Hydraulic System Modeling

Introduction

Hydraulic systems are present in most automotive, aerospace, industrial, and power generation equipment. Proper design of these systems is critical to achieving optimal system performance and component life. Czero engineers possess both breadth and depth of experience in modeling, designing, building, testing and controlling complex and high bandwidth hydraulic components and circuits including novel hydraulic valve actuation systems for automotive research, diesel, gasoline and propane fuel systems, hybridized powertrains and work circuits for on-road and off-highway applications, large oil and gas sub-sea assemblies, wave energy converters, and test equipment for aerospace components to name a few. Depending on the specific application, the simulation models may need to include wave dynamics, cavitation, two-phase flow, heat transfer and/or all of the above. Czero's extensive experience with design and modeling hydraulic systems gives our clients confidence that the necessary level of detail is modeled. This whitepaper briefly covers the generalized approach used by Czero for modeling hydraulic systems. In addition, examples of select prior projects highlighting different systems and products to give the reader an overview of some of Czero's capabilities.

Czero's Approach

Hydraulic circuits are the life blood of many engineering applications including engine fuel systems, drivetrains, power transmission, and component actuation. Often these systems exhibit complex internal interactions while the pressure dynamics within the hydraulic circuit strongly influence on the overall system's performance and stability/ controllability. Czero's proficiency in hydraulic component and system level design and analysis, coupled with our client's insights and application specific expertise, aid in determining the best modeling practices and physics which are needed to capture the desired phenomena efficiently and effectively.

Hydraulic Modeling Problem Formulation

The general approach taken when performing hydraulic analysis for our clients' projects include:

- Define the purpose of the model (for example):
    - Specific problem or failure
    - General understanding of circuit
    - Component selection
    - Controls development
    - System optimization
    - Other?
- Define the hydraulic circuit geometry, components, and operating conditions.
- Determine required model physics and level of detail for model to address desired goals.
- Select data for validation if available and desired.

Czero prefers utilizing MATLAB/Simulink as the platform for the majority of hydraulic modeling projects due to our experience with the MathWorks platform, our extensive internal library of hydraulic elements, and the ability to customize the model and components for our client's needs. Czero is also a MathWorks Integration Partner ensuring Czero remains up to date on the latest MathWorks advances and ensures our clients have access to the most effective and modeling processes available.

During the early modeling phase, decisions about the software platform, model geometry and physics are made in concert with our clients to ensure that the desired outcomes are achieved. In addition to the large library of hydraulic blocks already developed by Czero, new blocks encompassing additional physics or specific data are frequently developed and incorporated into the MATLAB/Simulink model based on the objectives of our client's specific project. The decision between using other commercially available software (such as Amesim, Modelica, or GT Suite), and designing a full model in MATLAB/Simulink, is a question of portability, compatibility, customizability, and cost. There are numerous benefits with using MATLAB/Simulink models from a co-simulation and/or controls development standpoint, but they may not be as portable or compatible with a given client's needs. Czero has prior experience in both causal (preferred) and a-causal modeling of hydraulic systems using a range of commercial modeling tools and can utilize these alternative tools when deemed necessary.

Modeling and Simulation Steps

Once the basic modeling approach is agreed upon, the general modeling process is as follows:

- Model build
- Model validation
- Simulation Runs
  - Parameter Sweeps
  - Trade studies
  - Sensitivity studies
  - Controls evaluations

During the model build, the level of detail of each component will be evaluated based on the tradeoff between accuracy needed and simulation run time. For example, if the wave dynamics in a hydraulic line are determined to be important, the discretization level needed to resolve the correct wave speed in a line will be determined. The line will also need to be subdivided to capture the location of tees, restrictions, and critical instrumentation. The discretization should be limited to only that needed to capture the relevant physics and local state properties. Further refinement will lead to larger models and slower simulation times.

When modeling hydraulic systems Czero utilizes a predominantly physics-based approach resulting in models which are generally highly accurate and predictive in nature. However regardless of the quality of modeling, there will invariably be some level of discrepancy between model results and the real world due to either second/third order effects which were not simulated, or more commonly inaccurate parameters (such as the pressure dependent stiffness of a certain hydraulic hose). Trust in model results is critical and validating the model results with measured data from the actual system is the best way to both enhance a model's fidelity and build that confidence. It should be noted that such data is often not available, especially when supporting early-stage design, in which case Czero relies on internal expertise and prior experience with evaluating the given type of system to help ensure the simulations provide realistic outputs.

