An analytical approach for assessing CVT alternatives

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ABSTRACT

This paper discusses the technical comparisons and tradeoffs for assessing different variable ratio transmissions, how system level analyses are implemented into the customer focused concept design process, and how sizing and application details are evaluated for a specific implementation. Examples are presented based on CVP (continously variable planetary) technology.

A "System-V" approach is presented which seeks to align the value proposition with customer requirements through concept and detailed design, correlating back through system validation.The technical factors to be considered in the initial design phase are driven from customer and system level requirements: efficiency, ratio range, operating conditions, durability requirements, complexity and power density are differentiating features of CVT (continuously variable transmission) technologies that separate them from other technologies in the market. Other attributes related to weight, packaging and inertial considerations need to be considered at the system level and are best evaluated with custom analysis tools incorporated into this process.

The NuVinci® CVP transmission system allows for additional flexibility similar to a traditional planetary gear set functioning as a power summing device, allowing multiple options for both input and output power paths. It can also be configured as an IVT (infinitely variable transmission) without having to split power between a mechanical and variable branch. This requires additional consideration when doing system level analysis and demonstrating the customer value proposition.

The robust potential of this technology requires an efficient, methodical process to quickly configure it for new applications. This paper outlines a process for concept design and sizing of a *NuVinci* CVP system given a generic set of requirements. Included is a discussion on design considerations for alternate CVT technologies, the roles of analysis in the design process, a description of analysis and simulation tools developed and used by Fallbrook Technologies Inc. (FTI), and a look into a simple example sizing exercise of a CVP system.

I. Introduction

Drivetrain design and architecture development is a critical and complex effort that has significant ramifications on vehicle performance, cost, fuel economy and overall user experience. Further, the development of new drivetrain configurations is costly and time consuming and - in a competitive landscape - there is a need to quickly and cost effectively compare alternative configurations with all factors considered. Many trade offs are made in each type of competing technology between efficiency, power density, complexity, performance, and cost. Push belt and chain CVT systems have slowly gained acceptance in automotive and other light vehicle applications, whereas traditional elastohydrodynamic (EHL) traction drives (e.g. full and half toroidal systems) have yet to commercialize on a large scale. The *NuVinci* CVP traction drive offers several advantages over competitive offerings and opens new opportunities in packaging flexibility and power density.

Three topics will be addressed in this paper:

- Technical factors in evaluation of CVT technology
- The role of system analysis in the design process
- Example configuration of a CVP system.

The topics are arranged to walk through, at a high level, the trade offs that are needed in transmission system design and how FTI utilizes its simulation tools to architect and validate a system. To provide a deeper level of understanding an example is presented for configuring and sizing a basic *NuVinci* CVP system.

II. Technical Factors for Consideration

When comparing CVT technologies it is important to understand the basic functions and value propositions. These are simply described in Figure 1.
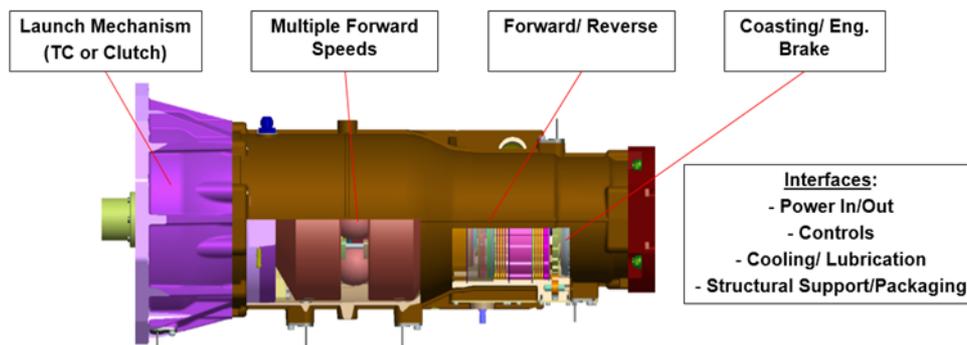

Figure 1: Graphic representation of basic transmission system

Basic Functions

At a very high level, the primary function of any multispeed transmission system is to enable the vehicle to respond to user inputs for desired control of the vehicle, while attempting to keep the engine or motor at or near its peak power output or efficiency.

