HEAVY MOVABLE STRUCTURES, INC.
SEVENTEENTH BIENNIAL SYMPOSIUM

October 22-25, 2018

Technology from Offshore Jack-Up Vessels to Enhance Movable Bridges

Seth Stansbury & A.W. (Chip) Griepenstroh
Supreme Integrated Technology, Inc.

Executive Summary

Rack and pinion bascule, swing, and vertical lift bridge technology has been around for a very long time, and the design of such bridges is well documented in the AASHTO LFRD Moveable Highway Bridge Design Specifications. Likewise, offshore jacking systems for lift boats have long been in service to facilitate the raising of a ship or platform out of the environmental effects of the open seas. These systems are regulated through certification agencies such as American Bureau of Shipping (ABS) and Det Norske Veritas – Germanisher Lloyds (DNV-GL). Although all of these regulators exist for very different applications, they share the unique fact that no real agency can adequately regulate the design of the pinions and racks for the service they perform in these slow rotational, heavy lift environments. Modeling and FEA software, such as KISSsoft, is catching up to the practice of proving load and life cycle durability, but still must be manipulated manually to describe the results presented.

This paper is not just a look at the commonalities in design application problems, but also the advancements made in offshore technology and how they may apply to civil projects. These include such items as the rack and pinion design, gearbox design, hydraulic and electrical drives and brakes, sensors, power units and motor control centers, and operator control systems. Both jacking systems and moveable bridge systems work in extreme environments, and in this paper we inform engineers and operators of new technology by sharing the knowledge gained between the two industries.

Alameda County, CA - ABL-Fruitvale Tower Drive Vertical Lift Bridge over Oakland Inner Harbor.

Introduction

The purpose of this paper is to discuss technologies, as applied in the offshore jack-up vessel industry, and how they may be utilized in a cross-platform manner with the movable bridge industry and other heavy lift endeavors. As with all mechanical design, one should always consider the various technologies available to produce more robust, effective, and efficient systems that are safe and easy to maintain. It can be seen throughout numerous systems currently in service in the movable bridge industry that proven technologies (such as geared reduction drives and rack and pinion systems to produce linear and rotary motion) are a mainstay within bridge system designs. Similar methodology is prevalent within offshore systems, and more specifically, within offshore jack-up vessels, or lift boats. Although the basis of these designs is founded on some of the more basic engineering design principles, advanced analytical methods such as finite element analysis using computer aided design software have opened the door for much more in-depth investigation into the limits to which the technology can be utilized. Rack and pinion design software such as KISSsoft are known to meet American Gear Manufacturers Association (AGMA) guidance, but due to AGMA’s own admission that their specifications are not meant for slow speed, high torque, low tooth count systems, the software company is trying to catch up to proven industry workarounds. Luckily, AASHTO publishes work arounds for use by the bridge designer, but both are based on the work hardening of the larger than normal surface profile of the pinion teeth due to high surface tension and plastic deformation limited to the contact areas.

Four-Legged (Pipe Leg) Lift Boat built for Wind Turbine Maintenance

The best thing about bridge design over lift boat design is the ability to plan for counter weights in the bridge structure or the bridge towers to reduce loading. In jacking system designs, there is no opportunity to counterbalance the vessel being lifted, only to add more or larger drive assemblies to account for larger vessels.

Lift Boats

It is important to understand the general principle behind the development of offshore jack-up vessels to understand how the design and technology can be transferred to the movable bridge industry. First, a jack-up vessel can be generally defined as a buoyant vessel hull integrated with various numbers of movable leg structures that are driven down to the seabed eventually producing vertical lift of the buoyant hull. These vessels serve many purposes, but the basic principle is that if the vessel can get the appropriate seabed penetration with the movable leg structures and can then lift the hull to a vertical level away from the wave action of the ocean, then work can be accomplished on the deck and through or over the side of the stabilized vessel, independent of the constantly changing nature of the ocean surface. This provides safety to equipment and personnel descending to the ocean bottom or working on other non-moving structures. As with all mechanical systems, a multitude of methods exist to produce linear deployment of the movable leg structures (i.e. crawler systems, cylinders, linear actuators, or winch systems) to eventually lift the vessel, but for the purposes of this paper, the focus will be on the rack and pinion system and its means of control.

Three-Legged (Truss Leg) Lift Boat built for drilling and maintaining oil wells.