When suitable data is available for validation this process often leads to model refinement in certain areas and model simplification in other areas. The validation efforts also help build a better understanding of the level of detail needed in the model build for different applications. A typical validation effort for a diesel fuel injector (where the fuel delivery and often actuation method are fundamentally hydraulic in nature) involves matching both fuel injection quantity and fuel injection rate over a set of operating conditions. The injection timing commands, and rail pressure are inputs to the model (potentially originating from other models) while flows and pressures throughout the injector are model outputs. A typical validation comparison for a diesel fuel injector is shown in Figure 1. The measured and simulated rate of fuel injection are compared for a given operating point.

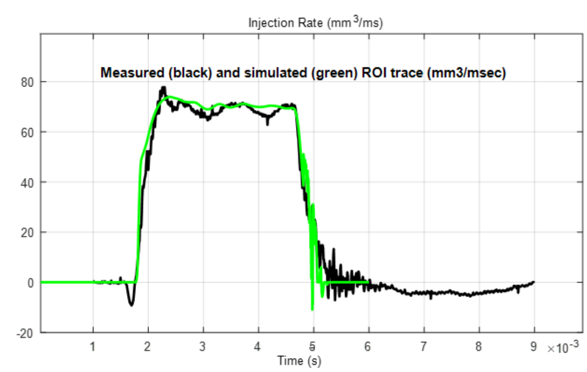

Figure 1: Injector ROI Trace Validation

If other data is available, such as injection pressure in the nozzle, it will also be compared to the model predictions for better overall confidence in the model predictions. Parameters in the model that may not be known with high confidence, for example aeration levels in the fuel that affect the fuel bulk modulus, can be adjusted to match the data.

Once confidence in the model is established (either through validation or engineering judgment based on prior experience), the main goals of simulation can be pursued. An advantage of modeling the hydraulic system is the ability to evaluate many geometric, architectural, and operational changes quickly and safely. The model also provides prediction of system states (flows, pressures, and temperatures) that may not be easily measured in the hardware. Depending on the client's needs, the model can be exercised to provide different metrics. A common analysis would be to provide a sensitivity to model to varying input parameters. This could be a standard sweep or a full factorial sweep of different parameters resulting in surface graphs describing the operational space or pareto graphs of a specific performance metric vs geometric and/or operational inputs. In many cases a client is interested in specific operating conditions that lead to system or component failures. The model can then be exercised at specific operating points, sweeping specified parameters over expected ranges to understand what are the most likely causes of the failure. These same hydraulic system models (or variations thereof) can be used for more than design exploration and failure analysis. Frequently these models are also leveraged for control system development including model and hardware-in-the-loop analysis.

Select Prior Projects

Please note Czero holds the confidential nature of our client's projects in the highest regard. The example projects described below have been approved by our clients for public release.

Subsea Hydraulic Supply Unit and Control Module

Czero was part of a team that was tasked with designing a new hydraulic supply unit and control module for sub-sea (up to 15,000') applications. Goals of this project included design of a more robust and fault-tolerant system that was modular and allowed for higher pressure operation. As part of that task, the existing hydraulic systems were modeled to determine the current performance of the system, and their inherent failure modes. Once the objectives and current failure modes were identified, Czero engineers developed a new hydraulic system architecture (fully evaluated using dynamic system models) and hardware design which was then built and tested in Czero's facility (Figure 2).

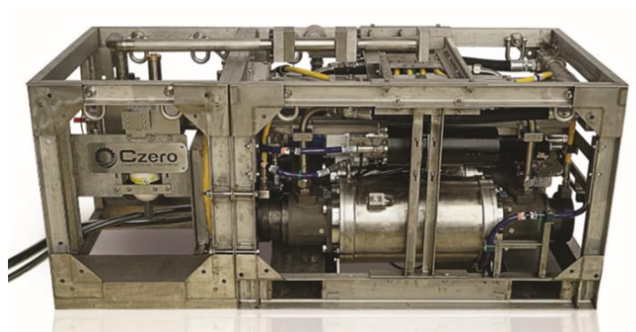

Figure 2: Subsea Hydraulic Power Supply

In addition to system level modeling and design, Czero also worked on component level design and system analysis for the sub-sea project. Specifically, Czero engineers worked to develop new valve designs optimized for this application, as well as employing various analysis tools for valve failure analysis.