In order to accomplish this nearly every transmission in the world has several basic functions. For a combustion powered system these functions include capability to launch the vehicle (typically with a torque converter or a clutch); manage several modes (or speeds),

including reverse; and free-wheel or absorb braking energy back through the drivetrain. Obviously there are some specific functions for each application on top of these basic elements, but these describe the core operation of the transmission system.

Basic Interfaces

Another important factor is packaging and flexibility in the interfaces. All transmissions interact with a drivetrain system via at least four common interfaces: power in and out; controls; cooling and lubrication; and structural mounting to the vehicle. These interfaces define much of the packaging requirements for a given drivetrain design. Some technologies such as push belt, pull belt, and toroidal require offset shafts, an axial configuration with a jackshaft, while others can support multiple configurations such as in-line, concentric U-drive, and pancake (e.g. center shaft input and housing output).

Value Metrics

Given that the overall role of a transmission is to transmit power and manage the ride feel of the vehicle throughout its life, at least three paramount metrics emerge. These are system efficiency; control capability and associated NVH/ shift quality; and durability. All transmission systems strive for the highest levels in all of these metrics and minimums must be achieved for market acceptance (e.g. 100k mile warranty, perceived shift quality, etc.). What differentiates any given drivetrain solution is not just how efficient it is or how well it shifts, but how well it achieves the above metrics at the lowest overall component or system level cost, size and weight. Thus, we recognize at least two other metrics that differentiate one transmission technology from another, assuming some minimum efficiency, shift quality and life. These are torque density and power density which define how much value a transmisison system provides versus a cost such as price, size, or weight. These are especially important when comparing CVT systems and include all features required for implementing a given technology, such as controls, lubrication, clamp requirements, and additional gearing and connections, among others.

III. Role of System Analysis and Simulation in Initial Design

The ability to compare competitive technologies based on fundamanetal system performance and packaging allows us to look at applications and show the end user value when integrating CVT or CVP technology versus other conventional transmission configurations quickly and efficiently.

The FTI approach to meeting customer specific applications is best described with a System-V process model. Analysis is integrated into all steps of the process beginning with analytical demonstration of the value proposition and ending with prediction and validation of the customer value in the final application. Figure 2 is a graphic representation of this process.
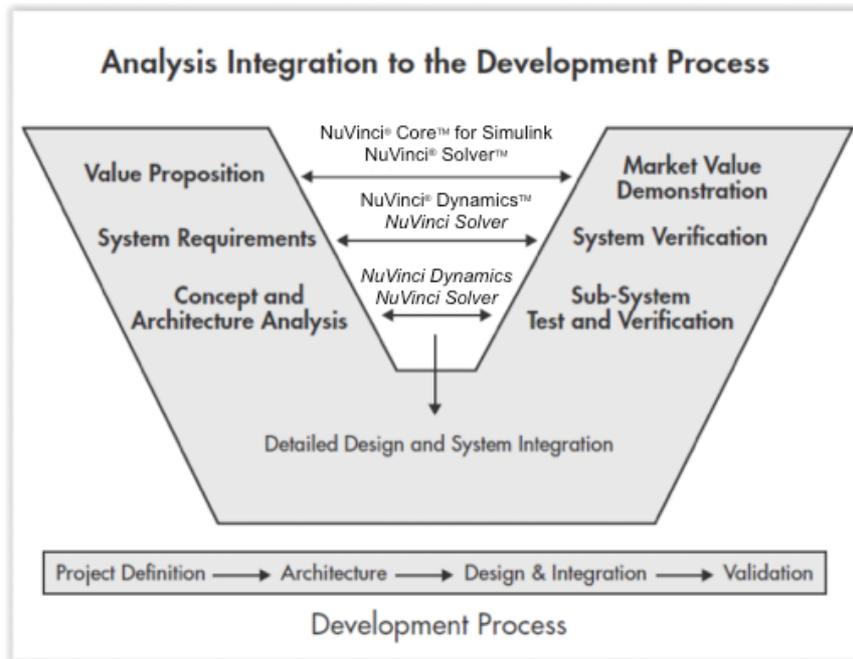
Figure 2: System-V Illustration of Engineering Process and Analysis Integration

To facilitate this engineering process FTI has developed several analytical tools for quickly evaluating drivetrain architectures during different phases of a project. *NuVinci* Core™ for Simulink® provides a simple dynamic representation of a CVP including the system torque loss that may be used for modeling and simulation. *NuVinci* Solver™ incorporates a robust set of tools for traction modeling, focusing on steady state performance and durability analysis. *NuVinci* Motion™ for Adams®, is used for dynamic system and subsystem development. The following paragraphs discuss the use of of these tools within each phase of the engineering process.

