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ANALYSIS OF A NEW FORM OF INTRINSICALLY AUTOMATIC CONTINUOUSLY VARIABLE TRANSMISSION

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ABSTRACT

Effective continuously variable transmission (CVT) designs have been sought after for many years as their integration into many different mechanical systems can give many advantages over a discrete transmission system. Currently, CVTs are becoming popular for applications from automotive power transmission to wind power generation. Most CVT technologies, however, are friction- or hydraulic-based designs limited by both performance and system characteristics.

This paper will evaluate a new, patented form of purely mechanical, intrinsically automatic CVT which is not based on belts, pulleys, gears or hydraulics. This new transmission is based on a deformable four-bar design incorporating a one-way clutch for positive displacement of the output. As torque demand on the system output is varied, the output's displacement varies inversely to maintain a constant peak torque on the input shaft. The end result of this behavior is a possible instantaneous variation of speed ratio over an extreme range with a lightweight, simple mechanical design.

This paper provides an analysis of the mechanism and its performance, as well as simulation results incorporating real-world measurement of system output into several different mechanical applications: a human-powered vehicle, an automobile and a centrifugal pump.

INTRODUCTION

CVT designs have been around for centuries, several concepts even coming from Leonardo DaVinci. The ability to shift speed ratios and torque conversion seamlessly while providing positive-displacement motion has proven a difficult task. Even now, CVT systems are under intense development due to the significant prospects of energy savings and performance increases [1-4]. A class of CVT's known as Infinitely Variable Transmissions has also come to light, where speed ratios reaching nearly 1:0 can be achieved by several different methods, which lack in efficiency but provide extreme torque conversion [4-6]. These systems are typically comprised of a CVT system coupled with a planetary gear which can distribute speed and torque per the needs of the system. All these systems have been analyzed in research dating to even the most current [1-6]. Most CVT systems are based on either a cone-belt approach, a ball-disc approach or a hydraulic approach. All three of these CVT types have advantages and shortcomings. Typically, CVT systems suffer from inefficency due to their driving principles, as well as limited torque conversion range (excepting IVT's, as well as some other recent developments such as that described in [7]).

The Beale CVT is a continuously variable transmission that in itself requires no outside system control to adjust speed ratio. The effective speed ratio of the mechanism varies with the torque demand on the output shaft for a given input speed from 1:1 to nearly 1:0, as it scales output torque inversely to output speed. Figure 1 shows a basic system diagram from US Patent 7011322.

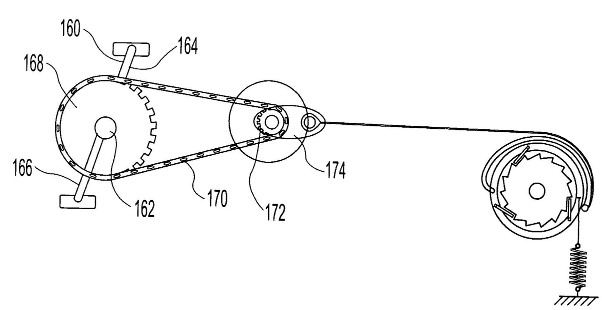

Figure 1. OPERATIONAL DIAGRAM OF BEALE CVT FROM US PATENT 7011322

The system as shown here operates as follows: a displacement of the cable attached to part 174 to the left pulls on the ratchet-pawl mechanism on the right, turning the output shaft of the transmission, as well as stretching the grounded spring. The return of this positive displacement *does not* return the output shaft to its original position, as the pawls run over the ratchet, resulting in a net positive displacement of the output shaft for an input rotation.

Depending on the torque demand on the output shaft, the spring by which the cable is attached to the pawl will store more or less energy during the positive cable displacement. This results in two key operational characteristics: first, the output shaft's displacement varies somewhat inversely (this varies with the spring's behavior) to torque demand. Second, any energy still stored in the spring on the return stroke of the cable is put back into the input shaft. This system behavior is significant because without making any adjustments manually (or by any control system), this transmission can effectively trade speed for torque (conserving power) all the way to zero speed. This results in enormous torque conversion at low speed, for very little cost in weight, system complexity or efficiency.

This transmission can take many forms, from linear actuators and coil springs to a purely rotational system using cams and carbon fiber beams. System diagrams for many of these different incarnations of the mechanism are detailed in the US Patent documentation. The design of the testbed for this study is essentially a four-bar mechanism, with one bar arranged as a beam spring in contact with a backstop. A sketch of such a system is shown in Fig. 2.

