Experimental Setup to Characterize Shift Time for High Performance Hybrid Transmissions

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EXPERIMENTAL SETUP TO CHARACTERIZE SHIFT TIME FOR HIGH PERFORMANCE HYBRID TRANSMISSIONS

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ABSTRACT

Hybrid vehicles are increasingly common due to fuel efficiency regulations in place worldwide. High performance hybrids have typically been designed with a focus on improving performance, rather than the combination of both performance and efficiency. In order to improve efficiency of high performance cars, new hybrid architectures are necessary. When incorporating an electric motor, careful focus on operational modes allows for removal of certain elements, such as the reverse gear. Additionally, installing an electric motor directly coupled to the transmission without a clutch gives performance benefits, but requires detailed control of motor speed and novel methodology for shifting. In this paper, the design of an experimental setup for the electric drive in a high performance car hybrid transmission is presented. This architecture allows for characterization of synchronizer behavior during two different shifting methodologies. The first methodology is synchronizing a large rotational inertia with a small shaft speed difference (this differs from a gear shift in a traditional transmission with a large speed difference but small inertia). This situation is encountered when coupling an electric motor to the drivetrain, as the inertia of the electric motor is relatively large compared to a transmission layshaft, but the speed difference is small. The second is testing shifting of a synchronizer where dog tooth engagement happens immediately, with no friction cone to match the speed. This type of shifting is possible with precise electric motor speed control, sensing of the dog tooth position, and fast actuation. This methodology eliminates the need for a friction cone in the synchronizers, while maintaining fast gearshifts for performance driving. Our experimental setup for the electric drive in a hybrid transmission will be used to characterize synchronizer performance with these new shifting methodologies. The insights gained from this setup will aid in designing advanced hybrid architectures.

INTRODUCTION

Due to increasing emissions regulations, many automotive manufacturers are looking towards new technologies to meet stricter emissions targets in the near future. While everyday hybrid vehicles have been readily available in the USA since the year 2000 (when the Toyota Prius was introduced in the US) [1], even high performance vehicle manufacturers are moving towards hybrid and all-electric vehicles to achieve emissions metrics while aiding performance. Porsche is producing its first all electric car, the Mission E [2]. Ferrari has announced that by 2019 all vehicles for sale will be hybrid [3]. McLaren produced its first hybrid in 2013, the McLaren P1 [4]. Lamborghini is developing its first hybrid vehicle, the Lamborghini Urus SUV hybrid [5].

When creating a hybrid vehicle, it is especially important to focus on customer experience. To date, less than 1% of vehicles sold are hybrid. Existing hybrid technologies suffer drawbacks that can include short range, limited speed, high cost, and inadequate charging infrastructure [6,7,8]. In addition, some customers associate the technology with compromised driving experience [9]. For a high performance hybrid, customer expectations are great. To illustrate, the Lamborghini Asterion was canceled based on customer feedback. According to Stephan Winkelmann, former president and CEO of Lamborghini, "A

Lamborghini super-sports car is driven maybe 3000 miles a year, not every day, so the electrification has to offer an added intensity to justify its inclusion” [10].

Designing powertrains for performance vehicles requires careful optimization of weight, size, sound, components, and feel during operation. Shifting characteristics are especially important, as a fast shift is necessary for optimal 0-60 mph performance. Understanding how to shift and investigating new shifting methodologies will allow for high performance hybrid transmissions that are optimized based on these metrics.

An important component that adds to customer experience for a high performance vehicle is fast shifting optimized for 0-60 mph acceleration. In this paper, we focus on addressing this overall goal by focusing on synchronizer performance.

Synchronizer Details

The synchronizer is a critical component of the transmission (Figure 1). As lateral force is applied to the shifting sleeve, the friction cone in a synchronizer dissipates power, bringing both sides of a shaft to equal speed before engagement. Next, the dog teeth on the sleeve lock to the dog teeth on the gear, completing the shifting event. Transmissions can have a single friction cone, or several for higher performance, faster shifts where more power must be dissipated.

Typically, a clutch decouples the large inertial forces imparted on the transmission from the engine, so that the only energy that must be dissipated is from the inertia of the spinning gears within the transmission. The speed difference between the two shafts can be large; typically the difference is equal to the engine RPM difference from one gear to the next. In this paper, we focus on the design of a system to study the effect of large loads on the transmission from both the input and output shafts. This will help simulate synchronizer behavior in scenarios where an electric motor is directly coupled to the transmission gears. The overall goal is to prove feasibility of such transmission architectures for future high performance hybrid vehicles.

