Innovations in Shiplift Navigation Concepts

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1 Introduction

Shiplifts are one of the main types of navigation structures in canals and high dams in natural rivers. In the 21st PIANC International Navigation Congress, the development of shiplifts was emphasized, and it is recognized that shiplifts have several advantages over navigation ship locks when the lift height is over 40 m. In 1984, PIANC established a "Study Commission of ship lift" and published a technical report in 1989 named "Ship lifts", which introduced and summarized the experiences in design and management of shiplifts from 1950 to 1986.

Since the 1990's, shiplift technology has been developing rapidly in the world and particularly in China, UK, Germany and Belgium. Many different types of shiplifts have been built or are being designed, e.g., Strépy-Thieu Shiplift in Belgium, Three Gorges Shiplift and Jinghong Shiplift in China, new Niederfinow Shiplift in Germany, Falkirk Wheel in UK. Many advanced and innovational construction techniques and design concepts have been used in these projects.

The tasks of the PIANC WG 207 report provides guidelines and recommendations to persons involved in shiplift research, design, construction, management and maintenance, with a specific focus on the historical ship lifts. Database of shiplifts, including

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brief lists of the types, dimensions and technical parameters of representative shiplifts in the world. Evaluation of research, design, construction, management and maintenance of Shiplift and approaches used for operational, engineering, financial and policy decision-making. WG 207 report includes conceptual design, design research, analytical models, numerical models, desktop and physical models, prototype survey and test, which are used to address the new developments of shiplifts in the world.

2 Layout of Shiplifts

General the primary layout and components of vertical ship lift contain the upper approach, tower, chamber, drive system, safety mechanism, balance system, lower approach and etc., which given below and shown schematically in Fig. 1.

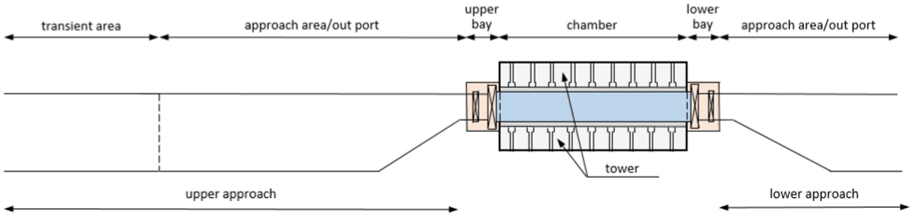


Fig. 1. Scketch of shiplift layout

The determination of the ship lift type should take into account the impact of the flood discharge, sediment, power station operation and etc. When there are no engineering cases to reference, it should be determined through special studies.

Normal the shiplift should be designed single stage. When restricted by terrain, geological conditions or the lifting height is too large, a multi-step scheme can be adopted. Open channels, water bridges, water tunnels and other types of intermediate channels can be used between the stages of the multi-step shiplift.

When the variability of navigable water level is small, the all balanced vertical ship lift should be used; when the hydrological water level fluctuations or short-term operational water level fluctuations is large is large, the partial balanced vertical ship lift or special upper/ lower docking station should be adopted.

3 Innovation of Typical Shiplifts

3.1 Strépy-Thieu Shiplift

The Strépy-Thieu Shiplift lies on a branch of the Canal du Centre in the municipality of Le Rœulx, Hainaut, Belgium. With a height difference of 73.15 m between the upstream and downstream reaches, it was the tallest shiplift in the world upon its completion, and remained so until the Three Gorges Dam ship lift in China was completed in January 2016.

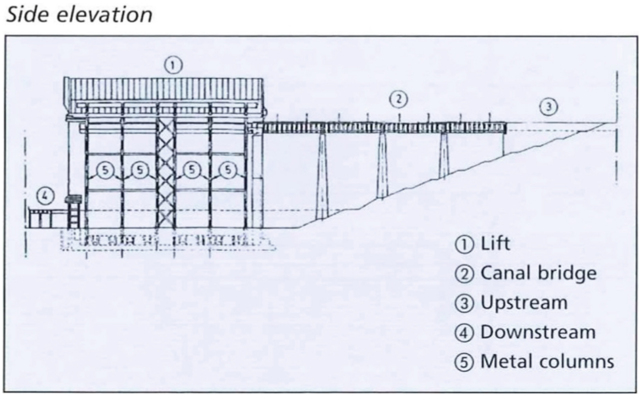


Fig. 2. Side view of Strépy-Thieu Shiplift

The structure at Strépy-Thieu Shiplift consists of two independent counterweighted caissons which travel vertically between the upstream and downstream sections. Because of Archimedes' Principle, the caissons weigh the same whether they are laden with a boat or simply contain water (Fig. 2). In practice, variations in the water level mean that the mass of each caisson varies between 7200 and 8400 tonnes. The caissons have useful dimensions of 112 m × 12 m and a water depth of between 3.35 and 4.15 m.