Automatic Transmission Control Assembly

Czero was tasked by a client to assist in developing the hydraulic control assembly for an automatic transmission. This work included both system level analysis of the entire hydraulic control system to ensure stable operation and controllability over a wide range of operating conditions, and component level spool valve design and analysis.

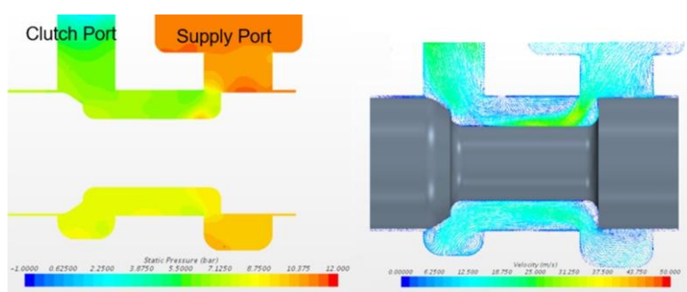

Figure 3: CFD Results for Clutch Spool

Similar to many hydraulic modeling projects where either highly detailed valve dynamics are required, or custom valves are being designed, this project required CFD to be performed on the spool valves as a function of both spool positions and differential pressures. These CFD results (example in Figure 3) were then incorporated into the dynamic system model using interpolated lookup tables to enhance the model's fidelity. In this project both MATLAB/Simulink and GT-SUITE were used to evaluate the hydraulic system.

Pump Modeling

Czero was tasked by an OEM to improve and correlate their existing GT-SUITE model of a supplier's gerotor hydraulic pump (Figure 4) in an effort to identify and address certain unfavorable operating characteristics.

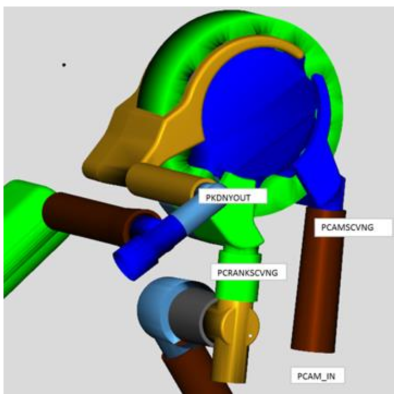

Figure 4: Gerotor Pump Discretized in GT-SUITE

Czero was able substantially improve the existing model's predictive capabilities to achieve a relatively high degree of correlation with the measurement results and used this information to suggest several likely areas for component improvement.

Hydraulic Drivetrains

Czero has developed and evaluated hydraulic drivetrains (both hybrid and hydrostatic) internally and for various clients over many years. This work has included both detailed component/system level modeling, design optimization, and power management (all leveraging dynamic hydraulic models). In one example (Figure 5) shows a comparison of the simulated vs measured pressure profile in a hydraulic hybrid transmission where a client had a NVH (noise, vibration, and harshness) issues which they needed addressed.

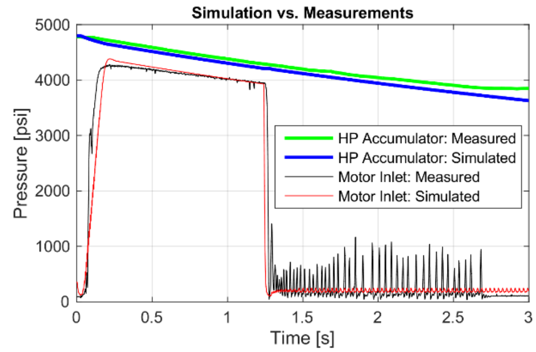

Figure 5: System Stability Analysis

The system analysis identified the root cause of the NVH as stability issues within a COTS reducing/relieving valve. To fully capture the dynamics of this valve Czero sectioned and modeled the existing valve (Figure 6) to obtain the various pressure areas, orifice diameters, spool mass, and spring forces which ultimately allowed corrective actions to be identified.