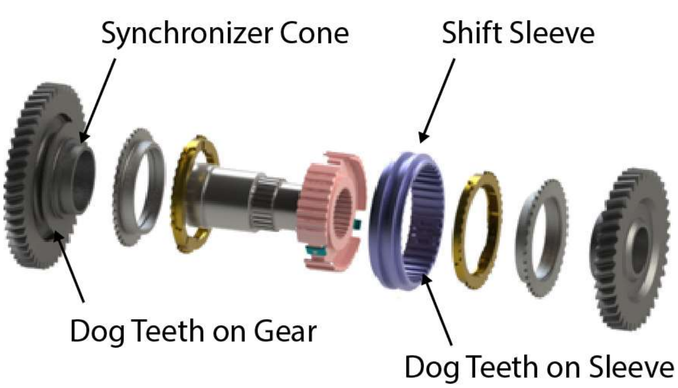

Figure 1: EXPLODED VIEW OF GEARS AND SYNCHRONIZER. A typical synchronizer including the synchronizer friction cone, shift sleeve, and dog teeth. An actuator pushes on the sleeve, causing the friction cone to bring the gear up to speed.

Once the speeds are matched, the sleeve can slide over fully, engaging the dog teeth.

New Shifting Methodologies

To understand shifting in a high performance hybrid transmission, we designed and built an experimental setup for characterizing synchronizer performance. The setup was designed such that two shifting methods can be studied.

- *Large Inertia Shifting*: Shifting with large inertias and a small speed difference. We will evaluate the time required to synchronize the shaft speed as a function of angular velocity difference between two shafts, the respective inertias of each, and the force used to shift the synchronizer.
- *Dog Tooth Shifting*: Shifting when the dog teeth are aligned, but without the speed synchronizing phase that occurs from the friction cone engagement. This is similar to shifting a dog box transmission, but is performed automatically, and with standard synchronizer teeth. We will determine what sensors and control methods are needed to complete successful shifts.

These two shifting methodologies differ from the way shifting typically occurs in a manual or automated-manual transmission. Dog tooth tracking for a shift is similar to how a face dog clutch behaves in some ways, but without initial contact of dog tooth faces to ensure alignment [11]. While significant development of traditional frictional synchronizer models has occurred [12,13], little has been found in literature describing a method for tracking dog tooth position for shifting gears. Understanding the behavior of the components during a shift is crucial for designing a vehicle that utilizes either method. Modeling the test setup using Simulink, and comparing results from the tests to Simulink simulations will allow for predicting full vehicle performance using the model.

EXPERIMENTAL SETUP

In order to test the synchronizers in the large inertia and dog tooth shifting modes, the experimental setup shown in Figure 2 was designed and constructed.

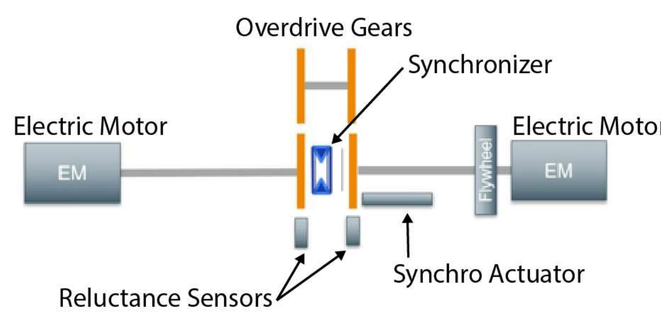

Figure 2: EXPERIMENTAL SETUP OVERVIEW. Two electric motors drive the system. Flywheels can be added to vary the rotational inertia of the system. The positions of the dog teeth can be determined with variable reluctance sensors. The synchronizer sleeve and fork are actuated with a pneumatic piston.

The setup consists of two electric motors with speed feedback, an overdrive gearset with a single synchronizer from a 1984 Ford F-150 transmission, a pneumatic actuator for actuating the shifter, variable reluctance sensors for sensing dog tooth position in the transmission, and the ability to mount flywheels of different inertias. Figure 3 shows the hardware setup with the F-150 transmission installed.

System Requirements

The setup was designed to achieve speeds in excess of 3000 RPM, as this speed is greater than the speed difference that will be encountered in a production transmission. This is sufficient to test the energy dissipation limits of the synchronizer. Actuation of the synchronizer can be performed with 1500 N of force for the large inertia shifting mode.

