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Computerized Simulation Optimizes Hydraulic Drive System Design and Performance

Paul Stavrou
Bosch Rexroth Corporation

HEAVY MOVABLE STRUCTURES, INC.

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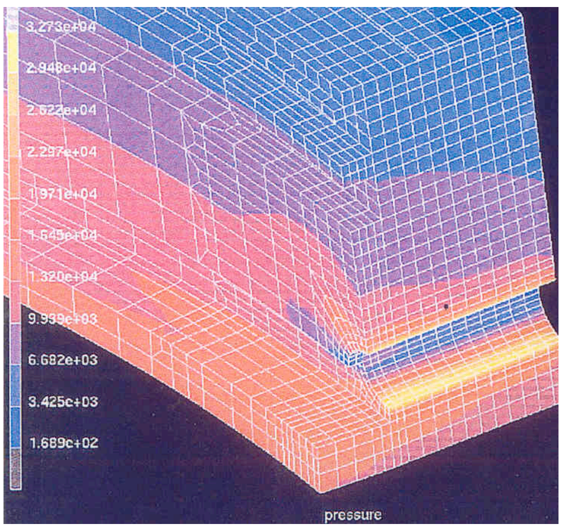
Historical Background of Simulation

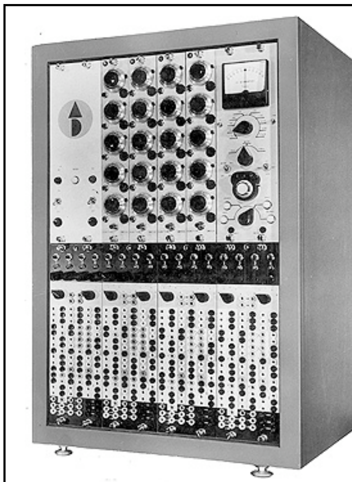
For many years, it has been the practice in many engineering disciplines to use numerical simulation, or as we call it today, Computer Simulation, to predict the operational performance of a component or system design. This technology progressed rapidly in the 1970's and 1980's with the proliferation of higher performance computers and workstations in industry. Key sectors that led the simulation revolution were electronics, aerospace and mechanical structures. In particular, the mechanical structures simulation, known as finite element analysis, while theoretically conceived in 1943, started having a major industry impact in the 1980's, as the cost of the required computing horsepower became affordable.



Typical Finite Element stress analysis

Oil hydraulics, as used for machine and equipment drive and control, became a common technology in the 1940's. Through much of it's early history, estimating the performance of a hydraulic drive system was limited to static and simple dynamic models, based on differential calculus. Simulation of hydraulic systems was often based on analog computers, which in the 1960 could more quickly predict the performance of these systems. Multiple non-linearities that exist in many elements of the hydraulic system, as well as poor characterization of various components made numerical modeling a difficult task for the capabilities of period computers.

During the 1980's and into the 1990's, as the use of computer simulation and FEM expanded, there was lack of hydraulic system simulation in the market. As a result, simulation of hydraulic systems was limited to specialized niches, in particular in the aerospace industry, where hydraulics performs many flight safety critical roles. In that industry, the need to predict exact system performance was critical. However in the general industrial world, hydraulic simulation and modeling was a rare technology.