Jacking System Rack and Pinion Design

Looking first at the advancements of the rack and pinion drive system one should note that the basis of the general mechanical design is rooted in basic engineering principles. The movable leg structures are fitted with a custom designed gear rack within a pre-defined rack profile. This defined rack profile matches driving pinions that are installed in large gearboxes and are driven by either electrically or hydraulically driven motors. The rack and pinion interfaces are designed to ensure that the loss of any single drive assembly will not cause a failure in operation, and amounts to a minimum of four gear boxes, two to each side of the leg, when designing for loads. Due to the overall size and weights of the various jack-up vessels, drivetrain assemblies are required to generate a very substantial force which can grow rapidly based on the size of the vessel. Conventional calculation methods readily produce results that may be deemed unacceptable when looking at isolated contact stresses however these systems have been in existence for decades operating safely and efficiently. The reliability occurs despite traditional calculations due to the fact that when using traditional linear FEA techniques, plastic deformation (work-hardening) strengthens the overall mechanical properties of the gear-to-rack interface.

Drive Trains

The drive trains are like those on a bridge system. A hydraulic or electric motor is attached to a hydraulic or electric brake. The brake is attached to a gearbox that produces greater torque at slower speeds. Typically, a jacking system pinion raises the vessel at a speed of 1 m/min, limited only by the number of gearboxes employed and the vessels ability to produce a fixed amount of horsepower via its electrical distribution system. The wind farm industry is pushing this limitation and is desirous of speeds up to 4 m/min. The pinion is inserted into the gearbox and is typically supported by two bearings, one in the gearbox and one on the opposite side of its supporting leg tower. The use of two speed hydraulic motors are used where the high-speed, low-torque arrangement provides for a more rapid deployment of the legs and a low-speed, high-torque arrangement provides for a slower lifting or lowering of the vessel. This two-speed arrangement could provide for same bridge opening and closing cycle times where one pump of a dual pump operating arrangement was disabled, and a higher pressure could be demanded of the single pump. On electrical systems, VFD motors are used to control the speed and torque generated at the pinions.

Feedback Sensors

On an electrical motor drivetrain, most of the readings are recovered through the use of VFD motors and the motor control center. VFD motors can provide the number of revolutions, the speed of rotation, the motor torque generated, and temperatures inherent to the motor and brake assembly. On a hydraulic system, a Pulse Pick-Up unit on the hydraulic motor is used to monitor the number of motor revolutions and jacking speed. On either system, separate encoders can be put in place on the rack to ensure that the rack phase differential of any leg does not become out of balance and monitor the position of each leg. Additionally, load cells can be incorporated between the brake and gearboxes to determine the actual load distribution between legs. Because there is active position and load monitoring, this feedback can be integrated into the Programmable Logic Controller (PLC) to allow for the programs to adjust for variances in position and ensure that the desired position of the movable legs and speed of the drive system is always maintained and monitored for safety and reliability. Alarm conditions are preset and provide the operator complete situational awareness. All these sensors are applicable to moveable bridge design.

Power and Control Systems

The application of technology from the offshore jack-up vessel industry into the movable bridge industry would consider the rack and pinion system as a common tool producing motion in both industries. Even a motor driven gearbox pinion could translate linear motion via a sliding rack that then might operate a separate bull gear attached to the bridge. Although space is constrained under a bridge, the use of rack and pinion design is not unlike the use of hydraulic cylinders when producing linear movement or converting that movement to rotational movement. Yet some of the best technology from the offshore jack-up vessels that applies to movable bridges is in the power and control systems.

Since the two industries have differing rules governing design acceptance it is important to note in jack-up vessel design the systems are designed to lift the structural vessel, customer payloads, and, more critically, the personnel onboard. Even though AASHTO rules for power and control systems are onerous and may even swing or lift the operating house, the requirements of ABS and DNV-GL are just as restraining due to the inherent requirements to protect the safety of ship and crew. It is always a fine line on which activities to make automatic and activities to make operator controlled as well as which activities are PLC driven, and which are strictly relay driven or essentially back-up controlled.