Flexibility was a key requirement for the design of the experimental setup. Therefore, our setup was designed such that flywheels of varying inertia can be installed for performing tests. Additionally, the synchronizer can be replaced with other styles of synchronizers for testing the affects of different friction angles and number of synchronizer sleeves. Finally, the open architecture allows for easy modification of sensor quantity and placement, as we did not design a specific housing for all of the components. In our setup, sensors can be mounted to rails that align and hold system components in place. This modular architecture allows for components to be replaced with ease.

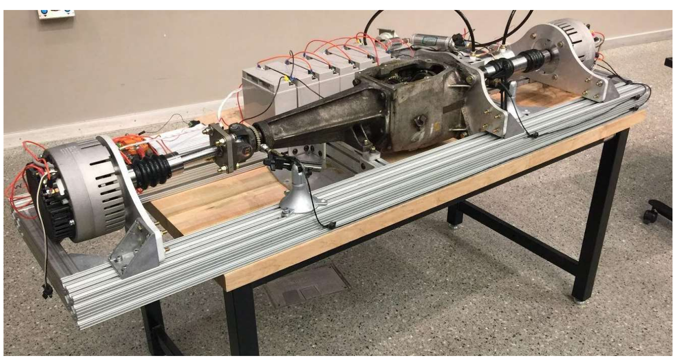

Figure 3: IMAGE OF EXPERIMENTAL SETUP. The electric motors can be seen at either end. Located in the center is the Ford F-150 transfer case, with the 72 V battery behind.

Motor Selection

For the design of the benchtop setup, two motors are used in order to load the transmission in a variety of configurations. This allows for testing and data collection in both high and low energy conditions. For example, data can be collected with the input shaft rotating at 100 RPM and the output shaft at 0 RPM. A second test can be conducted to collect data with the input shaft rotating at 3100 RPM and the output shaft at 3000 RPM. Both tests investigate a speed differential of 100 RPM, however the latter theoretically requires the synchronizer to dissipate approximately 60 times the amount of energy. Both of these cases can be applied to real world situations, which is why the setup requires two independent motors.

When sizing the motors and speed controllers, several criteria were taken into consideration:

- Power and Torque Capability: Long term, the setup should be capable of integrating with a small internal combustion engine, therefore power should be in the range of 3-8 kW (4-10 HP).
- RPM Range: In order to test high energy shifting configurations, the setup must be capable of at least 3000 RPM. Brushless motors provide the best performance with lowest anticipated maintenance.
- Regenerative Braking: To remove power from the system and rapidly decelerate the motors, speed controllers with regenerative braking functionality are necessary.

To meet these requirements, we selected the Mars M907 EM paired with the Kelly Controller, KBL72301X, rated for 72 V with peak current of 300 A and regenerative functionality [14]. This system has a maximum speed of 5000 RPM and is sold as a kit with throttle and preprogrammed controller by Kelly Controls. The system is paired with six 12-Volt batteries wired in series for a total of 72 volts DC.

Transmission

The transmission module consists of the housing, shafts, and gears. For this test setup, a manual 1984 Ford F-150 transmission was used. The Ford F-150 transmission is readily available in the market and reduces the need to build a new housing enclosure. Future versions of the setup will test synchronizers provided by our industry partners. Modeling the synchronizer and comparing analytical results to our experimental results is expected to allow for predicting synchronizer behavior based on geometry.

The Ford transmission has several desirable features:

- The pre-existing housing mitigates the risk of misalignment between the two transmission shafts. With the existing housing the accuracy of the alignment meets production specifications.
- The housing provides an enclosure for lubrication. Adequate lubrication is important to the system, so that it does not overheat, and for proper frictional effects during synchronization.
- The housing provides a safe enclosure to prevent pinching, and eliminates the possibility of broken or loose components from injuring an operator.
- The housing has a shifting mechanism in place. The actuator can be attached to this linkage and used to engage the synchronizer.

Actuation System Design

The actuator module is used to physically move the sleeve in the transmission to engage and disengage the synchronizer. This module consists of the shift fork and pneumatic system. The shift fork is mounted on a shaft that is parallel to the power transmitting shafts and can be moved linearly to move the sleeve. Pneumatics have the following benefits that lead to their selection for this application.