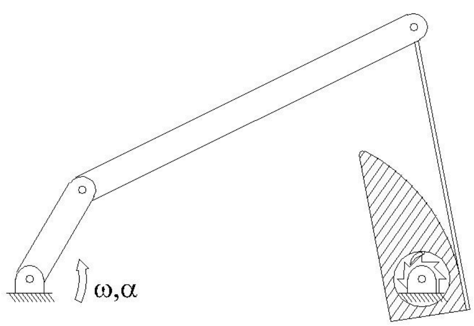

Figure 2. WORKING DIAGRAM OF FOUR-BAR ARRANGEMENT FOR BEALE CVT – THIN BAR ON THE RIGHT IS ASSUMED TO BE DEFORMABLE OVER CONTACT WITH THE ROUNDED BACKSTOP.

Note that input power drives the link on the left, and the output is driven by the overrunning clutch on the right. As torque is applied through the output shaft, the spring deflects over the rounded backstop. As this contact takes place, the effective spring constant of the beam spring changes according to the geometry of the curved contact. This step of the problem in and of itself is highly complex, requiring finite element analysis to solve; this is beyond the scope of this study. Instead, some assumptions and estimations from measured data on the physical prototype will be made as to the spring's behavior.

PSEUDOSTATIC ANALYSIS

Because of the discontinuous behavior in the overrunning or sprag clutch, the differential equations that govern this system are very difficult to solve outright. A simpler pseudo-static model can at least describe some basic performance characteristics of the system with the understanding that dynamic effects at high speed will affect the system's behavior. For the purpose of this study, it will be assumed that the overall system output can be tuned at high speed to emulate that at low speed, and for the three system simulations (human-powered vehicle, automobile and centrifugal pump), that its performance can be effectively controlled. The simple analysis to be performed here will consist of measuring the actual output of a physical prototype, and approximating the measured behavior with a simulation.

The key characteristic measured was speed ratio from input to output, given a set of different torque loads on the output shaft. Here, the system was assumed to conserve power, so the input-to-output torque ratio is assumed to be inversely proportional to the speed ratio. A prototype transmission was constructed and modified to turn a cable drum for measurements, shown in Fig. 3.

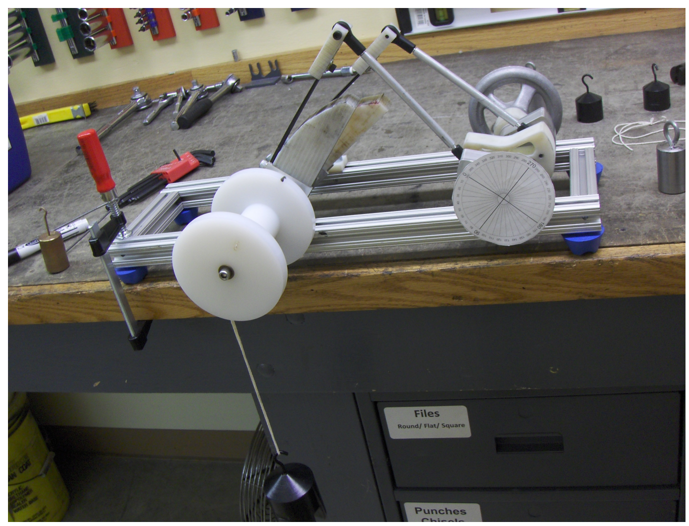

Figure 3. BEALE CVT MODIFIED TO MEASURE OUTPUT

Different torque loads from 0 to 2.2 N-m were applied to the cable drum by hanging calibrated weights, and the input shaft was turned at approximately 60 RPM. The system's output was not sensitive to changes in input speed, as long as acceleration of the applied weights remained low (as this would increase the applied torque to the system), so it was assumed that variations to output due to small variations in input speed were negligible. The speed ratio of the mechanism was measured for each applied load. The angle through which the input shaft was turned for one rotation of the output shaft was recorded along with the applied torque load.

Results from this test are shown in Fig. 4, with the torque load plotted on the x-axis and the resulting speed ratio on the y-axis. This data agrees closely with the plotted relationships from the patent application of the original mechanism. The function fit to the curve is not derived from first principles, but provides a way to easily approximate the transmission's real behavior in simulation.