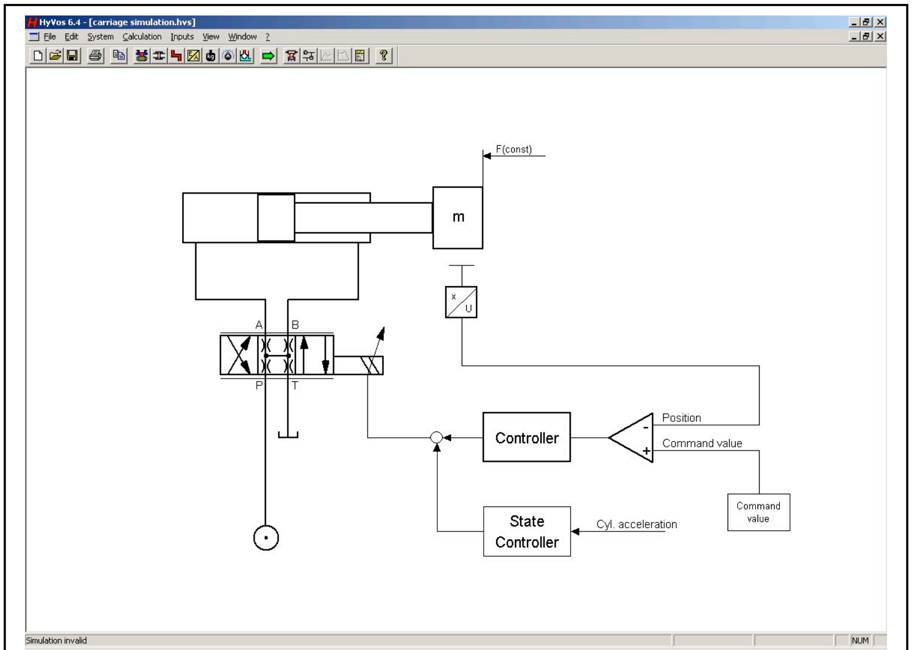


Analog Computer

Development of the First Simulation Tool by Rexroth - HYVOS

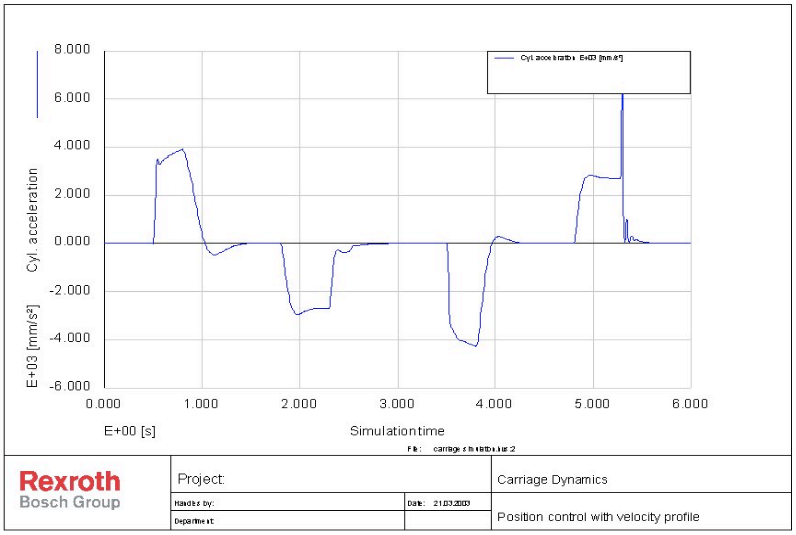
It was during that period that The Rexroth Hydraulics organization developed a family of hydraulic simulation tools. Working along with Universities and Institutes, several high fidelity simulation programs were developed. While nearly all dynamic simulation programs use known numerical integration as the basis for calculation, Rexroth focussed on the inherent complexities and non-linearities of the hydraulic elements. Backed up by extensive laboratory and field testing for comparison, the component model elements were "fine-tuned" until the simulation results produced a faithful view of how a system would behave when the actual hardware was commissioned in the field. This enabled the system designers to avoid the costly field redesign and retrofit of systems that did not meet required performance and/or stability criteria.

The first commercially used simulation developed by Rexroth is called HYVOS. HYVOS allows a user to simulate hydraulic systems when a 3 or 4 way valve is used to control a hydraulic cylinder. Each defined system element can be defined and configured to match the performance,



HYVOS Simulation

characteristics and range of products available to a designer today. Results show the motion state variables (position, velocity and acceleration), hydraulic parameters of flow and pressure and the dynamic conditions of the control valve. The results from HYVOS provide a detailed and highly accurate picture of how a system will operate. It must be cautioned, however, that the extensive range of parameters needed to define system components, can lead dangerous conclusions, if the parameters are not well understood or known. The computer age phenomena of "garbage-in garbage-out" applies to computer simulations, and when the values required for parameters are not understood, or values are "guessed", good systems can be made to look bad and bad systems look good. This can give a sense of false security when a system meets the required performance criteria in simulation, but fails in practice. Simulation is not a substitute for a detailed knowledge of the underlying engineering.