Value Proposition

While evaluating customer needs, convential powertrain and system level models are established to simulate system performance and study dynamic and steady state metrics such as efficiency, effects of inertia, and ratio range options. Figure 3 shows a system level model in the form of *NuVinci Core* for Simulink
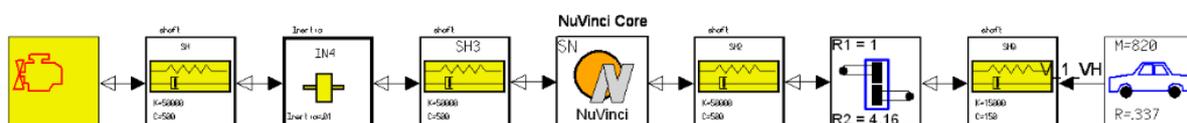

Figure 3: System level model with *NuVinci Core* for Simulink integrated

With this tool, both steady state system modeling and dynamic system modeling are conducted to demonstrate value and predict system performance. *NuVinci Solver* can also be implemented in this initial phase to evaluate multiple power path configurations and size based on steady state performance.

System Requirements

The next step in the development process is utilizing system requirements to define the architecture and concept design. With a typical CVT system, the analysis required to evaluate efficiency, ratio, and power capacity for a given drive size is simplified since there is only one power path. When evaluating *NuVinci* CVP configurations there are a multitude of power path and configuration options that affect ratio range, power recirculation and durability calculations. Therefore, subsystem models are leveraged to analyize specific sizing activities detailed in Section IV. These options are evaluated in a tool called *NuVinci Solver*, which has several embedded tools tailored specifically for this process.

Detailed Design

During the detailed design and integration of a CVP system, analysis plays a critical role in defining internal geometry and kinematic relationships of the traction drive system. This is a very iterative process and the developed tools have been focused to create maximum value and speed in this process. A list of factors analyzed using each tool in this phase are listed below:

- *NuVinci Solver*- Steady State Modeling
    - Kinematic relationships
    - Power capacity and sizing
    - Shift forces
    - Durability and force results
    - Efficiency and performance metrics
    - Tolerance studies and trade off analysis

- *NuVinci Motion* - Dynamic System Modeling
    - Control system development and dynamic shift forces
    - Detailed component analysis and contact modeling
    - Dynamic system and subsystem responses
    - System stability and control analysis
    - Test correlation and prediction
    - System level efficiency and performance modeling

Validation

As physical hardware is fabricated and tested, the analytical models are correlated. Correlated models drive iterative development and design cycles to achieve targeted performance and durability requirements. System level models are then confirmed via testing in physical applications or transmissions. The final phase is customer validation and correlation to the orginal value proposition.

IV. Configuring and Sizing of CVP System

As a practical application of the process described above, the following example is provided for evaluating the sizing of a CVP.

Drive Geometry Basics

*NuVinc*i technology has been written about in [1]-[6] and Figure 4 shows the basic geometry. The *NuVinci* drive is a planetary gearing system using spherical planets. As in any

planetary, multiple power paths are allowed by changing what components - the carrier, sun, and two rings - are the input, output, stator and idler.
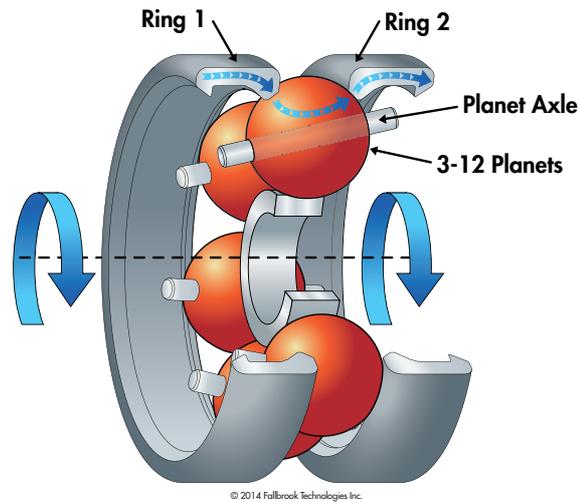

Figure 4: CVP geometry. This shows the CVP configuration where the left ring is input, right ring is output, and sun is idler. From [1].