- High pressure air is readily available, and more manageable than high pressure hydraulics used for actuation in vehicles
- High power density can be achieved easily
- Low cost compared to similar power electromagnetic or ballscrew actuators
- Force can easily be modulated between different trials

The pneumatic system consists of a pneumatic cylinder with integrated position feedback [15], two solenoid valves, two pressure accumulators, and a pressure regulator. Figure 4 shows a schematic of the test setup. Pressure can be varied from 0 – 100 psi to control the speed and force with which the actuator moves. The output of the piston is coupled to the shift fork shaft controlling the movement of the hub sleeve in the transmission.

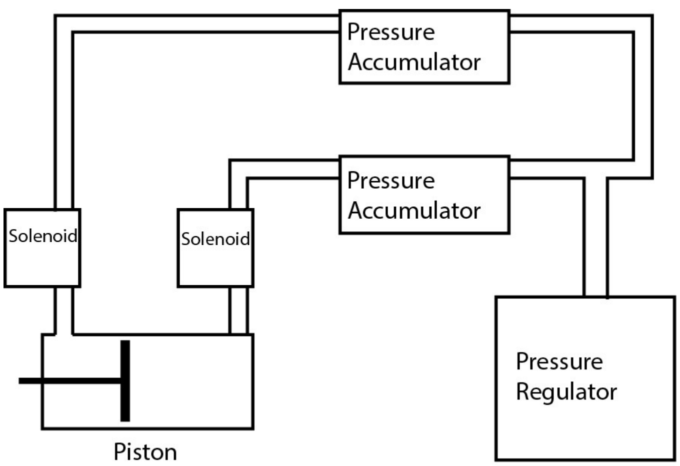

Figure 4: ACTUATION SYSTEM SCHEMATIC. The elements of the actuation system including the pressure regulator, accumulators, solenoids, and actuation piston is shown here. Future iterations of the system can include a 3 position piston for engaging with either gear and moving to neutral, as both gears cannot be engaged with a two position piston as shown. A large piston is used for high force, and a smaller piston is used for high speed.

Two pneumatic actuators were selected. A Bimba PFC-092-bf with a 1.0625" bore is used for dog tooth shifting and a PFC-502-BF with a 2.5" bore for large inertia shifting. The 2.5" bore piston can generate a maximum of 2180 N of force. A 500 RPM differential requires close to 1500 N of force to engage the synchronizer [16], which can be obtained with an air pressure of 70 psi (482 kPa).

The smaller piston was selected for dog tooth shifting, as lower force is required, and faster velocity is desired. Compared with a larger piston, a smaller piston gives lower force at a given air pressure due to the smaller piston area, and can move faster due to the smaller volume of air needed to fill the cylinder. For a given displacement, the volume of the smaller piston is 18% the volume of the large piston, so given a set airflow rate, the piston can move significantly faster.

Alignment of the linear actuator, shift fork and load bearing shaft is a critical aspect of this design. Failure to align the components could lead to the shift fork binding on the gears or sleeve rather than pushing the sleeve over the synchronizer to engage with the intended gear. To address this issue, many of the existing features in the housing were utilized including the original shaft supports.

Actuator Validation

To validate the actuation design, tests were performed with each actuator to characterize the response time. While fast actuation is desired for large inertia shifting, it is critical for dog tooth shifting, as a successful shift depends on engaging between a set of dog teeth faster than the relative speed difference between the teeth.

A series of tests was run to validate using a pneumatic actuator for this setup. The piston was set to the fully retracted position and the solenoid valve was triggered to open. Air then flows into the piston and the motion of the piston is recorded. Figure 6 shows the series of tests performed with the small piston from 20 – 60 psi. As expected, operating at higher pressure leads to faster piston motion.

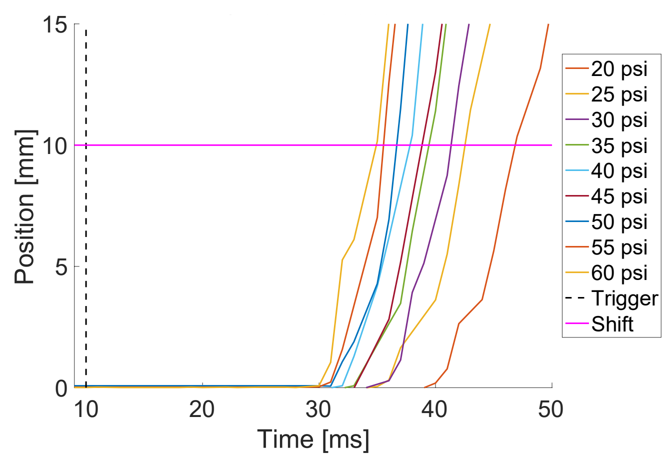

Figure 6: ACTUATION TESTS 0-60 PSI. As the pressure increases, the actuation time for the piston decreases. Most of the delay in actuation can be attributed to triggering of the solenoid and pressurizing of the inside of the cylinder to initiate motion.