Hydraulic Power and Control

When looking at conventional methods for control of hydraulic flow, generally related to the speed of operation of movable bridges, a couple different options are readily used in traditional bridge design. First, mechanical cam linkages can physically control the output flow of the hydraulic pump. As the bridge travels throughout the range of operation, a mechanical cam linkage travels likewise and physically increases and decreases flow from the hydraulic pump on the Hydraulic Power Unit (HPU) which increases and decreases the travel speed of the bridge during opening and closing operations. Other options can be arranged to drive the pump control or a separate flow valve to positions of no flow, creep speed or full speed based on limit switch actuation at fully open or closed, within nearly open or closed, or between nearly open and closed. Another option is a proportional directional valve to control the flow that is sent to the driving mechanisms for opening and closing operations of the bridge based on similar positions of limit switches. This option generally requires amplifier cards to convert the digital signals from the PLC to analog signals and control the position of the directional valves to proportionally control the flow and therefore the speed of the opening and closing operation of the bridge driving mechanisms. This valve actuated method grants more accurate control of the speed of operation and can be readily adjusted for safe and efficient operation. However, it does require various components to produce the desired proportional control including the proportional directional valve, amplifier card, PLC programming or joy stick control, and usually a pressure-compensated, variable-displacement pump. A fixed displacement pump is not normally used in this application as it will generate excess heat since the proportional directional valve is metering the output flow and will not require the full flow from the pump during the entire operation. There are some applications that use additional valving to dump the excess flow, but the addition of extra valves in a circuit offers another means for failure that requires further analysis.

In a typical offshore jack-up vessel system, a closed loop pump with supercharge tandem pump and electronic controls is used to power the hydraulic motors. These power units are a minimum of a two-pump system per leg (ranging from 100 HP to 300 HP per pump). One major supplier of this type of pump is Danfoss in their H1B model. The literature provided by Danfoss from their website provides a clear description of the functionality of the electrical proportionally controlled hydraulic pumps.

"The electric proportional control consists of a proportional solenoid driving a two-position, three-way porting spool. When activated, the spool ports high pressure to the larger diameter of the servo piston. The servo piston and rotating group move to change the displacement to the point where the pressures on the servo are in balance with the force from the feedback spring."

By adjusting the pump output electronically, the pump directly controls direction of flow to raise or lower the leg. The supercharge pump is used to replenish the case drain flow from the associated hydraulic pump and hydraulic drive motors, release the brake, and change the displacement setting of the motors. This small change alone, reduces heat buildup in the system and reduces horsepower requirements by limiting pressure losses through the proportional valve and the pump only delivered power when commanded to do so.

The control system for the hydraulic jacking system monitors many aspects of the system for each leg, namely:

- Electrical Power Available
- Electrical Power Demand
- Electric Motor Status
- Pump Stroke
- System Pressure
- Supercharge Pressure
- Jacking Speed
- Jacking Position
- Jacking Load

- Incline (if included)
- HPU Status

Armed with this information, the operator must lift the vessel in synchronized mode, all legs at one time or single leg operation to regain a level condition. This same process could be utilized in moving a bridge. It would be up to the bridge designer to incorporate an automatic system of pressing a button to open the bridge by automatically raising barriers, unlocking the bridge, and raising or swinging the bridge with a similar button to start an automatic means of closing a bridge. As more and more bridges become remotely operated, this type of system would be very easy to operate and monitor. However, it would still be desired to retain a backup operator control capability.

Electrical Power and Control

Many conventional electrical bridges are those that incorporate constant speed electrically driven winches. However, with the growing trend of less expensive VFD motors, motor control centers (MCC), and control software, many options exist to employ electrically controlled rack and pinion designs. As stated earlier, the VFD motors each transmit much of the feedback required of the hydraulic control system, and the direction of movement and release of brakes is all electronically driven through the MCC. Inherently, the control system would inform the operator of all system status, including:

- Electrical Power Available
- Electrical Power Demand
- Electric Motor Status
- Electric Brake Status
- Jacking Speed
- Jacking Position
- Jacking Load
- Incline (if included)

Once again, the system lends itself to operator control, automatic control, and remote operation.

Conclusion

Should the movable bridge industry adopt similar attributes as the offshore lift boat industry in the design of their rack and pinion systems, drive trains, power, and control systems they will be building on their vast amount of knowledge with another industry's advances. Although a plethora of additional data exists and could be shared during the seminar, for proprietary reasons, it is difficult to include in this paper. Numerous industries are moving forward in electronic control, drives, and feedback implementation, and we are seeing benefits in fully-electric systems energizing multiple power users and in electrohydraulic systems that utilize single sourced power density transmitted multiple locations. Each design project requires evaluation of specific power requirements, safety and environmental factors to make the best decision on type of technology to use. We hope that this information has been beneficial and desire that each industry continues to see new developmental growth in the overall safety of the systems designed and produced.