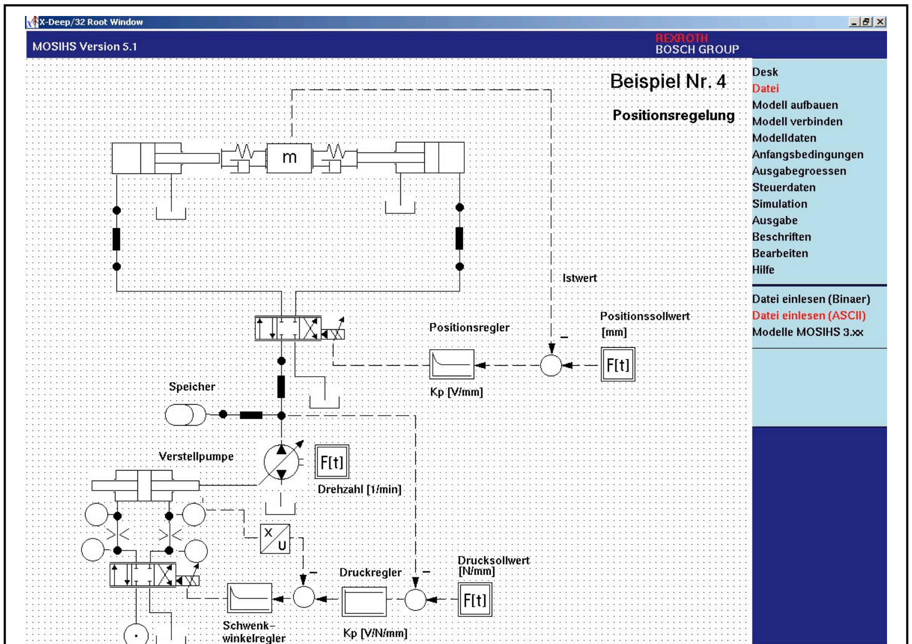


Results of Hyvos Simulation

Complex Hydraulic Simulation Tool - MOSIHS

For all of its benefits, HYVOS presented designers with a significant limitation. While a large percentage of hydraulic systems fit the circuit model of HYVOS, many other designs required the use of a variety of additional valving in the operational portion of the circuit. Valves such as counterbalance valves, load holding valves, safety relief valves and others, which could affect the dynamic performance of the system, could not be considered in a HYVOS simulation due to the program's fixed hydraulic structure. This resulted in the development of Rexroth's next generation simulation software, MOSIHS (pronounced Moses). MOSIHS allows the user to build a hydraulic system schematically. The resulting system can then be simulated. With a library of standard valves and components, the engineer can design a system of any size and complexity and determine how it will behave. Each component can be parameterized to match the design requirements. An extensive array of electronic control and mechanical components are available in MOSIHS to replicate the real world application.

Another powerful feature in MOSIHS is the ability to build "subsystems", or subroutine-like blocks. This provides a means to include components that do not exist in the standard component library that is in the program. One example is that of a servo controlled hydraulic pump. By taking a variable displacement pump and controlling the displacement with a hydraulic cylinder, the elements of a servo controlled pump are seen. Adding the servo or proportional valve and an electrical position transducer (feedback), the pump is a complete element. This group of parts can be contained in a "sub-block" and treated as a single component in the overall simulation. Nearly all hydraulic systems can be modeled and accurately simulated using MOSIHS to determine the real world performance



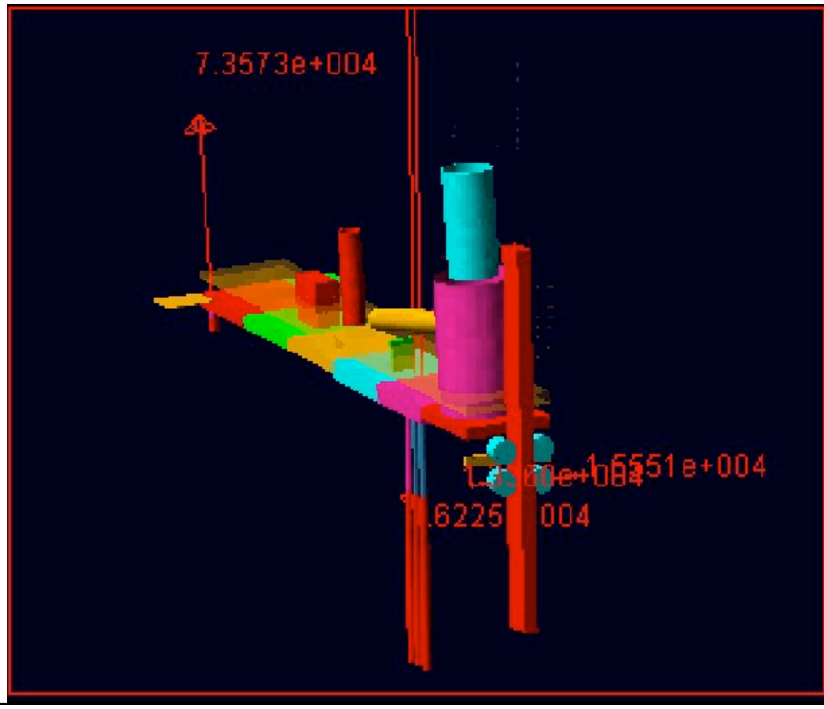
MOSIHS Simulation

Another limitation that became apparent in certain systems is the interaction effects between a hydraulic system and the dynamics of the mechanical system that it is driving. As is well known, all mechanical systems and structures exhibit dynamic behavior that may be in the area of response that is required for operation. In other words, a structural flexibility or resonance could exhibit an undesirable effect on the end process. With the ability of a hydraulic drive to apply high input forces with high dynamics, the chance that a mechanical system is dynamically excited is high. This can result in 2 or more resonant elements being coupled and driven in potentially destructive operating modes. If the mechanical resonance is close to the desired dynamic operating envelope, then the characteristics of the system can deviate widely from what was expected, due to large variations in apparent mass and compliance.

Modeling of Combined Mechanical and Hydraulic Systems

If a system with known mechanical resonances is modeled, it is possible to include the known resonant modes in the model. With MOSIHS, one or more spring-mass-damper systems can be included in the hydraulic simulation to try to predict a system's overall performance. This works well when a known mechanical resonance is well characterized and dominant. Normally in more complex structures, such as bridges and trusses, there are many resonant modes that are not easily characterized as simple lumped elements. These mechanical systems are typically modeled using kinematic/dynamic modeling programs such as MSC Software's ADAMS. Using ADAMS, an engineer can build a graphic based model of a complex mechanical system. Weight, flexibility and other parameters of each element can be defined to generate an accurate model of the mechanical system. The ADAMS model can then be driven with inputs from elements such as hydraulic cylinders, and the effect on the mechanical system can be seen. But ADAMS can not include the complex dynamic characteristics of a hydraulic drive, so the problem of "system interaction" still remains.