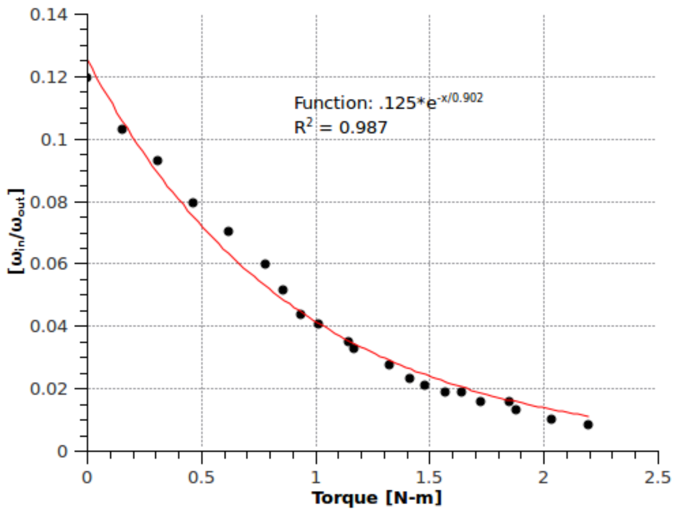

Figure 4. SPEED RATIO VS. APPLIED TORQUE FROM PROTOTYPE CVT, 60 RPM INPUT

The next steps in the analysis of this transmission were to verify the measured output with a more detailed model of the system. This type of model will allow rapid optimization for different applications of the transmission in the initial design phase. This more detailed model starts with a standard four-bar simulation, which will not be presented here. Figure 5 shows the vector diagram to which variables will correspond through the rest of this paper. Output angle θ_4 is plotted versus input angle θ_2 in Fig. 6.

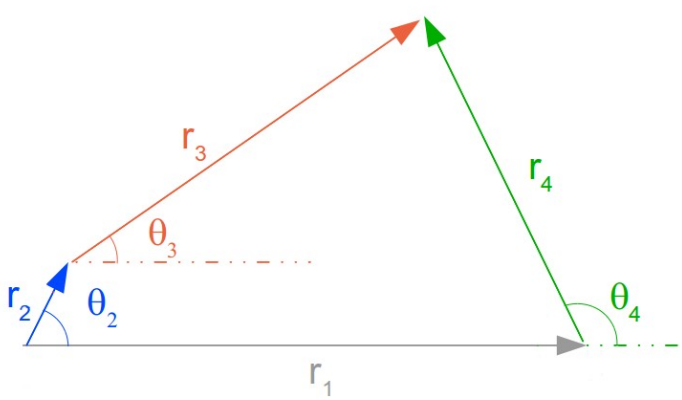

Figure 5.CRANK-ROCKER VECTOR LOOP DIAGRAM OF CVT PROTOTYPE. INPUT IS R2, OUTPUT IS R4

Since the output shaft only rotates when θ_4 is increasing, each input rotation turns the output shaft through 21.5º. This results in a maximum speed ratio of 1:16.7, or 1:8.4 for the coupled 2-sprag system shown in Fig. 3, since each input rotation results in two output cycles. A quick measurement of the system's behavior at no load confirmed this number as correct.

The next step of the pseudostatic analysis was to incorporate the force-deflection behavior of the spring system into the four-bar model, and to try to extrapolate from the result overall system behavior. The prototype previously shown uses a carbon fiber beam spring deflected against a curved backstop to increase the spring stiffness as load increases. Different geometries with such a system can be employed to provide optimal force-deflection behavior while maintaining simplicity, torque conversion and light weight. These are, however, very difficult to model analytically. A finite element model will be developed` for future use in optimization, and is beyond the scope of this analysis. Here, an additional test was performed by simply measuring spring deflection per applied force. Weights were applied to the beam spring, and deflection was measured with a dial indicator. Measured values are graphed in Fig. 7.