Each caisson is supported by 112 suspension cables (for counterbalance) and 32 control cables (for lifting/lowering), each of 85 mm diameter (Fig. 3). The mass of the counterbalance was calculated to keep the tension in each of the control cables below 100 kN at all times. The suspension cables pass over idler pulleys with a diameter of 4.8 m. Four electric motors power eight winches per caisson via speed-reduction

Fig. 3. Machine hall of Strépy-Thieu Shiplift

gearboxes and the 73.15-m lift is completed in seven minutes. The structure is massively reinforced to provide rigidity against torsional forces during operation and has a mass of approximately 200,000 tonnes. The vertically moving watertight gates are designed to withstand a 5 km/h (3.1 mph) impact from a 2000-tonne vessel.

3.2 Three Gorges Ship Lift

The Three Gorges ship lift is the largest rack and pinion climbing ship lift in the world, with a lifting height of up to 113 m, internal dimensions of 120 × 18 × 3.5 m (useable space) and moving mass of approx. 15500 tons. The technical level of complete equipment manufacturing, installation and commissioning of the Three Gorges ship lift have reached the world advanced level.

Four sets of rack and pinion climbing drive mechanisms of the Three Gorges ship lift are installed on the ship compartment, and four sets of accident safety mechanisms are arranged adjacent to the drive mechanism. The safety mechanism adopts the long nut column short rotating screw type, and uses the friction self-locking condition of the screw and nut trapezoidal thread to realize the safe locking of the ship's cabin. The driving mechanism and safety mechanism of the Three Gorges ship lift have complex forms, and the upstream and downstream water levels change greatly and rapidly during operation. There are many technical problems as follows:

- Shifting control of cabin equipment and tower structure.
- Clearance design of thread pair of safety mechanism.
- Rack, BSO support and force transmission design.
- Super large cabin structure design.
- Influence of water level variation and rate of change on gate arrangement and gate.
- Concrete tower column construction and major equipment installation.

The ship chamber is the core equipment of the ship lift, and the design of other structures, equipment and facilities is centered on the ship carriage. Self-supporting ship carriage is generally composed of two main girders, two safety beams, two driving beams, a chamber panel structure and a head of ship carriage structure and an accessory structure. Both ends of the safety crossbeam and the driving crossbeam are suspended to the outside of the main longitudinal beam to form a flank platform structure (Fig. 4).

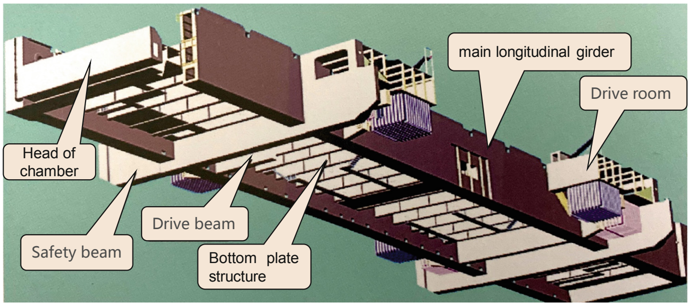


Fig. 4. Layout of self-supporting ship chamber

The Three Gorges Ship Lift adopts the scheme of stacking beams with the same gate slot and lifting flat gate. The scheme has outstanding advantages in gate sealing reliability and equipment operation safety, and has good applicability for large navigable water level variation. The upper gate of the Three Gorges Ship Lift has 7 working overlapping beams and 1 working flat gate. The upper gate of the Three Gorges Ship Lift has 7 working overlapping beams and 1 working flat gate. The auxiliary water retaining gate is arranged in the form of the same slot overlapping beam and the lifting flat gate, which is located upstream of the working gate. The auxiliary gate is used as the accident maintenance gate. The auxiliary overlapping beam has 8 sections (Fig. 5).