Starting in the mid 1990's, Rexroth started a development with ADAMS engineers to connect MOSIHS to ADAMS. The ADAMS-MOSIHS coupling bridges the gap between the two



Example of ADAMS-MOSIHS Coupled Simulation

simulations to offer accurate results with complex mechanical-hydraulic systems. When coupled, for every integration "time slice", MOSIHS passes the cylinder state, or its acceleration, velocity and position, to ADAMS. ADAMS in turn uses that data as an input for its model for the next calculation. The results of the ADAMS calculation passes the resulting state variables back to MOSIHS as starting points for the next "time slice" calculation. The output of the coupled model offers the most accurate results for mechanically complex hydraulically driven systems.

FEM software is another tool available today to designers. While not directly used in hydraulic drive simulation, it does offer better characterization of mechanical components and structures. The results of FEM are often used to better quantify elements in ADAMS, making the overall model higher in fidelity.

Benefits of Simulation Tools

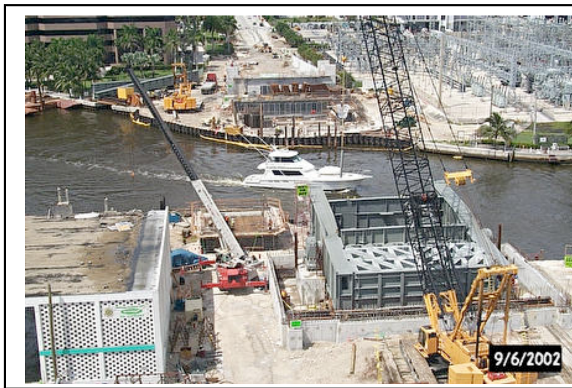
Having the above tools available when designing a system can provide keen insight in circuit design and component selection. Once set-up, the designer can perform any number of "what if" scenarios on the system. One test condition could be varying loads. An example we will see is that of wind gusts on an open or opening bridge leaf. Since hydraulic oil is a compressible working medium, large cylinder volumes can result in significant system compliance. A steady state or gusting wind can cause inconsistency in the movement of the bridge leaf. Higher than expected forces and accelerations resulting from an instability may require changes in the mechanical design in order to account for these factors. Simulation allows the designer to predict the effect of a range of wind forces, and estimate worst case conditions.

Another condition that is of interest to designers is emergency stop or power loss conditions. Any number of conditions may result in the immediate switching of hydraulic valves in a large hydraulic drive. This is sometimes a defined "E-Stop" condition, but conditions, such as loss of electrical power, may cause an "ungraceful" shut down that was not considered in the primary design criteria. In these cases, valves may shift out of normal sequence, and the hydraulic drive may behave in an unexpected manner. While a properly designed system will not cause the load to be dropped, higher than normal pressure spikes may be present, and require additional hydraulic valves to accommodate these conditions. Using simulation, the sizes, response, flow rates and settings of these safety valves can be determined and included in the final system design. These “E-Stop” cases are normally simulated for a number of conditions to characterize the envelope of system operation. Variations in velocities and loads can provide a wide range of operating conditions that the system must accommodate safely.

Other uses of high fidelity hydraulic drive simulation is in determining the best methods to design systems that are by nature marginally stable. By their nature, hydraulic drives use fluids that are compressible. When combined with the mass of the driven load, a mass-spring system is present, which has a natural frequency or resonance. Additionally, many of the improvements in modern hydraulic components, such as reduced leakage and better seals, combine to reduce the available damping in the drive system. The result is dynamic system that can have low stability margins in some systems. The function of these systems can result in sub-par performance, equipment damage and even risk of injury. Instability in the drive can also cause shorter than expected life in the machinery, due to higher than expected forces and premature fatigue failures. It is therefore desirable to be able to predict the risk and magnitude of drive instability during the design stage. If simulations indicate that stability may be marginal, changes in the drive’s configuration or the addition of passive or active damping schemes can be included to insure proper system operation.