Dog Tooth Engagement

To engage the dog teeth during a shift, the actuator must be capable of moving fast enough such that the dog teeth are engaged successfully. Moving too slowly will cause the tooth to move in, but it will collide with the tapered surface of the next tooth and be pushed out of engagement.

For teeth where the tooth sizes on the sleeve and gear are approximately the same, the criteria for successful engagement is the following.

$$actuator\ velocity \geq \tan(\theta) \times\ tooth\ velocity \qquad (1)$$

where *actuator velocity* is the speed at which the actuator can move the shifting sleeve as measured and described in the "Actuator Validation" subsection, θ is the angle of the dog tooth, and *tooth velocity* is the differential surface speed of the teeth as they rotate past each other due to a speed mismatch between gear speed and sleeve speed. Surface speed is calculated using

$$tooth\ velocity = \pi \times d \times \omega \qquad (2)$$

where π is the ratio of the circumference of a circle to its diameter, d is the diameter of the dog tooth portion of a gear, and ω is the angular velocity of the gear in rotations per second.
If the actuation speed is higher than this criteria, engagement will be a change in speed of the gear, and the actuator will decelerate as contact is made between the angled surfaces of the sleeve and gear dog teeth. Figure 7 depicts the criteria determining a successful shift.

There is typically a small amount of backlash between the teeth. This extra gap helps contribute to successful engagement. This small gap has been neglected from the criteria determining a successful shift. Teeth with larger gaps can be designed such that achieving a successful shift is feasible for larger velocity differences and slower actuation.

For the experimental setup, the angle of the dog teeth θ is 54 degrees, as defined in Figure 7. The outer diameter of the dog teeth on the gear is 82 mm. Using this criteria, with a speed difference of 336 RPM between the sleeve and gear, the *tooth velocity* is 1.45 mm/ms. This is the limiting case with an actuation velocity of 2 mm/ms measured from the pneumatic actuator at 60 psi.

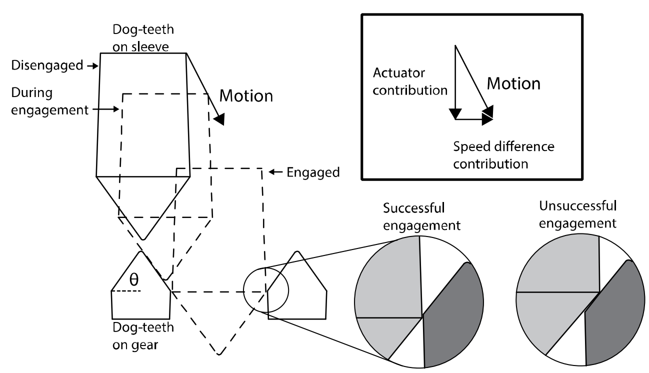

Figure 7: SYNCHRONIZER DOG TEETH MOTION. Shown at left is the motion of the sleeve dog teeth as they engage. Top right shows the motion of the synchronizer sleeve, with vertical motion as a result of actuation, and tangent motion as a result of the speed difference between the sleeve and gear. Bottom right shows successful and unsuccessful shifts based on the alignment of the teeth.

Reluctance Sensor Tooth Position Sensing

To achieve a successful dog tooth shift event, in addition to having a quick actuation, it is critical to understand the position of the synchronizer teeth on the sleeve and the gear before the shift. To achieve this, the test setup uses variable reluctance sensors, similar to what is found on a vehicle's anti-lock braking system (ABS) wheel speed sensors. When the steel tooth surface passes by the sensor, a voltage spike is produced. This signal can be converted to a square wave indicating the position of the tooth relative to the sensor, as shown in Figure 8. By locating sensors on the dog teeth of each gear and the sleeve, the position of the teeth on the sleeve with respect to the location of the teeth on the gear can be determined. Use of a high speed camera will help facilitate this process, as the camera can be triggered to take an image at a desired time, and the actual position of the dog teeth can be compared to the reluctance sensor signal. This calibration is not needed to determine relative positions between the sleeve and gear dog teeth, but is necessary to know absolute position.