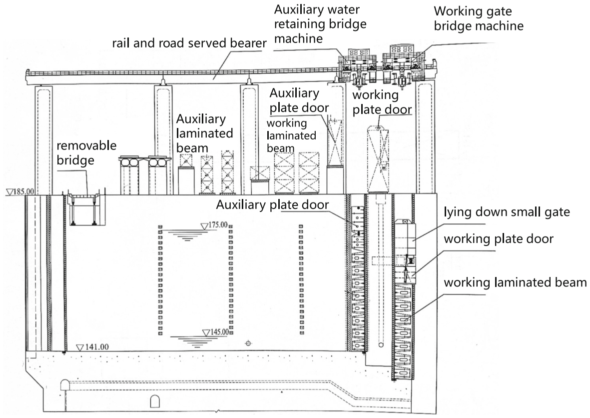


Fig. 5. Layout of upper ship lift gate and equipment

The water level of the downstream approach channel of the ship lift is generally affected by the negative adjustment of the unit, the flood discharge of the junction and the downstream flood, and the change rate is generally fast. The change amplitude of the downstream water level of the Three Gorges ship lift is about ±0.5 m/h. In order to adapt to the change of water level, the working gate of the lower lock head of the Three Gorges ship lift is a super large double leaf flat sinking gate with pressure adjustment, inflatable water stop, step-by-step locking, and a small lying down gate (Fig. 6).

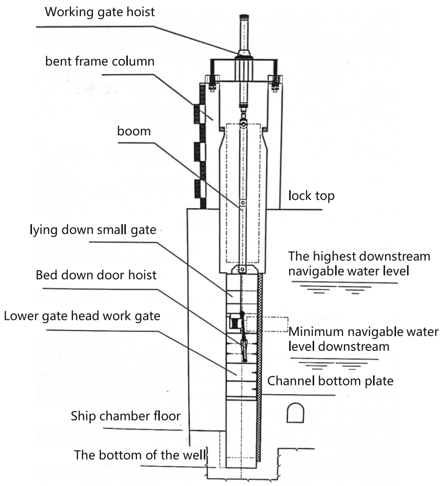


Fig. 6. Layout of lower ship lock gate and equipment

3.3 Jinghong Hydro-Floating Shiplift

Jinghong Hydro-Floating shiplift is located in the Jinghong hydropower project on Lancanjiang River in Yunnan Province (China), which is the first hydro-floating Shiplift in the world. It is also the biggest navigation structures in Yunnan province. The lift's preliminary study is at 2004, and has gone into operation in Nov, 2016.

Hydro-floating ship lift (HFSL) is a new type of ship lift invented by Chinese Engineers in 2000's, which main components are consist of ship chamber, counterweight, shafts, F/E system, mechanical synchronization system and so on. The lift uses water energy to drive ship chamber moving up and down.

The principle of Hydro-floating lift is similar with lock, water filling or emptying from 16 different shafts which longitudinal arranged in tower both side of the chamber, the counterweights in the shafts are ascend or descend (filling process or emptying process) with the variations of shaft water level. The ship chamber connected to the counterweights with steel cables will lifting with the movement of the counterweights (Fig. 7).

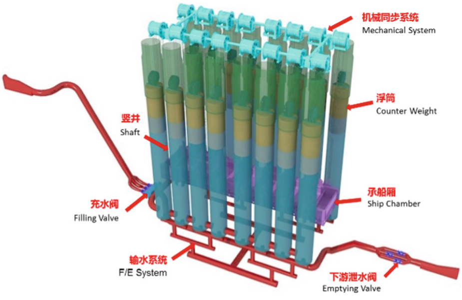


Fig. 7. Components of HFSL

Fig. 8. Filling valves of F/E system

HFSL is different with the motor-driven ship lift, which using the water power to drive the chamber, the lift weight of hydro-floating ship lift is no longer limited by the motor capacity. Therefore there is possibility to design larger-sized ship chamber.

Filling/emptying valves are main control devices of HFSL, which is comprised of 3 piston valves with diameter of 1.6 m (Fig. 8). The piston valves can precisely control the operation of ship lift by regulating flux in F/E system. F/E system adopted equal inertia layout. The water flow in the main pipe with diameter of 2.5 m is distributed both horizontally and vertically twice to 16 branch pipes with diameter of 1.6 m which connected to 16 shafts.

Hydro-floating ship lift applies the advantages of simple maintenance and high safety standard of ship lock, and the advantages of high efficiency of motor-driven ship lift. The hydro-floating ship lift has high-level safety standard. When the load of chamber changes, the draught of counterweight is auto adjusted by the buoyancy, the chamber and counterweight are keep balanced again, which resolved the shiplift's safety in accidents such as chamber leaking.