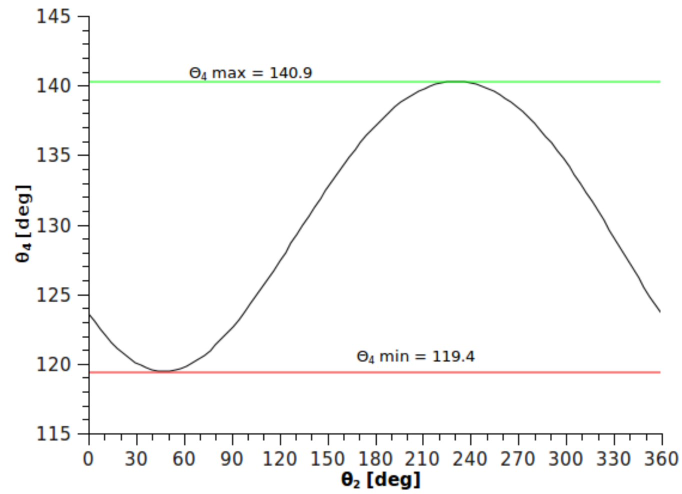

Figure 6. OUTPUT ANGLE VS. INPUT ANGLE FOR FOUR-BAR REALIZATION OF CVT CONCEPT

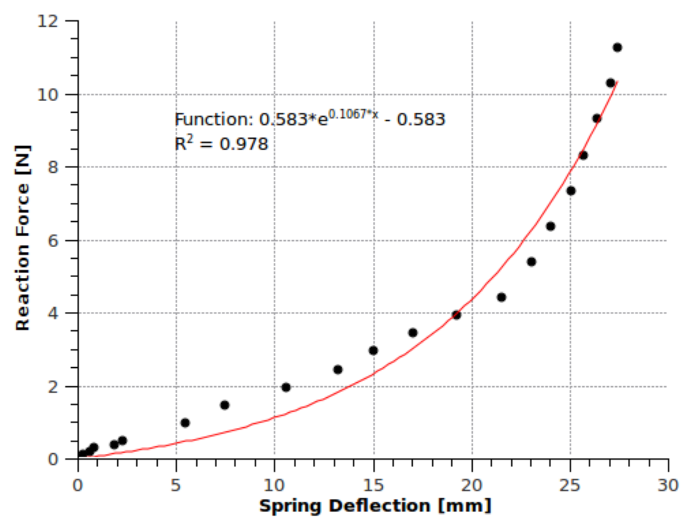

Figure 7. APPLIED FORCE VS. SPRING DEFLECTION

As can be seen in Fig. 7, the added force per additional unit spring deflection increases as deflection increases, resulting in very non-linear spring behavior. This feature is key to the resultant performance of the transmission. The next step in this analysis was to incorporate this spring behavior into the four-bar model already discussed, and compare results to the actual transmission output. With an accurate overall model, this will allow simulation of different spring behaviors for future optimization.

Recalling that r_4 is fixed, spring deflection can be approximated by the chord of a circle with radius r_4. The resulting chord angle is related to deflection by Equation 1. The difference between this deflected angle and the four-bar output angle θ_4 is the actual output angle of the transmission. This relationship allows simulation of the transmission's output using only the spring-deflection curve and the previously explained four-bar analysis. Assuming that the force on the spring is always nearly perpendicular to r_4, Fig. 8 shows the spring-deflection relationship in terms of torque transmitted by r_4 and deflected angle. For the purposes of this analysis, *r* in Eqn. 1 was assumed to be equal to r_4 (in reality it is slightly shorter than this).

$$ds = 2r\sin\left(\frac{\theta}{2}\right) \tag{1}$$

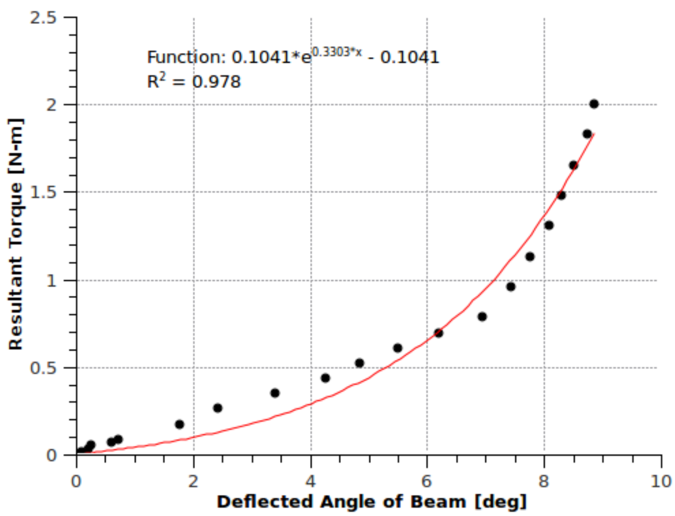

Figure 8. SPRING DEFLECTION CURVE AS CHORD ANGLE VS. RESULTANT TORQUE

It is still not possible to directly equate the deflected beam curve to transmission output because of the current design of the transmission. As dynamic analysis of this mechanism at high speed is complicated, so is a pseudo-static analysis at high torque. Without any inertial effects to carry the output shaft from one sprag engagement to the next, it becomes evident that the output does not produce smooth rotation at low speed. This results in torque spikes when also operating the input shaft at a low speed. Fig. 9 depicts the interaction of the two sprag units (180º phase difference) on the existing physical prototype at two different torque levels.

The displacement angle θ_4 (displacement of the link between r_2 and r_4 with respect to the output shaft) for each of the prototype's two sprag units are represented by the two black curves, which have been attenuated to zero. These curves are separated in phase by 180º, but are not necessarily symmetrical. Their behavior varies with the properties of the four-bar mechanism, and therefore cannot be easily described analytically. The two gray horizontal lines represent deflected angles for given torque levels from the spring data in Fig. 8.