Examples

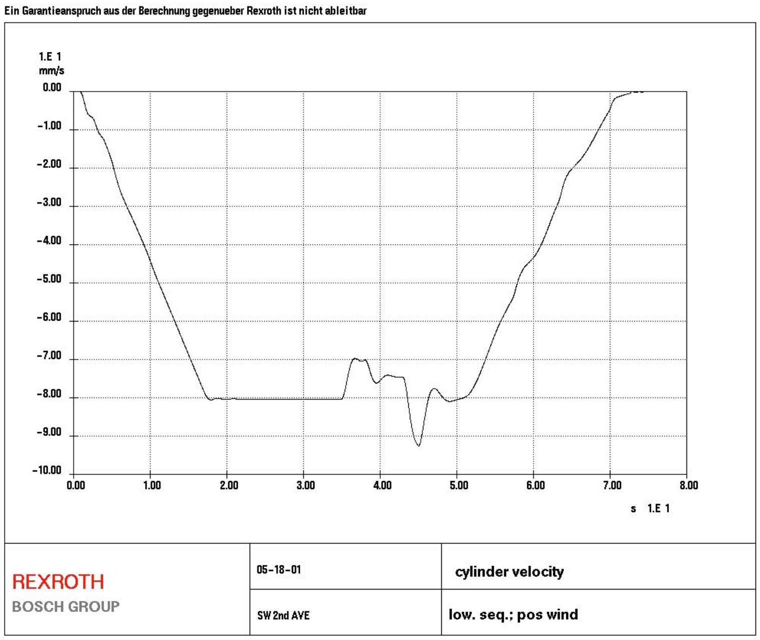
Southwest 2nd Avenue Bridge, Miami, FL



2nd Ave Bridge under construction

The Southwest 2nd Avenue bridge, under construction in Miami Florida, is believed to be the second longest span bascule bridge in the world. As such, the hydraulic drive responsible for raising the leafs of the bridge will operate under more extreme conditions than typical in other bridges. Consequently, Bosch Rexroth was required by contract to guarantee the design and verify system performance prior to construction. Very low hydraulic cylinder-mass natural frequency is a result of the high mass bridge leaf assembly and its associated counterweight. The low natural frequency determines the limits of the allowable motion-time envelope and can cause excessive pressure and forces if the hydraulic drive is not controlling properly. Additionally high wind load forces can adversely effect the counterbalance circuit elements that safely hold the load while lowering. Lastly with such a large moving structure, emergency stops must not cause excessive structural loads.

The SW 2nd Avenue bridge was modeled using the Bosch Rexroth MOSIHS simulation software. MOSIHS was chosen due to the complexity of the hydraulic counterbalance circuitry. This aspect of the circuit was required due to the high oil flow requirements of the large cylinders combined with the high ratio fast-to-slow speed range needed to softly decelerate and stop the lowering leaf. MOSIHS was used to simulate normal operating conditions, the effects of wind gusts and a variety of emergency stop cases. Minor circuit adjustments were made, and final results confirmed safe and proper operation. Testing during startup has further confirmed the accuracy of the simulations.



Simulation of Wind effect on bridge motion

Boeing Fixed Pad Erector, Cape Canaveral, FL

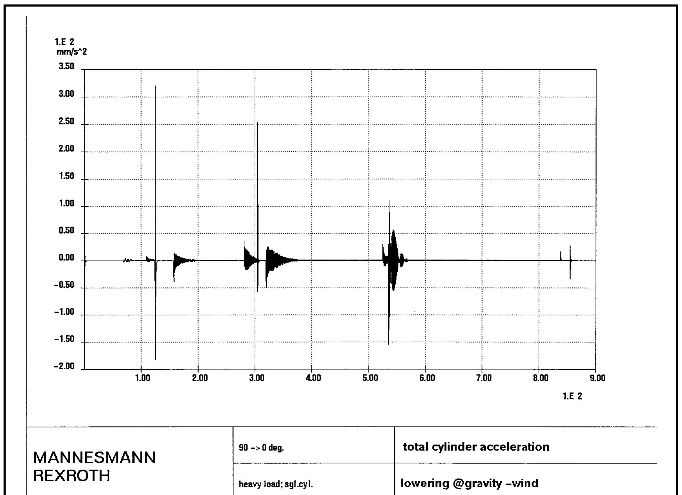
A large movable truss was designed for Boeing for a new rocket launch pad facility at Cape Canaveral. As part of Boeing's new Delta IV launch complex, the truss is used to lift assembled and tested expendable launch rockets from a horizontal transport vehicle to 90 degrees on the launch pad. As part of the cost savings design of the Delta IV, the rockets are "stacked" or assembled horizontally in a large environmentally conditioned hanger-like building. The completed vehicle it transported to the launch pad on a multi-wheeled transporter, where it must be lifted to a vertical position on the launch pad. Lifting the 200+ foot non counterweighted structure is performed by a Bosch Rexroth provided hydraulic drive. Utilizing 2 cylinders for redundancy , the 71 foot stroke 4 stage telescoping cylinders, each nearly 1 meter in bore diameter, raise the structural truss and the attached rocket to 90 degrees, for attachment to the pad. Critical design factors were lift time, to minimize rocket stresses during the lift; and limiting acceleration forces applied to the vehicle, that are not in the normal plane of the rocket's travel. Since telescopic design cylinders were required to accommodate the combination of long working stroke and short collapsed length, concerns were focussed on the start-stop accelerations that naturally occur as a telescoping cylinder transitions through its stages. Additionally winds, which can cause large variations in overall cylinder load, needed to be evaluated as an operational factor.