3.4 Goupitan Multi-step Shiplift

Goupitan multi-step ship lift is located in the main stream of Wujiang River in Guizhou Province, China, which is part of Goupitan Hydropower Station with a dam height of 225 m. The maximum water difference needs to be overcome for ships is 199 m. The variance of the upstream navigable water level is up to 40 m. It is the current navigable building with the highest head and maximum water level variation in the world. Three-step vertical ship lifts are built for the first time at home and abroad. In order to fit the large variation of the water level both the upstream and the downstream, the first and third step lifts take the rope hoist type with chamber entering water. So, they are also the largest ship lifts with chamber entering water. The lifting height of the second step is up to 127 m, which is the highest lift. The three ship lifts are connected with navigable tunnels and aqueducts, and the operating conditions are complex. A number of technical indicators have exceeded the domestic and foreign built ship lift (Fig. 9).

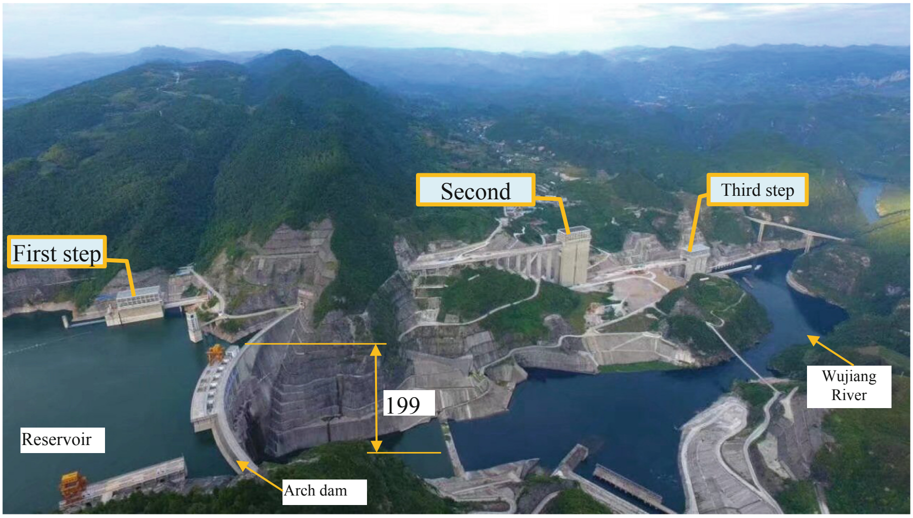


Fig. 9. Goupitan three-step ship lift in China

The main buildings include upstream approach, first step vertical lift, first step intermediate channel (including navigable tunnel, aqueduct), second stage vertical lift, second step intermediate channel (including aqueduct), third step vertical lift and downstream approach (Fig. 10). Among them, the first and third steps adopt the wire rope hoisting vertical lift with chamber entering the water. The second step adopts the wire rope hoisting full balance vertical lift. The total length of the three-step vertical lift line is 2181.7 m.

The first step lift is arranged in the upstream reservoir to adapt to the change of navigable water level from 590.0 m to 630.0 m in the upstream. The lower gate head is connected with the first step intermediate channel through the aqueduct. The water level of the first step intermediate channel is 637.0 m, the maximum lifting height of the first step lift is 47 m. The second step lift is arranged between the two intermediate

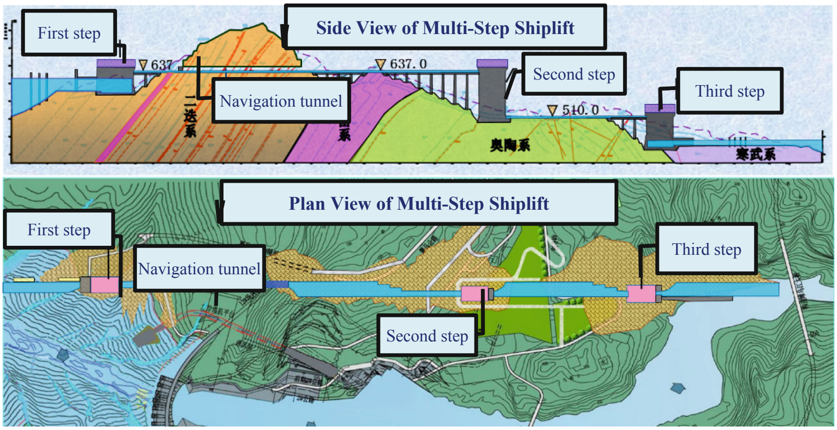


Fig. 10. Layout of Goupitan shiplift

channels to overcome the head drop between the two channels, and the upper and lower gate heads are respectively connected with the two intermediate channels through the aqueduct, the water level of the second intermediate channel is 510.0 m. The lifting height of the second step ship lift is 127 m. The third step lift is arranged in the downstream, which is used to adapt to the change of downstream navigable water level from 431.0 m to 445.82 m of the hub. The upper gate head is connected with the downstream intermediate channel through the aqueduct, and the lower gate head is connected with the downstream approach, and the maximum lifting height is 79 m.

