheel. Another design has been developed that combines an internal-combustion spark-ignition engine and the Vadetec CVT, the total assembly being named the TRANSENGINE. Here the CVT replaces the usual crankshaft, and change in the CVT ratio changes the length of engine stroke. It is said that the engine could be run unthrottled, as the engine in effect "grows and shrinks" as a function of the power requirements of the vehicle. Since varying the length of stroke affects the compression ratio, a device to compensate for this effect has been designed. The concept of unified engine-Vadatec CVT package is said to also be very attractive with the Stirling engine.

For additional information, contact Vadetec Corporation.

B.2.2.5 Citroen Centre Technique
Velizy, France

Citroen is doing research and development work on a rolling contact traction drive CVT consisting of a series of rim disks driven by pairs of tapered cone disks similar to V-belt sheaves. By varying the distance between the input and output shaft axes, the tips of the driven disks contact the drive disks at different radii, producing a CVT with a ratio range of about 3. The basic concept [Fig. 5(e)] has been around for many years, and is often called the Beier drive after the inventor Josef Beier of Austria.

Citroen has installed the CVTs in several of its otherwise conventional cars, and has put on many test miles with favorable results. There is no indication, however, as to whether they have any plans for going into production with the unit.

B.2.2.6 Fafnir Bearing
Division of Textron, Inc.
New Britain, Connecticut 06050

Fafnir has developed a traction drive CVT for garden tractors and similar applications in the 12 to 24 hp range. This development is of particular interest because the unit is designed for a mobile type of application and has a power capability approaching that required for a small automobile. The unit is essentially ready for production.

The CVT consists of a variable speed planetary traction drive in combination with a regenerative planetary gear set that puts it in the category of an inverse power-split system. It is an IVT with reverse output capability. The traction drive races and rollers are similar to precision rolling element bearing parts in form, material, and manufacture. The original design used a fixed preload for the rolling contact surfaces, but newer versions use a hydraulic loading force proportional to the torque being transmitted.

For additional information, refer to T. W. Dickinson, "Development of a Variable Speed Transmission for Light Tractors," SAE Paper 770749, 1977.

B.2.2.7 Die Mesh Corporation
629 5th Avenue
Pelham, New York 10803

Die Mesh Corporation is developing a traction drive CVT that is based on roller cones in combination with a power transfer wheel. Several variations are under development. To maximize efficiency, special attention has been paid to matching geometry that will minimize slip at the traction interface. A ratio range of 9 is available with good efficiency and low slip. Hydraulic loading proportional to the transmitted torque is used. The drive is designed to handle the torque and power of a typical passenger automobile. Design studies have also been made for combining the drive with an energy-storage flywheel. Prototypes have been built and tested.

For additional information, write Die Mesh Corporation.

B.3 OVERRUNNING CLUTCH CONTINUOUSLY VARIABLE TRANSMISSIONS

B.3.1 Powermatic Corporation
830 West 2500 South
Salt Lake City, Utah 84119

For the past several years, Powermatic Corporation has been working on the development of a proprietory IVT called the "Mechana-Power." This IVT is based on the overrunning clutch principle in combination with variable-throw cranks. One principal feature of the design is the use of hydraulic one-way clutches rather than the more common mechanical type. The control system is also based on hydraulics, with spool valves and other control elements.

Much of the research and development work has been done under a contract with the U.S. Army Tank-Automotive Research and Development Command in Warren, Michigan. The developmental unit was designed for 50 hp with a speed ratio (output/input) varying from 0 to 2.5. Efficiencies of 92 to 96 percent are claimed for this unit.

For additional information, refer to L. Gogins and C. P. Russell, "Mechana-power: A New Approach to Infinitely Variable Transmissions," SAE Paper 760586, 1976.

B.3.2 AVCO Systems Division
201 Lowell Street
Wilmington, Massachusetts 01887

AVCO Systems is currently engaged in research on a proprietary CVT based on the overrunning clutch principle (U.S. patents 3803932 and 3874253, and patents pending 737632 and 836727). The unit is being designed for automotive use and is in an early stage of development.

For additional information, refer to the patents listed above.

B.4 ELECTRIC CONTINUOUSLY VARIABLE TRANSMISSIONS

Generator-motor drive systems have been used for a number of different applications, including the propulsion of railway locomotives. A number of researchers have also experimented with such systems for electric internal-combustion engine hybrid cars in configurations that would allow the engine output to be converted to electric energy to drive through the traction motor. We know of no significant development in generator-motor systems for this type of application, however, that would warrant discussion here. The one significant electric CVT program with which we are familiar is described below.

B.4.1 AiResearch Manufacturing Company
Garrett Corporation
2525 West 190th Street
Torrance, California 90509

AiResearch is currently involved in a program to develop an electric-flywheel automobile, under the sponsorship of the U.S. Department of Energy. The energy for driving comes from a battery pack, and the flywheel is used as a load-leveling device to improve the average efficiency and to provide regenerative braking.

The system contains an electric power-split CVT of unique design. The CVT contains a generator, a motor (which is also the drive traction motor), a gear differential, and a controller. The traction motor can receive energy from both the batteries and the generator. It serves the two basic functions of driving the car and accelerating the flywheel. The torque to drive the generator comes from the flywheel. The torque control is handled by controlling the motor and generator field circuits. Regenerative braking is obtained by reversing the flow of power in the transmission. In the regenerative mode the traction "motor" acts as a generator and applies electrical power to the "generator" (now acting as a motor) which causes the flywheel to speed up. Since a large fraction of the power goes through a mechanical path in both the regular drive and regenerative braking modes, the effective efficiency of the CVT exceeds the product of the generator and motor efficiencies.

For additional information, contact AiResearch.

B.5 SLIPPING CLUTCH CONTINUOUSLY VARIABLE TRANSMISSIONS

The slipping clutch concept has been used in a number of applications where precise speed or torque control is required and energy efficiency is not an important consideration. Some early experimental flywheel cars have used rudimentary slipping clutch designs. System parameter optimization studies and preliminary designs for more sophisticated versions have been done at the University of Wisconsin-Madison.

For additional information on this concept, refer to the following:

1. A. Dietrich, "Design Study of Variable Torque Control Devices for Use in Continuously Variable Power Transmission," M.S. Thesis, University of Wisconsin-Madison, 1977.

2. A. A. Frank, et al., "Continuously-Variable Transmission Concepts Suitable for Flywheel Hybrid Automobiles," Proc. 12th Intersociety Energy Conversion Engineering Conference, Sept. 1977, pp. 26-33.

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