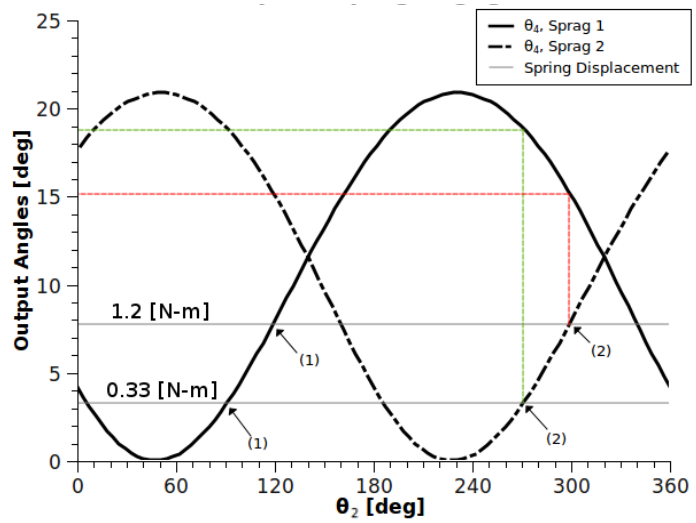

Figure 9. 2-PHASE SPRAG ENGAGEMENT AT DIFFERENT TORQUE LEVELS.

As the input shaft is turned, the first sprag unit (the solid black line) begins positive motion, deflecting the beam spring until it reaches Point (1). Until this point, the output shaft has not yet moved since the torque from the beam spring was less than the torque demand on the output shaft. Recall that in this system, the shaft cannot turn backwards with respect to either sprag unit. As the first sprag unit continues to displace, the beam spring no longer deflects (for low speed and constant torque), and the output shaft is turned through the remaining output angle to the peak, at approximately 230º. Because the second sprag unit (the dotted black line) has not yet reached Point (2), its respective torque equilibrium point, the shaft will turn backward with the first unit until the second unit causes forward motion.

The overall resultant output angle is equal to the difference between the horizontal gray line and the corresponding horizontal dashed line on θ_4, Sprag 1. A cursory comparison of the tested torque levels and their respective speed ratio outputs from Fig. 4 correspond closely with hand-calculated displacements from Fig. 9, verifying the example. A more detailed simulation in which these values can be computed and compared accurately is beyond the scope of this study, but is of particular interest for the very near future of this continued analysis progression.

The cut-off peaks shown result in both the back-and-forth output motion and the torque peaks felt on the input shaft. At high speed, these can be overcome by inertial effects in the system, further use of statically-mounted sprag clutches or by the use of extra sprag units in the transmission. Fig. 10 shows equivalent output for a 3-unit system at the same high torque level. Note that the peaks are effectively eliminated at this torque level, but the problem of analyzing the transmission's output quickly becomes a complex multidimensional root-finding problem, as several sprag units are bearing the torque by different spring displacements at once.

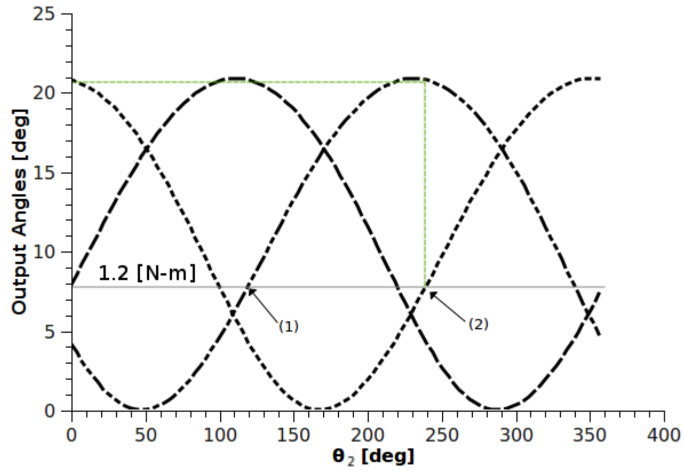

Figure 10. A REPRESENTATIVE 3-SPRAG MODEL (120º PHASE SEPARATION) WITH THE SAME FOUR-BAR CHARACTERISTICS.

SIMULATION EXAMPLES

The measurements taken in this study have shown that the Beale CVT is capable of easily producing a wide range of torque conversion ratios. When used as a torque limiter with multiple sprag units, the transmission can provide extremely high torque conversion, while still being capable of scaling up to a reasonable maximum for most applications. Some simple simulation results for application of the properties of the Beale CVT to a human-powered vehicle, an automobile and a centrifugal pump will be discussed here.

