Precise Hydraulic Controls

Help Create Spectacular Special Effects for the World’s Largest Underwater Moveable Stage

Hydraulics has long had a role in theatrical productions where heavy stages and scenery need to be moved smoothly and safely. One of the most recent projects to be completed is also one of the most spectacular. The House of Dancing Water show in Macau’s City of Dreams complex, an artistic vision of Franco Dragone, the originator of Cirque du Soleil, uses eight underwater platform sections on hydraulic lifts that make up the main stage platform (Fig. 1). The platform sections can be raised and lowered to create different stage effects in and above a pool of water, which, at 3.7 million gallons, is the largest commercial pool in the world. The lifts can be moved independently, or they can be instructed to move in lock step to create a virtually unlimited set of effects. There are three additional stage entrances called vomitoria and associated hydraulic lifts that are also independently controlled. These three vomitoria can be moved in concert with adjacent main platform sections to create a seamless stage floor.

Each platform section is moved by four hydraulic cylinders mounted symmetrically to the bottom of the lifts. The cylinders are controlled by remote valves located in the basement of the theater, beneath the pool. The cylinder rods come out of the floor of the pool (Figs. 2 and 3). Due to the construction of the theater, which incorporates multiple water-holding and dry enclosures (Fig. 4), the valves and cylinders are located a distance apart, with a huge amount of hydraulic oil (approximately 70 gallons) in the plumbing between each valve and its cylinder. The capacitance in the system resulting from the compressibility of this much oil made for a difficult hydraulic control challenge. An added challenge was due to the fact that the multiple rods that move each stage platform have to move in lock step in order to avoid twisting or jamming the structure.

Projects of this magnitude frequently involve the efforts of many companies working together to build the system and solve the problems. Controlled Motion Solutions (Comoso) of Santa Ana, Calif., an integration firm with expertise in putting together complex hydraulic systems, was hired by Handling Specialties of Grimsby, Ontario, Canada to provide the hydraulic power unit (HPU), hydraulic cylinders, plumbing, control systems, and enclosures and to perform full integration of the system into the theater.

Specifying The Components

To control the hydraulics (50 total axes of position control: 32 main platform axes and 18 vomitoria axes), Comoso selected RMC150 electro-hydraulic motion controllers from Delta Computer Systems, Inc., Battle Ground, Wash. Each controller (there are eleven in total) controls the hydraulic cylinders that operate one lift. To select and integrate the control hardware and tune the entire system, Comoso involved Fisher Technical Services, Inc. (FTSI) of Las Vegas, Nev., a design firm that specializes in theater systems design. Comoso and their subcontractor FTSI had personnel onsite for over a year to support the installation and integration of this large system into the theater.
Comoso engineer Matt Schoenbachler designed the system. His team utilized AutoCAD Inventor to build a CAD model of the entire system including the thousands of hydraulic components involved, and worked with Parker to design a custom cylinder for the main platforms. Each main platform cylinder was eight inches in diameter with a seven-inch rod and 325" stroke (27 feet). The long stroke is required to allow the platform lifts to carry large scenery elements, including a pagoda and a 26-ton ship, which are placed on the lifts under water so that they can be raised out of the water as a magical special effect. The cylinders are fed by Parker servo-quality proportional valves. To provide a measure of its position, each cylinder was instrumented with a 27-foot-long magnetostrictive displacement transducer manufactured by MTS Sensors. The HPU that Comoso designed for the project (Fig. 4) included seven electric motors totaling 2100 horsepower driving twenty-one (21) Parker pumps with a capacity of 1694 gals/minute, working from a 4500-gallon fluid reservoir.

Closing The Control Loop

Closed-loop motion control is needed to coordinate and synchronize the positions of the stage sections and to compensate for the compressibility of the large volumes of hydraulic oil that are used. Comoso’s engineers understood that a simple PID control algorithm would be difficult to tune in this application. The gains could not be increased without causing the system to oscillate, and the system performance would be low. Even with low gains, starts and stops could cause the system to oscillate; the oil would act like a large spring due in large part to the distance between required between the valve and cylinder. The PID algorithm in the motion controller needed to be augmented with an additional factor in order to avoid the oscillations.