The chambers of the first step and third step ship lifts are directly entering the water to connect the upstream and downstream without docking with gate heads. This ship type has several advantages. For instance, it could adapt the large variation of the water level to solve the problem of the distribution of the gate head. Also, many devices in the normal gate head are saved and the operation procedure is simplified. The transporting ability is promoted as well.

3.5 The Falkirk Wheel

The chambers of the first step and third step ship lifts are directly entering the water to connect the The Falkirk Wheel, opened in 2002, is the only rotating ship lift in the world. It is located in central Scotland at Falkirk and was conceived as the centerpiece of a large economic and social regeneration project known as The Millennium Link that aimed to restore the Forth and Clyde Canal and the Union Canal, both of which had been closed to navigation in the 1960's (Fig. 11).

Whilst most shiplifts are built to support commercial goods transport, the Falkirk Wheel was envisaged as a visitor attraction to move leisure traffic and to boost tourism.

Fig. 11. Layout of Falkirk wheel and union canal

Aesthetics thus played a huge role in the design and layout of the Wheel and the approach aqueduct with many of the design decisions being guided by aesthetics rather than purely technical reasoning.

The wheel has an overall diameter of 35 m and consists of two opposing arms extending 15 m beyond the central axle and taking the shape of a Celtic-inspired, double-headed axe. Two sets of these axe-shaped arms are connected to a 3.8 m diameter central axle of length 28 m. Two diametrically opposed water-filled caissons, each with a capacity of 250,000 L, are fitted between the ends of the arms.

The caissons or gondolas always carry a combined weight of 500 tonnes (490 long tons; 550 short tons) of water and boats, with the gondolas themselves each weighing 50 tonnes (49 long tons; 55 short tons). Care is taken to maintain the water levels on each side, thus balancing the weight on each arm. According to Archimedes' principle, floating objects displace their own weight in water, so when the boat enters, the amount of water leaving the caisson weighs exactly the same as the boat (Fig. 12). This is achieved by maintaining the water levels on each side to within a difference of 37 mm (1.5 in) using a site-wide computer control system comprising water level sensors, automated sluices and pumps. It takes 22.5 kW (30.2 hp) to power ten hydraulic motors, which consume 1.5 kilowatt-hours (5,100 BTU) per half-turn, roughly the same as boiling eight kettles of water.

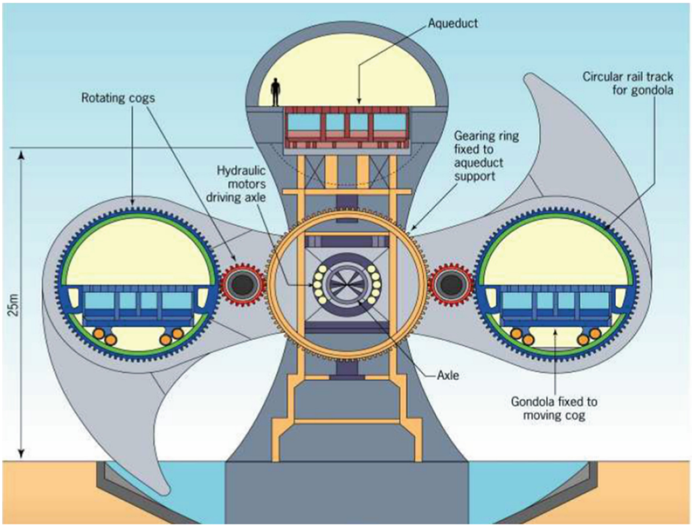


Fig. 12. Cross section of the wheel's arms

The caissons are required to turn with the wheel in order to remain level. Whilst the weight of the caissons on the bearings is generally sufficient to rotate them, a gearing mechanism using three large identically sized gears connected by two smaller ones ensures that they turn at precisely the correct speed and remain correctly balanced.

Each end of each caisson is supported on small wheels, which run on rails on the inside face of the 8 m diameter holes at the ends of the arms (Fig. 13).