Delta IV leaving the assembly building

For simulating the Fixed Pad Erector, the coupled ADAMS-MOSIHS simulation software was used. Adams was well suited to model the distributed mass truss structure and the geometry of the cylinder forces applied to the truss. Likewise MOSIHS was able to handle the complex hydraulic circuit, which had several active hydraulic components to provide redundant, fail-safe load holding capability for each of the two cylinders. There were also a number of additional hydraulic valves needed to control and limit pressures in order to meet stringent U.S. Air Force complex safety requirements.

Delta IV being erected on the launch pad. Note the 2 black telescoping cylinder rods to the left.

Simulations indicated an overall acceptable performance. The simulation was then used to determine the optimal velocity profile for the lifting cycle in order to minimize the cylinder stage transitions, while meeting overall lift time requirements. To minimize the accelerations during transitions of cylinder stages, the velocity is ramped to a slow speed as the stage change is reached. The cylinder movement then stops as the system pressurizes the large oil volumes to a higher pressure consistent with the area of the subsequent cylinder stage. Once the new pressure is reached, the cylinder starts moving again, and is then accelerated back to a nominal velocity. Simulation allowed a range of accel and decel ramp rates, as well as the stage impact velocity to be tested. A set of running parameters was determined that kept the acceleration forces within specification while meeting overall time to lift requirements.



Rocket lift simulation showing accelerations

Additional simulation was performed to confirm valve sequencing and settings needed to meet acceleration specs during a range of e-stop and fault shutdowns. Lastly the effects of winds were examined to assure that the truss would operate within specification while influenced by a range of wind forces and direction.

Anderton Boat Lift, Cheshire, England

Originally built in 1875, the Anderton Boat Lift used two water filled caissons to raise and lower small boats and barges between a river and a canal which have an elevation difference of 50 feet. The system would allow the watercraft to be transported between these waterways without unloading, thus speeding their transit. The original system used water hydraulic rams and lowered one caisson while raising the other. Water was pumped from one ram to the other, with the 250 ton weight of the water filled caisson acting as a counterbalanced for its partner. The only pumping force needed was to overcome the weight differences of the two caissons and the watercraft.

The boat lift was rebuilt in 1908 to utilize an electric motor drive along with a system of cables and pulleys. The balanced system concept was replaced with 255 ton cast iron counterweights for each caisson.

Boat Lift ship entry side

In the 1990's it was decided to rebuild the now unused boat lift as a historical tourist attraction. The decision was made to return the operation to the balanced hydraulic system, but using oil hydraulics instead of water. Bosch Rexroth was contracted to provide all of the required hydraulic equipment for the rebuild. There was concern with the operation of the system due to the long cylinder stroke and high lifting masses. This results in a low natural frequency, which can limit operational performance. Additionally there was concern that the low frequency oscillation of the water-boat "bounce" in the caisson might interact with the hydraulic drive dynamics.

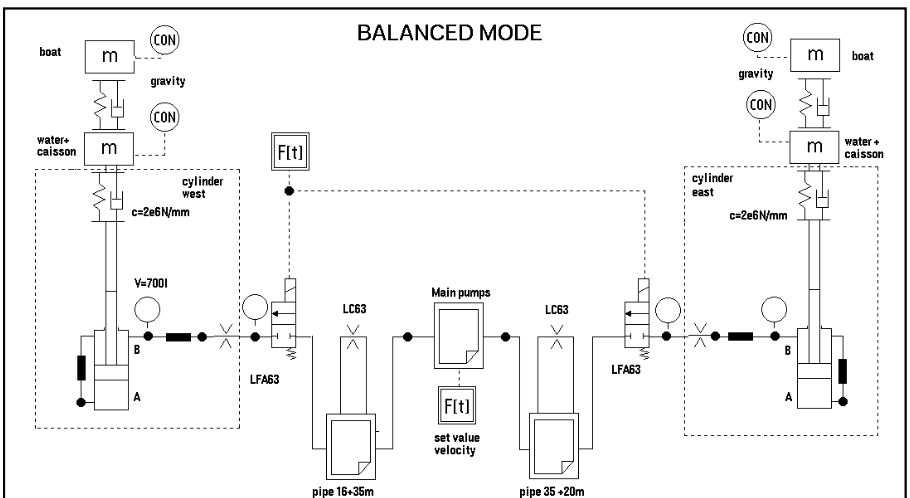
To increase model fidelity, a finite element model of the lift cylinder's 50 foot long piston rods was used to determine it's stiffness characteristics. The results of the FEM were used to make a discrete flexible model of the rods in ADAMS. This allowed the ADAMS model to simulate the effects of the rod's flexibility coupled to the moving caisson mass. Coupled with ADAMS, MOSIHS was used to model the hydraulic system, as well as the dynamic aspects of the water-boat "bounce".

Simulation confirmed the ability of the system to perform as needed. During commissioning, the operational performance became severely limited, as unexpected low frequency oscillations occurred during movement. Operational velocity had to be limited in order to prevent the undesirable oscillation. This caused the lift cycle times to be many times longer than desired.