Human-Powered Vehicle

Human-powered vehicles are nearly exclusively driven by a discrete-gear dérailleur system. This system, while highly efficient, often falls short in applications needing high torque conversion, or the ability to change gears when the driveline is under load. Currently, several non-conventional bicycle transmissions are under development as products in the United States, one of which is a recently developed CVT technology, however incapable of providing augmented torque conversion compared to a traditional dérailleur.

Figure 11 shows human torque and speed production on a bicycle from [8]. Typical pedaling speeds for long-term operation of a human-powered vehicle are denoted by the two vertical lines at 60 and 90 RPM. Continuous pedaling at speeds outside this range is uncomfortable for most cyclists, and has been shown to be less efficient in terms of muscular oxygen use [9]. Dérailleur systems are generally capable of speed ratios from nearly 1:1 to 1:3.5 (pedal rotation to wheel rotation), which can maintain operation of a standard diamond-frame bicycle inside the shown human performance envelope between 75W and 225W for normal conditions.

At increased slope (above roughly 4.5% for most riders) or decreased torque input capability, use of a dérailleur system does not provide sufficient torque conversion. Also, at low speed, spikes in pedal forces occur due to the small tangential component of pedal forces early in the pedal cycle from top dead center [10]. These spikes cause difficulty in maintaining balance, as the rider must compensate by shifting his or her weight to drive the pedals. During these periods, it is also difficult to downshift, often causing the rider to either stop or risk mechanical failure by jamming the chain in between gears.

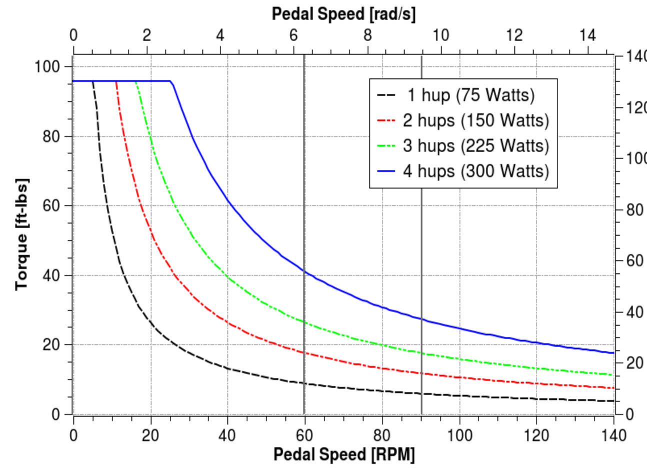

Figure 11. HUMAN POWER PRODUCTION CAPABILITY: TORQUE VS. SPEED FOR 170MM-ARM PEDALS

Application of the Beale CVT to a bicycle could eliminate many, if not all, of these problems. Properly selected spring behavior can allow for optimized riding on a per-rider preference, without the need to change system properties during riding. The automatic nature of the transmission can easily provide sufficient torque conversion when needed, while allowing enough torque input from the rider during level riding to drive the bicycle sufficiently fast. Also, since the input to the transmission simply needs a positive displacement input, an alternative input motion can be designed to maximize power- and torque-production capability of the rider's legs, only driving the crank arms through the optimal range of motion. This could eliminate much of the torque drop between crank cycles, and improve balance and comfort during low-speed, high-torque riding.

Automobile

Automobiles already use CVT technologies in some cases. The most common application in the automotive world for CVT's is hybrid drives, in which electric motors are synchronized with internal combustion engines by way of a belt or cone drive. Some automobiles even use CVT's as their main drive transmission. These CVT's, along with conventional, discrete-geared transmissions are still lacking in performance and production cost.

As a performance comparison, an automobile was simulated in FreeMat, an open-source software MATLAB clone, for an acceleration from 0 mph to maximum speed. The simulation was run using a conventional manual transmission (~220 lbs, fixed gear ratios, human shifter) and a Beale CVT (~50 lbs, continuous variation of speed ratio, automatically shifting with assumed speed control to maintain a constant engine speed). The CVT's torque conversion behavior was treated as a continuous function starting with a much higher torque conversion capability than the conventional transmission, as was physically demonstrated with the prototype. Also, the Beale CVT can transmit power directly from the engine's crankshaft to the driveshaft of the wheels. This could significantly reduce weight and all but eliminate the high moments of inertia in a multi-stage gearing system, increasing acceleration capability of the vehicle for a given power input. Another benefit not shown here is the ability to use a much lighter engine with a much smaller displacement at the same power level to obtain the same performance, much like turbo-charging an engine without the extra cost in fuel consumption. Results from this simulation are shown in Figures 12 and 13.