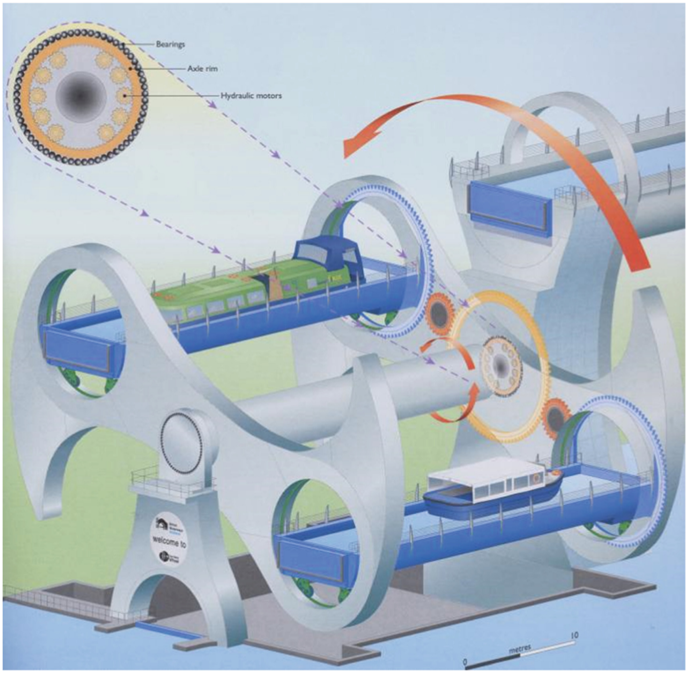


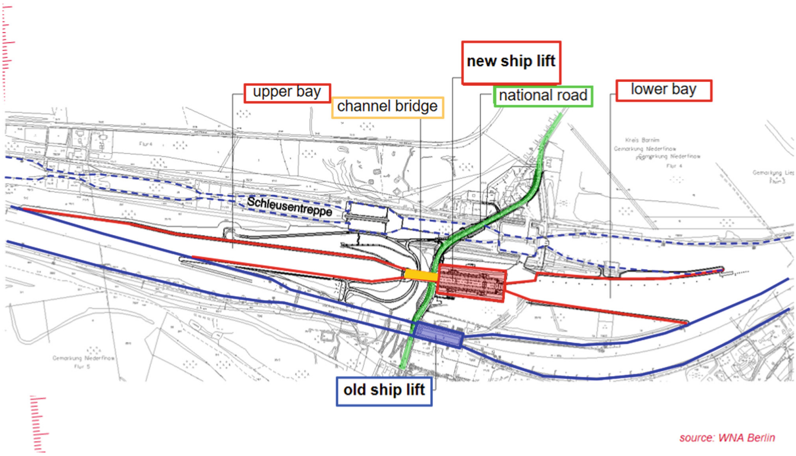
Fig. 13. Operation mechanism of Falkirk wheel

3.6 New Niederfinow Shiplift

The capacity of the existing ship lift is not big enough to manage the prospected traffic volume. Also after seventy years of operation, the costs of maintenance are increasing. Therefore the WNA Berlin was assigned the task to plan and erect a new construction to surmount the 36 m height incline in Niederfinow (Fig. 14). It takes navigability, environment, and costs into consideration (Fig. 15).

The ship lift consists of a ship chamber with counterweights and a supporting concrete construction. The main dimensions of the construction amount to length/width/height 133 m/46.4 m/54 m (Fig. 16). The foundation is constructed as an 11 m deep concrete trough. The construction is symmetrical and consists of four u-shaped towers, one in each quarter, and 12 columns. The lift operates with 14 sets of concrete counterweights balancing the deadweight of the ship chamber and the water volume up to the operation level. 224 wire cables run from the chamber to the top of the lift, over pulleys, and down to concrete weights. These vertical loads of 2 × 8,500 t are transferred into the concrete structure by two cable pulley beams, each of them placed along the side of the construction on top of two towers and six of the columns.

Four engines with total 1280 kW move the chamber by a rack-and-pinion drive; each engine comprises of two electric motors and corresponding gears (Fig. 17). They are situated in engine rooms at the sides of the chamber. The engines are synchronized by shafts and also electronically. Because of the counterbalanced system, only a small amount of power is required to overcome the friction in the bearing and guidance



source: WNA Berlin

Fig. 14. Layout of New Niederfinow Ship Lift and Old Niederfinow Shiplift

Fig. 15. New Niederfinow Ship Lift and Old Niederfinow Shiplift

systems and to accelerate the chamber. In the case of imbalance, for example caused by an empty chamber, the rack-and-pinion drive cannot stand the load. For this purpose the ship chamber safety system was developed. The system consists of a rotary-lock-bar, shaped like a screw with a diameter of 1085 mm, embedded in a 36 m long splitting side-thread. The rotary-lock-bar is connected with the chamber across the split (Fig. 18).