Analysis Methods

Several methods and models are used to analyze the *NuVinci* CVP technology and predict performance. They are the foundation for the tools discussed previously. Traction is in the form of elastohydronamic lubrication (EHL) modeled using methods outlined in Thomassy [7] and Tevaarwerk [8], [9]. Life predictions of the drive elements are based on the Lundberg-Palmgren formulation outlined in Harris [10] and Zaretsky [11], [12] with the correlation factors [13] derived from internal durability testing. Churning, bearing, and seal losses are curve fit to test data. Thermal predictions [14] are verified and supported through testing. Considerations such as power paths [3], inertial effects, fluid type/temperature, conformity, and other factors are also considered.

Sizing a CVP - Concept Level

There are three types of parameters. First, requirements are mandatory values for drive/system performance and are defined by the overall system needs. Control variables are inputs into the *NuVinci* analysis tools and are iterated. The number of control variables depends on the scope of the sizing and specific application. For example, requiring a reverse speed puts a higher emphasis on an IVT design. Lastly, outputs are analytical results from the iteration process. The goal of sizing is not only to identify a possible *NuVinci* system but also to recommend a "best" system based on the most desirable outputs. The specific variables used in each section vary by application, but the most common are listed below:

- Requirements and specifications
  - System duty cycle
  - Life requirement
  - Size requirement
  - Operating conditions
- Iterative Control Variables
  - Number of planets
  - Planet sizes

- o Planet spacing
- o *NuVinci* specific duty cycles
- o Power paths options
- o Geometric Considerations
- Outputs and results
  - o Efficiency and power loss
  - o Predicted size and life
  - o Temperature rise
  - o Component speeds

Example of Iteration

Consider the problem of evaluating a *NuVinci* CVP system for a generic application with the basic requirements of an L10 life between 10,000-16,000 hrs, a maximum size of 235 mm, and a system duty cycle with a speed ratio range of 0.5 - 1.7. The speed ratio range is a good fit for a CVP power path design - see Figure 4 - that has a speed ratio range of 0.5 - 1.8. Only the number of planets, planet size, and planet spacing are chosen as control variables with limited iteration. The scope of this example does not involve the full range of requirements, control variables and outputs common in a full sizing study.

The result of iterating over the number of planets (6 - 9) and planet sizes (43, 45, and 46 mm diameters) is shown in Figure 5. The solid points all use the same planet spacing of 2 mm. Planet gap was iterated for two points that originally showed up just below the 10,000 hr threshold; these planet gap iterations are indicated with hollow markers. Three acceptable solutions are indicated by the circled points.
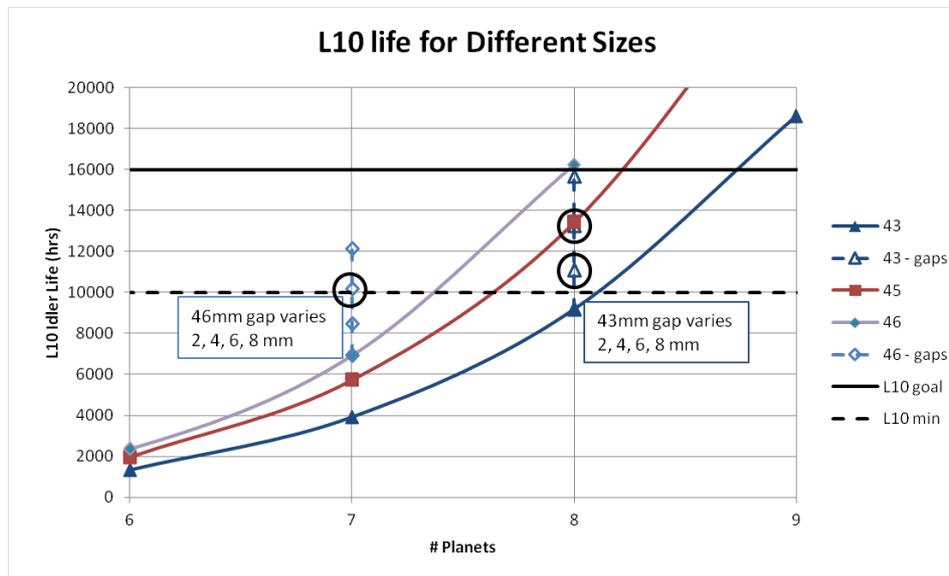

Figure 5: Example result showing L10 life by iterating over planet diameter and number of planets.