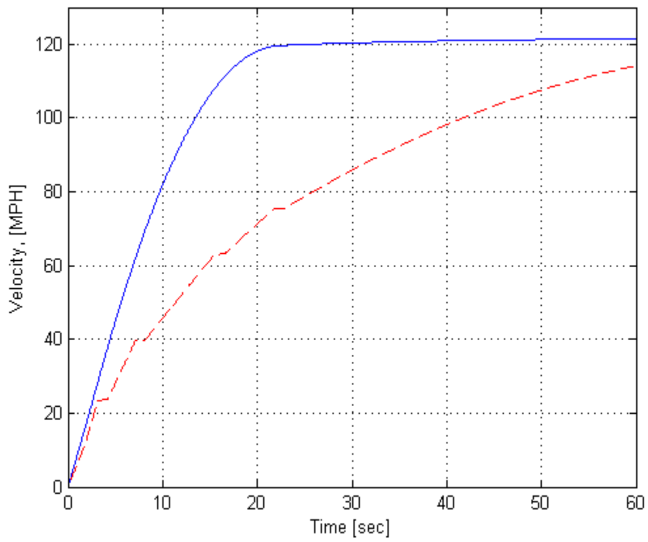

Figure 12. ACCELERATION OF A COMMON SEDAN (0 MPH TO MAX SPEED) WITH MANUAL TRANSMISSION (RED) AND BEALE CVT (BLUE)

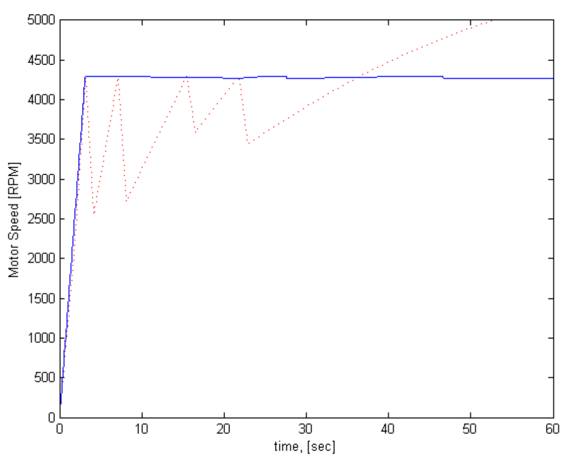

Figure 13: MOTOR SPEED OVER TIME DURING ACCELERATION SIMULATION. MANUAL TRANSMISSION IS IN RED, BEALE CVT IS IN BLUE.

Figure 12 shows the Beale CVT accelerating much more quickly and smoothly than the conventional transmission, while Figure 13 shows that the CVT keeps the motor speed at a constant (instead of changing speeds over a wide range of operating points with the conventional transmission) . This is a function of the assumed control system through the shifting subroutine, but this task is already performed in a limited fashion through conventional CVT's on some vehicles. One major benefit of this characteristic is that the wide range of speed ratios the Beale CVT is capable of would allow operation of the engine at its highest possible thermal efficiency at any output speed. This, combined with the ability to utilize a smaller, more efficient engine as was previously mentioned could translate into high increases in fuel economy.

Also, engine life will likely be favorably affected by running the engine at the same rpm all the time. This could result in more predictable life cycles and smaller individual torque loads on many of the mechanical driveline components. Add to these the reduced cost and ease of maintenance of the entire system, and the Beale CVT outperforms the conventional system in many respects. It remains to be seen what the expected design lives of the different parts in the Beale CVT will be, however, and balancing the system at high speed will remain a concern until usable dynamic models are developed and tested.

Centrifugal Pump

Pumps consume nearly 10% of all energy expenditure in the United States every year. They are used in virtually every manufacturing process, as well as in many consumer products and mechanical systems. Most common by far are single-speed, fixed wheel centrifugal pumps. These pumps have a predictable performance curve, excellent life cycles and low cost. The use of a single-speed pump for a variable flow application, however, suffers two major problems. First, adjustments are difficult and often not very repeatable, as the most common method is to choke the pump down to a given volumetric output. Second, the first problem results in a high energy expenditure for a given amount of output work.

Integration of variable-speed motor drives (VSD's) into direct-driven pumps is becoming more commonplace as users of such pumps (typically in industry) experience higher cost for extra expenditures of electricity. VSD's are themselves somewhat inefficient, large and have a high up front cost. These detriments prevent many users from applying a technology that could otherwise save them significant amounts of money, and traditional choking methods are typically used to vary volumetric flow of pumps.