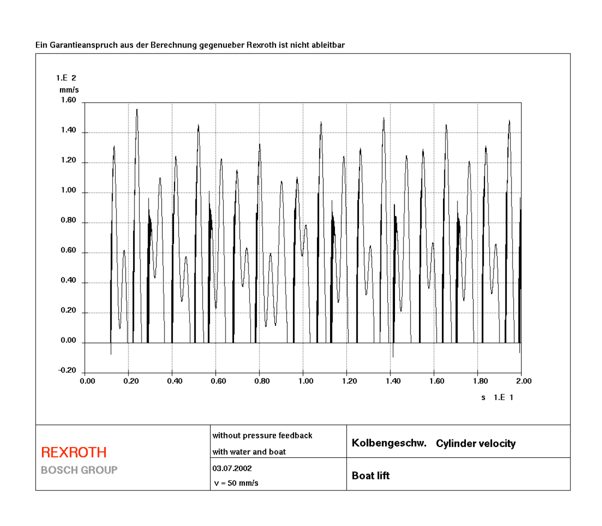
Caisson cylinder during construction

An on site investigation revealed that the breakaway and running frictions in guide column bearings was much higher than expected. When simulated, the measured friction valves caused the system to oscillate, as had been seen on site. A number of traditional damping schemes, to minimize the stiction induced oscillation, could not be used due to the size and scale of the system. Bosch Rexroth engineers proposed using an electronic based active damping system, which would modulate the servo controlled pumps, to dynamically damp the oscillations. Since active damping had never been used in a design of this type, simulation was used to validate the use of this technology. The damping algorithms were put into the simulation and the results confirmed the complete removal of the oscillation, while operating at design speeds.

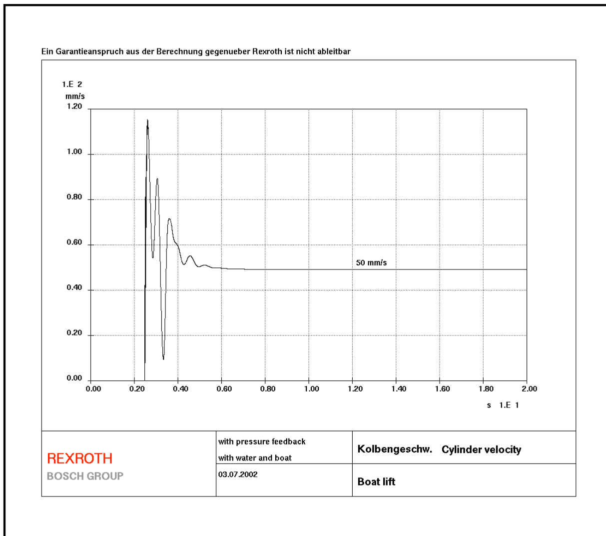
The electronics controller was added to the system, and full speed stable system operation was achieved within 1 day.