The L10 life increases with larger planets and more planets because the load is distributed over a larger area. Increasing the planet gap increases the sun diameter. A similar plot showing overall drive diameter is shown in Figure 6. The estimated diameter is not the traction radius, but is an output of the analysis tools based on other assumptions.
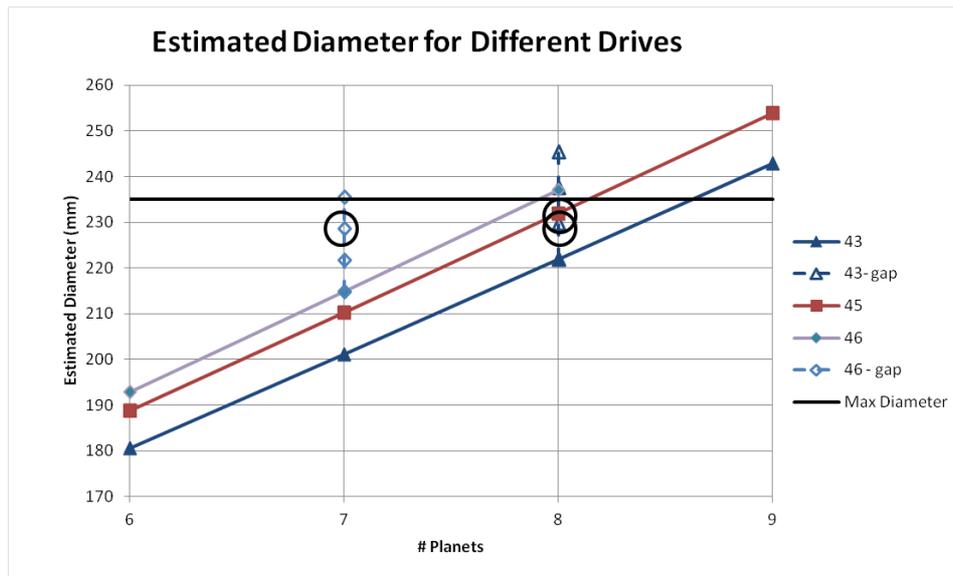
Figure 6: Example showing the estimated drive diameter iterated over number of planets and planet size. For two points, the planet gap is also iterated.

The same three points from Figure 5 are circled in Figure 6. These three points are below the maximum diameter and within the required L10 life. They warrant close scrutiny in the selection process.

Selection

Using the iterative process, several configurations are determined and the output variables are used to recommend one or more sizes for detailed study. The final recommendation of a drive size is based on the output parameters weighed with practical considerations. Results from the analysis such as overall efficiency or size are considered along with outside factors such as the level of desired risk and expected manufacturing cost. Each sizing study is different and tradeoffs are usually required.

The analytical tools described in this paper enable engineers to quickly study a large set of geometries and architectures and provide trade off matrices for the desired outputs versus the control variables.

V. Conclusion

The selection of core drivetrain technologies and system architectures requires meticulous analysis to benchmark a range of options against a set of application-specific requirements. This paper includes an overview of a process and tools developed for this analysis. Several key metrics are included for comparing the value of different drivetrain architectures, with a particular emphasis on efficiency, shift quality, and most notably torque and power density. It is recognized that differentiating technology and unique benefits should be measured against the "cost" they require from the overall system as either actual cost, size or weight. Obviously, the greatest value is defined by the ability to transmit higher torque and power levels efficiently with the lowest cost, lightest weight and smallest package space required.

FTI has developed a unique System-V process for developing new drivetrain technology that uniquely aligns requirements with validation throughout the development process. A method is described for analyzing a given drivetrain architecture including an example with the *NuVinci* technology. As a next step of this effort, FTI proposes a benchmark analysis study, utilizing the tools and processes described in this paper, to compare CVT and other drivetrain technologies as quantitatively as possible and highlight unique benefits and system costs for each.

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