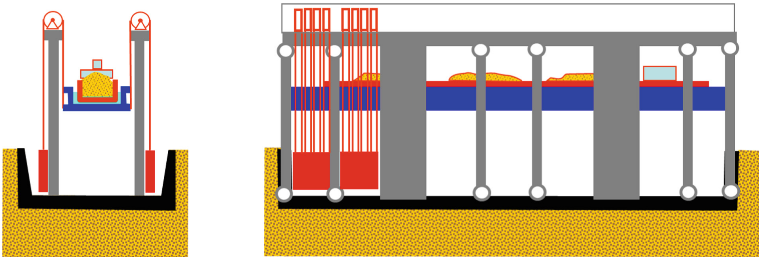


Fig. 16. Layout of counterweights and a supporting concrete

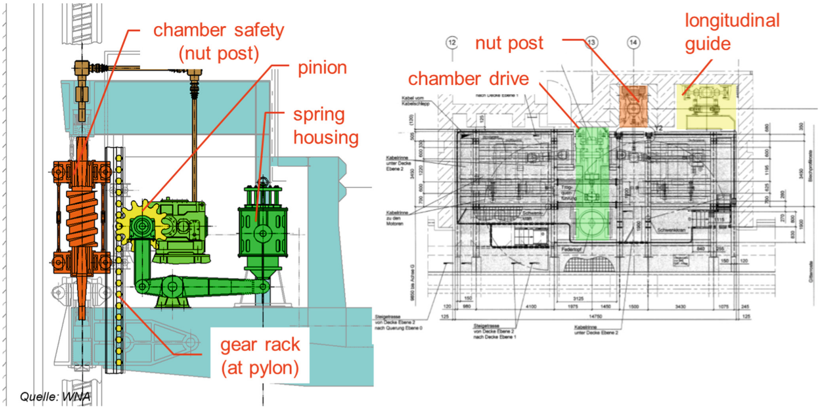


Fig. 17. Layout of chamber drives

Fig. 18. Photo of gear rack and nut post

4 Analysis Methodologies of Shiplifts

The construction of ship lift is a systematic project integrating hydrodynamics, civil construction, mechanical, hydraulic, steel structure, electric engineering, etc. Its overall operating characteristics are very complex. The overall physical model test of the ship lift can reflect the actual operation and force condition of the prototype ship lift more objectively, so the physical model test is its main research method. Numerical simulation has the advantages of low cost, short cycle time, and easy model modification, etc. It can also simulate accidents and extreme conditions that cannot be performed in physical model tests, guarantee the safety of test personnel and instruments, and provide technical guarantee for the safe operation of ship lifts under various conditions. With the rapid development of computer technology and numerical calculation methods, numerical simulation technology is playing an increasingly important role in the field of ship lift research. Besides, the prototype observation can find the problems existing in the operation of a new ship lift, deepen the understanding of the operation characteristics of ship lifts, and obtain a large number of measured data to guide the operation and management of ship lifts, it has also become an essential research tool after the construction of large ship lifts.

4.1 Physical Model

Shiplift research covers hydraulics, structural mechanics, electromechanical control and other subjects. The technical problems are very complex. It is difficult to reflect the complex interaction of “ship-water-ship chamber-driving system” of ship lift by partial physical model (Fig. 19).

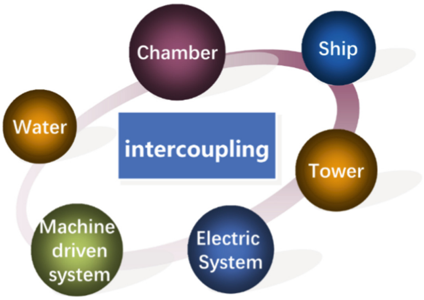


Fig. 19. Complex interaction of ship lift

Due to different research objects and scientific problems in different parts of the ship lift, the similarity rate and design method of each part are also different (Fig. 20).