MOSIHS model showing complex hydraulic configuration



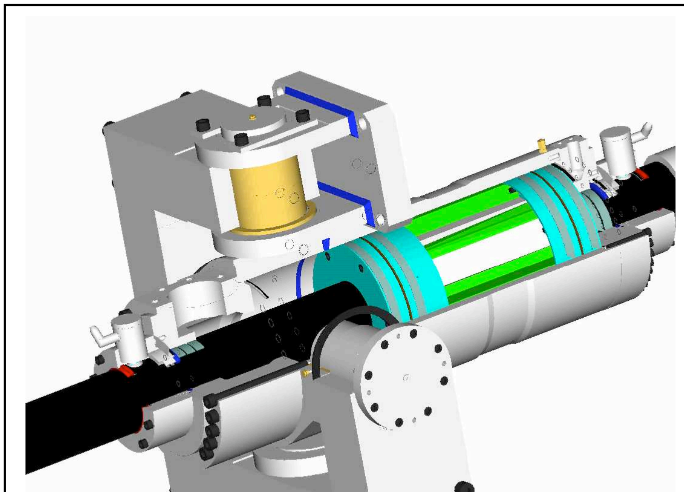
Velocity without active damping



Velocity with active damping

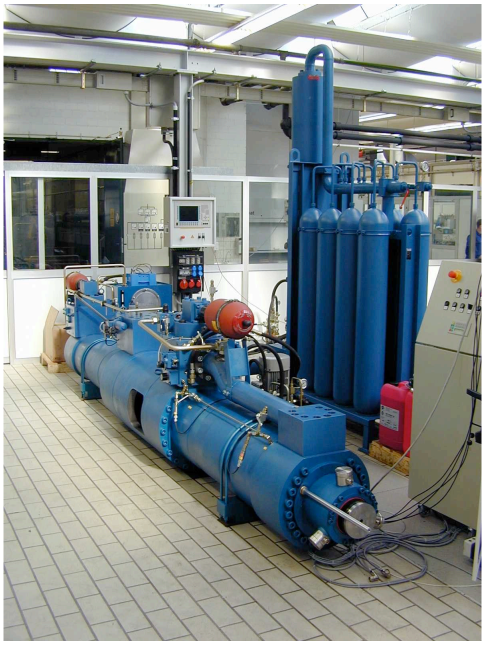
RoSafe Brake

In many areas of the world, it is often most practical to use ferries to transport vehicle traffic across bodies of water. Most vehicle ferries are designed as drive-on drive-off, or Roll-on Roll-off, ships. These "Ro-Ro" ships utilize loading and unloading vehicle ramps that are lowered into position when in use. The lifting and lowering of the ramps typically uses cables, chains or directly connected hydraulic cylinders. A risk of failure is present in each of the designs if one of the actuating/holding members breaks. The results of such a break would be to drop part or all of the ramp. This could lead to loss of equipment, vehicles and lives. Back-up holding elements are sometimes employed that rely on mechanical links that come into play after some free travel. One example is a second chain that would normally sit slack and allow a limited degree of overtravel. The backup links are often a compromise due to the variation in ramp positions resulting from changes in tides and boat loads. This can allow significant ramp travel before the back-up link stops a falling ramp. This overtravel not only reduces the effectiveness of the back-up stop, but more importantly it can allow the ramp to gain considerable velocity by the time the back-up halts the ramp's travel. The resulting energy of the accelerating ramp may cause the back-up to fail or may overstress the ramp's structure when it is abruptly stopped.



RoSafe Rod clamp assembly

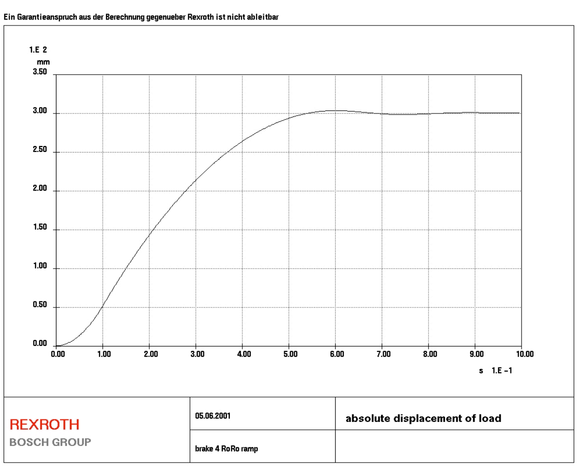
To address these limitations, Bosch Rexroth designed a cylinder based "catch" system for Ro-Ro ramps. Utilizing a smooth rod that attaches to the ramp, similar to a hydraulic cylinder rod, the



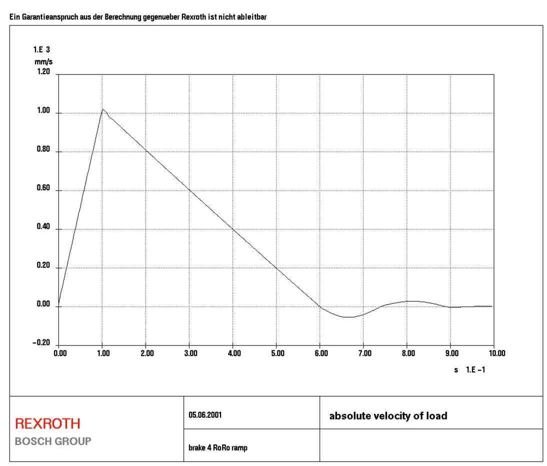
RoSafe lab test setup

RoSafe acts like a movable hydraulic shock absorber. The rod passes unattached through the RoSafe assembly and is free to travel as the ramp moves during normal operation. Within the RoSafe unit, a smooth column clamp is connected to a short stroke hydraulic piston. If an intelligent limit switch module detects uncommanded or differential motion across the two corners of the ramp, a fail safe electrical signal allows the spring actuated column lock to grab the rod passing through the RoSafe. Motion is then decelerated to a stop using the hydraulic piston that is attached to the column clamp. When operated, the RoSafe is completely passive, not requiring electrical or hydraulic power. An adjustable valve connected to the cylinder allows the decelerations forces to be set to match the ramp weight, minimizing the forces on the ramp as it is stopped in an emergency condition.

In order to design the RoSafe actuator, a wide range of variables were considered. Once a design was finalized, operation over a range of loads and speeds was examined by simulating the RoSafe system. A wide range of mechanical geometries, loads and speeds were simulated and provided the basis for safety agency acceptance of the functionality and performance of the RoSafe. Later, lab tests confirmed the fidelity of the simulations and provided a basis for qualification. Additional simulations confirmed the RoSafe performance on a number of proposed installations.



RoSafe simulation showing travel during braking



RoSafe simulation showing velocity during braking

Conclusion

From these examples, it can be seen that the ability to accurately simulate a wide range of hydraulic drives can increase the success of many applications. Confirming design concepts, looking at worst case conditions and validating modes of operation can reduce operational and financial risks. Being able to verify performance criteria during the proposal and design stages can result in higher performing and more cost effective designs. Additionally being able to "what if" the design and assure that emergency and failure modes will not cause an overall system failure permits the owner to be confident that the purchased product will not pose undue risk to man and machine.

Paul Stavrou
Manager – Technology Marketing
Bosch Rexroth Corporation
Bethlehem, PA