Figure 14 shows an example pump curve with 90m shut-off head at 1700 RPM, and the operating point 1.75m^3/s volumetric flow at 40m of head. In order to adjust flowrate down by 1 m^3/s, conventionally one would choke the pump to operate at the point denoted by the magenta star. With a form of variable speed drive, however, the pump affinity laws state that the same pump could be operated at a lower speed to effect the same change, for a significant savings in power consumption. Specifically, for a constant-diameter pump impeller, reducing the speed from 1700 RPM to approximately 1400 RPM to achieve the flowrate adjustment (moving from the green point to the black point in Fig. 14) would reduce power consumption of the pump by the cube of the ratio of speeds. The energy advantage of this method over choking the pump to achieve the same effect (the magenta point in the graph) is roughly 50%.

The Beale CVT can be used to vary speed for pumps since by adjusting pretension on the grounded spring. This effectively forces the torque limitation on the input up or down, thereby limiting output speed for a given load. Since the output speed can be adjusted to nearly zero without wasting significant amounts of energy, the advantages of such adjustable pumping systems could be realized with this system, at a significant cost and portability advantage over existing VSD systems. Also, precise adjustments or outside computer control could also be easily implemented to allow accurate, repeatable control over the pump's output. This still requires the ability to balance the transmission and overcome inertial effects from running the transmission at high speed. Several design concepts that have been explored will allow for this.

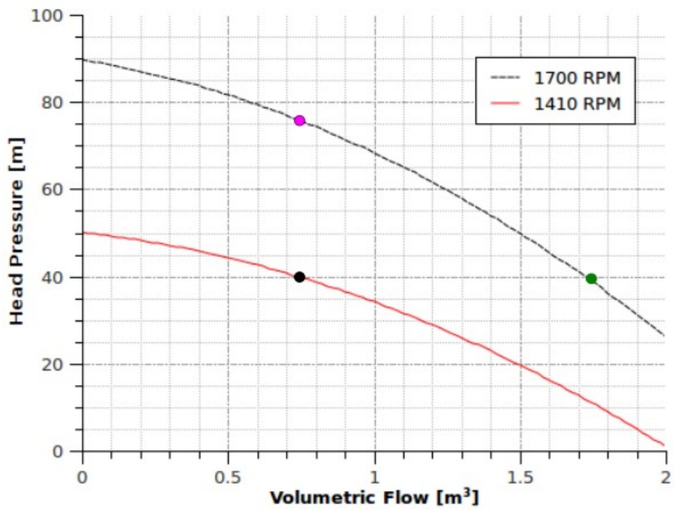

Figure 14. PUMP PERFORMANCE CURVES AT DIFFERENT SHAFT SPEEDS

CONCLUSIONS

The Beale CVT represents an important step forward for CVT technology in several respects. First, it is capable of changing speed ratio automatically without any special control or shifting mechanism. Second, its operating principle is based on a positive displacement, effectively avoiding some of the pitfalls of past CVT designs. Third, the transmission is capable of creating an extreme range of speed ratios, which can be very useful for a myriad of different applications. In addition to these, the transmission also effectively functions as a torque limiter, a differential drive and a hybrid drive through which independent power sources can be applied to the same shaft without synchronization.

The specific characteristics of this design are very promising for some applications that represent significant portions of energy expenditure in today's world. Also, they provide an avenue by which significant cost and performance improvements may be made on many existing mechanical systems. The three examples discussed in this study show that the observed behavior of the device can greatly change the design paradigms and performance specifications of different mechanical systems.

While this mechanism has many attractive properties, it is difficult to analyze dynamically, especially for multiple-sprag systems. The four-bar arrangement explored here can prove difficult to balance, and inertial effects can cause unwanted vibrations in the system. One-way clutch systems are as yet still young in terms of background literature and research. Creation of an accurate high-speed model to describe this transmission will heavily rely on a solid understanding of sprag clutches and their interaction with dynamic systems. Work is currently being done in this regard, as such a model will allow more effective application of the technology to electric motors, internal combustion engines and a resulting large number of further realizations. These, among other designs, are already being pursued by the inventor for commercialization.

ACKNOWLEDGMENTS

Special thanks are in order to William Beale, the inventor of this CVT concept. He has done much to augment this research as well as provide insights into new developments for the mechanism. Also, thanks to the developers of the excellent mathematical suite FreeMat (Samit Basu, Eugene Ingerman, Chuong Nguyen, Demetrios Kryakis and the rest of the development team), which was used to perform all the simulations in this paper.

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