- The scale of physical model is generally 1:10–1:20;
- Research on mechanical synchronous system focuses on synchronous shaft torque and torsional deformation during operation, so the model design should meet similitude of motion, stiffness and geometric deformation;

- Ship chamber hydrodynamics consist of the load changes caused by slamming force and adsorption force when the bottom of the ship chamber falling into or rising out of water, longitudinal tilting moment of chamber and mooring force of ships caused by water level fluctuation when the ship chamber's gate being in operation, the stern squat while ship driving into and out of chamber. Model design should meet hydrodynamic factors similarity.
- The running characteristics of ship chamber in normal operation and accident condition should meet gravity and motion similarity.

a) Rack and pinion ship lift（3000t） *b) Hydro-floating ship lift（2×500t）*

c) Hydro-floating ship lift（2×1000t） *d) Wire Rope hoist ship lift（2×1000t）*

Fig. 20. Ship lift physical model of different types

4.2 Numerical Model

Numerical simulation has the advantages of low cost, short research period and easy modification of the model. At the same time, it can also simulate accidents and extreme working conditions that cannot be carried out in the physical model test, so as to ensure the safety of test personnel and instruments and provide technical support for the safe operation of ship lift under various conditions. With the rapid development of computer technology and numerical calculation methods, numerical simulation technology is playing an increasingly important role in the research field of shiplift.

4.3 Integrated Simulation Technology

In view of the shiplift research involving multidisciplinary characteristics, the dynamic 3D virtual prototype of ship lift's overall characteristics is studied by means of data collection, theoretical analysis, model development and computer experiment. The subsystem of ship lift 3d virtual prototype (Fig. 21) mainly includes the flow-solid coupling simulation model of ship chamber entering/leaving water, ship chamber gate opening/closing, ship passing through the chamber, the dynamics simulation of mechanical lifting system, and tower structure.

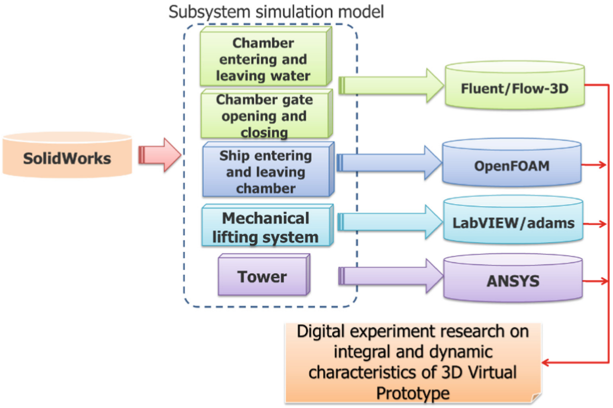


Fig. 21. Concept of ship lift 3D virtual prototype

4.4 Prototype Monitoring Technolgoy

Ship chamber hydrodynamics, ship berthing conditions, the forces of steel wire rope and other structures are important bases to determine the normal operation parameters of the ship lift, evaluate the safety of accident conditions, and guide the electrical control design. Therefore, it is very necessary to carry out the systematic prototype debugging and observation of the ship lift work characteristics and safety evaluation after the completion of the ship lift. The prototype observation can find the problems existing in the operation of a new ship lift, deepen the understanding of the operation characteristics of ship lifts, and obtain a large number of measured data to guide the operation and management of ship lifts.

5 Outlook

There are many types of ship lifts, and vertical ship lifts are the main development direction in the future. Among them, rope and winch type, rack and pinion climbing type and hydro-floating ship lift will be the mainstream type. Under some special topographical condition, inclined ship lifts also have certain application space, and water slope ship lift will gradually withdraw from history. In some tourist waterways and urban landscape water systems, there will be some new ship lift types, and the functions of hydraulic and floating ship lift will gradually transform from navigation to tourism, cultural heritage display and other functions.

In the future, ship lift will have a spread application prospect in artificial canals, water shortage areas and mountainous areas, especially in ship navigation of crossing the watershed in interconnected river system, and navigation of 200–300 m large hydropower hub, ship lift will be the main navigation type.

From the technical indicators and scale of ship lifts, the lifting height of large ship lift in the future will be increased from 100 m to 200 m, the lifting weight of ship lifts will be more than 20000 T, and 4 ships of 2000–3000 T can pass at one time. At present, some countries and institutions have carried out preliminary research work in this regard. The rapid development of civil construction level and mechanical manufacturing capacity has provided the conditions and ability to build large ship lift.

The construction of safe, efficient, green and intelligent ship lift is the overall development trend in the future, and the health monitoring, safety warning and operation guarantee technology of ship lift is one of the key concerns. Moreover, with the development of 5G, big data, artificial intelligence and other emerging technologies, more attention will be paid to the green and intelligent aspects of ship lift construction in future. Through a series research and development of innovative technology and intelligent equipment, the operation and maintenance of ship lift would form an organic integration with emerging technologies. The intelligence operation of ship lift is an important developing trend in the future.

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