Nathan Cross of FTSI performed the tuning on the system in consultation with Dennis Ritola, Delta Computer Systems engineer. The oscillation problem was avoided by adding a second derivative term to the control equation to damp out (reduce) the effects of changes in acceleration of the system (the rate of change of acceleration is sometimes called “jerk”). The control equation then became a PID+D2. Introduction of the second-derivative gain can create control problems due to the discrete-time sampling and digitizing of the feedback by the control system. The second-derivative gain requires that the measured position feedback samples be converted to measured accelerations. This process “creates” noise in the measurements and the resulting control output. To cancel the output noise effects, Ritola recommended a low-pass filter to the control output that drives the valves. This stopped the control output noise and allowed the control axes to be properly tuned.
cess was finished, the stage platforms moved and positioned smoothly with no oscillations.

The motion of the four cylinders on each platform needs to be synchronized to ensure that they all move by the same amount, to avoid racking of the platform frames and keep the platforms perfectly flat at all times. In fact, the system specification dictates that the extensions of the cylinders operating any lift never differ by more than 5mm dynamically while moving at a rate of four inches per second, with all eight ramps moving simultaneously. Normally, this may not sound like a tight tolerance, but one must consider the huge volume of hydraulic fluid to be moved in order to move the platforms at the rate of four inches per second (the platform surfaces are fitted with a pattern of holes to help them drain and move through the water quickly). Additionally, as the lifts break the surface of the water, the motion controllers must properly control the valves as the load curve dramatically decreases as the lift floor leaves the water.

Synchronizing The Motion

To meet the requirement for coordinated motion, the Delta controllers support a special synchronization function that allows some or all of the axes that the RMC150 controls to be configured as slaves, under the control of a master axis or a master input coming from an outside control source. In the case of the Dancing Water system, the motion of each lift cylinder is tightly controlled by the RMCs that are slaved to follow commands from a master PLC. The

Fig. 3 (Top) Because of the structure of the theater, the plumbing between the valves and cylinders in the Dancing Water theater can contain as much as 70 gallons of hydraulic fluid.

Fig. 4 (Left) 3D CAD drawing of the hydraulic power unit developed by Comoso.
MTS transducers provide the position information for each cylinder, and the Delta controllers close the control loop by sending precise commands to the proportional valve. Mike Wardle, an application engineer from MTS, worked with Delta to ensure the long, 325” MTS probes worked well with the fast, real-time updates that Delta RMC Controller used to deliver high-performance servo control. Though each RMC150 can control up to eight hydraulic axes, each controller is handling four axes of the main lifts, or six axes of the vomitoria in the Dancing Water application.

Fisher Technical’s Navigator software package was run on a single PC that was connected to the Delta RMC controllers via Ethernet. The Navigator software controlled the entire show sequence, which included issuing commands directly to the Delta RMCs. The initial programming and development tasks were made more efficient and quicker using the motion simulator that is built into the Delta controllers. Using the simulator, any number of “what if” scenarios can be tried out, and the motion can be tuned without risking damage to the equipment or endangering workers. The RMCTools software that supports the controllers contains a powerful, easy-to-use plot manager that produces a graphical representation of parameters including comparing target with actual motion values for use in tuning positions and speeds by adjusting the gains used in the control loops.

The smooth motion and precise positioning created by the controllers operating Comoso’s valve stands far exceed the expectations of the show’s production staff. Where the initial requirement was to be able to position the stages in some simple configurations, the producers learned that through the precision and programmability of the hydraulics, more special effects were possible. “Initially, they didn’t comprehend the magnitude of what the system could do and that the system could do more than the basic requirements,” said Matt Schoenbachler of Comoso. “Because of the capability of the motion controllers and overall system design, Dragoone had the capability to add more dynamic moves for the designers to choose from in making a world-class show.”

Fig. 5. Delta Computer System’s RMC150 multi-axis motion controllers with SSI feedback were used in the House of Dancing Water to control each stage platform section. The controllers interfaced to a programming PC and a controlling PLC via a built-in EtherNet/IP interface.