To achieve a successful shift, the delays in the system must be accounted for. Given a speed difference of 50 RPM, the period of the signal is 33 ms peak to peak for a synchronizer with 36 teeth. This time is on the same order as the 20 ms delay, and 5 ms actuation time for the pneumatic system. Reducing the delay is desirable, but accounting for the delay in the controls system will allow for successful shifts.

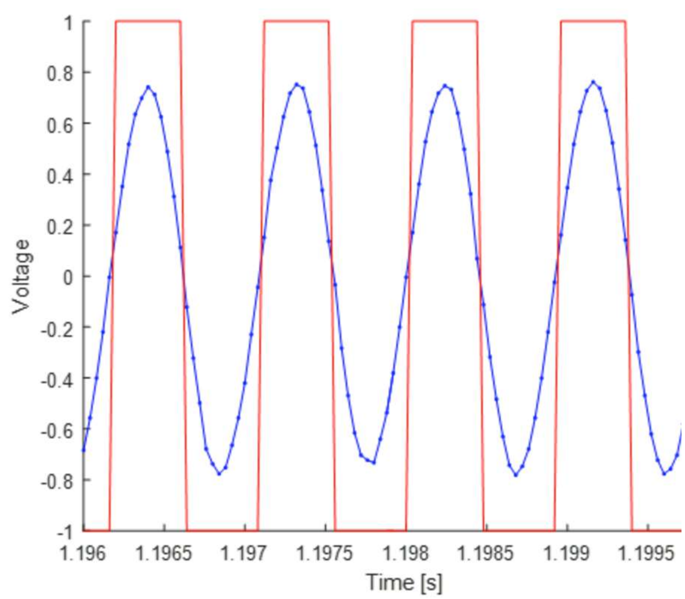

Figure 8: RELUCTANCE SENSOR DATA AND OVERLAID DOG TOOTH POSITIONS. This figure shows a reluctance wheel and the dog teeth passing by a fixed position. As a dog tooth passes the sensor, a voltage peak is recorded (shown with the blue sine wave). Calibration of the sensor will allow for accurate alignment of the peak with a square wave signal representing the physical dog tooth position in time. By recording the positions of the sleeve and dog teeth on a gear, a successful dog tooth shift can be made.

Data Acquisition and Control

A National Instruments myRIO [17] is used for the control of this setup. LabVIEW is used for control and data logging. The recorded signals are piston position, reluctance sensor signal, motor velocity from the speed controllers, motor current, and battery voltage. Piston position and dog tooth position are used for the controls logic. Outputs from the myRIO include triggering of the pneumatic solenoids, speed control of the motors and enabling the motor drivers to turn on a high power relay.

A test event for dog tooth shifting is as follows. The motors will enable and begin spinning, each at the commanded speed, motor 1 slowly, and motor 2 at a higher fixed speed. Reluctance sensor data will be used to determine when the dog teeth are aligned. Motor 1 is commanded to accelerate to a speed higher than motor 2. When the motor speeds are within the set threshold, and the teeth are aligned, the piston is actuated and motor 1 is set to torque mode.

Testing the large inertia shifting is a similar procedure. The only difference is that the reluctance sensor data is not used, and the only criteria for shifting is when the speeds are within a desired threshold. Flywheels can be changed to perform these tests at a variety of different inertias.

FUTURE WORK

Currently the setup is being revised to use a CompactRIO [18], which will have more inputs and outputs in addition to the ability to run at a faster clock speed. Additionally, upgrades to the hardware setup will allow for greater flexibility in replacing gears and quickly changing flywheel mass.

A detailed Simulink model is under development. The data acquired from the experimental setup will be used to validate the model. This will be repeated for several cases including varying the synchronizers, flywheel inertia, and velocity difference. Once the Simulink model can accurately predict behavior of the test setup, it can be used to predict performance for a real vehicle when using either large inertia shifting or dog tooth shifting.

CONCLUSIONS

An experimental setup was developed to study new methodologies of shifting for high performance hybrid transmissions. We have validated key aspects of the setup to allow for testing two new shifting methods. Large inertia shifting and dog tooth shifting will facilitate the creation of new transmissions architectures with an electric motor directly coupled to the transmission without the presence of a clutch. By controlling the electric motor velocity and timing the gearshift events based on motor speed and dog tooth positions, accurate shifts can be performed.

Using data from this test setup, the best method for each shift style can be determined. The details for how to control the motor, how to implement dog tooth position sensors, and control logic governing shift timing can be implemented in a full scale vehicle transmission. Given these details, electric motors can be implemented in new ways into hybrid vehicles, bringing performance and efficiency benefits.

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