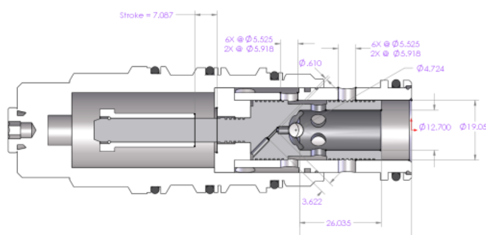

Figure 6: Cross-Section of Reducing/Relieving Valve

In addition to utilizing these hydraulics component/system models for both design and controls optimization, Czero also has experience implementing these models as part of hardware-in-the-loop transmission dynamometers for both system design and controls development purposes.

Wave Energy Converter

Drivetrains are not just for vehicle locomotion, but also for general energy conversion. Czero has worked on wave energy converter development for two clients, one utilizing a linear-electric generator, and the other which contained large hydraulic components within the power take off. For the hydraulic based system Czero developed a detailed hydraulic system model to aid in component sizing and predict transient system performance and energy recovery potential.

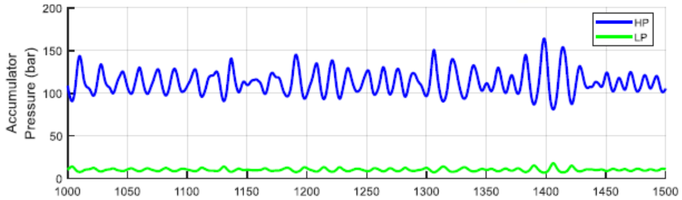

Figure 7: Wave Energy Converter - Accumulator Pressure Profile

Fuel Injectors

Czero has developed a number of fuel injectors for various clients over the years. These components are highly complex and require detailed hydraulic simulations (in addition to CFD, FEA, and magnetic modeling) to obtain the desired fuel delivery characteristics. Part of the difficulty in simulating these systems is the very small volumes and high pressures involved, along with the very short duration of operation and high degree of accuracy required.

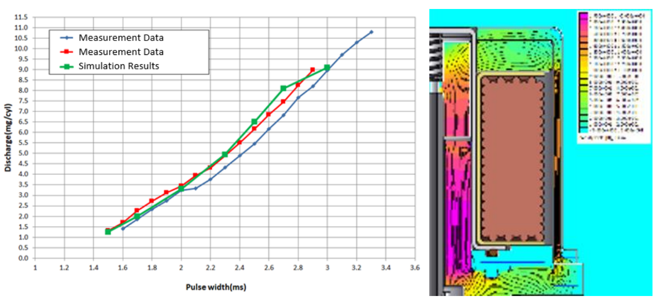

Figure 8: Fuel Injection Validation (left), Magnetic Force Modeling (right)

As an example, its critical to include the stiffness of the various metal components that experience high-pressure in diesel injectors as the deformation of these components during injection dramatically influences the amount of fuel injected. Figure 8 (left) shows a comparison of the fuel injected by an injector vs measurement data as a function of pulse width, while the right figure shows an analysis of the injector solenoid's magnetic force which is also incorporated into the dynamic model using a lookup table.

How Czero Can Help You

Czero's focus is on helping companies solve the toughest engineering problems through deep expertise, creative thinking, and sophisticated analysis tools. Turn your ideas and design concepts into reality with the help of our product development expertise.

Company Profile

Czero develops innovations for the automotive, defense, oil and gas, renewable energy, and clean technology industries.

Our award-winning engineers have 25+ years of experience working with innovation labs, startups, government agencies, and large OEMs in North America, Europe, Asia, and Australia.

Relative to hydraulic system modeling Czero currently has four experienced engineers dedicated to this type of analysis, with another four engineers functioning as design engineers but with prior experience in hydraulic system modeling. Multiple Czero engineers have 20+ years of experience modeling hydraulic systems, while two of the engineer's doctoral work involved significant design and evaluation of fluid power systems.

Concept-to-prototype engineering R&D

Specializing in early-stage research and product development, Czero helps companies solve tough challenges and transform concepts into robust, tested prototypes of new technologies.

Services

- Mechanical design & solid modeling
- Dynamic modeling & simulation
- Finite element analysis (FEA) & computational fluid dynamics (CFD)
- Embedded controls
- Prototyping and testing
- Program & project management

R&D Specialties

- Advanced machine design
- Mechanical, electromechanical and electrohydraulic systems
- Energy conversion, efficiency, and recovery
- High-bandwidth hydraulics
- Automotive powertrains
- Heavy-duty trucks
- Fuel systems
- Valve systems
- Hybrid vehicles