

# Innovative Concepts in Navigation Lock Design and Gate Contact Aspects

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## *Abstract*

*This paper presents the new report n°106 of PIANC InCom WG29 on Innovations in Navigation Lock Design, published by PIANC in August 2009, as well as some additional contributions on lock gates (gate contact technology). The paper highlights the main objectives and issues of his PIANC report with a specific emphasis on gates and specifically on the contact aspects.*

*Locks are key structures for the development of the navigation in canals and in natural rivers where weirs regulate water levels to enable navigation. They may also be strategic infrastructure for port development.*

*The core of this report has three major parts. The first part presents an exhaustive list of design goals associated with locks. This section is particularly important for decision makers who have to launch a new project. The second part reviews the design principles that must be considered by designers. This section is methodologically oriented. The third part is technically oriented. All main technical aspects (hydraulics, structures, foundations, including computational aspects, etc.) are reviewed, focussing on changes and innovations occurring since 1986. Perspectives and trends for the future are also listed. When appropriate, recommendations are listed.*

*It is impossible to give the details of all lock innovation areas in this paper. As an example, the lock gates and, in particular, the modern views on their contact issues have been chosen. These new solutions are welcome to limit the maintenance and to extend the service life of lock gates.*

**Keywords:** Gate contact, Gate hinge, Gate tightness, Lock design, Lock innovation, Navigation lock,

## **1. Introduction**

In 1986, PIANC produced a comprehensive report of 445 pages on Locks. For about twenty years this report has been considered as a world reference guideline, but it needed updating to include new design techniques and concepts. PIANC decided in 2006 to launch a new Working Group (WG) to update the report, and the present report is the result. The new report must be considered more as a complement to the 1986 report than an update version, and focuses on new design techniques and concepts that were not reported in the former report. It covers all the aspects of the design of a lock but does not duplicate the material included in the former report. Innovations and changes that have occurred since 1986 are the main target of the present report.

Major changes since 1986 concern maintenance and operational aspects, and more specifically how to consider these criteria as goals for the conceptual and design stages of a

lock. Renovation and rehabilitation of existing locks are also an increasingly important topic for the future.

The PIANC n°106 report also includes on a DVD more than 56 reviews of existing locks (or lock projects under development) which describe the projects and their innovative aspects (Figures 1-7). Some purely innovative and untested concepts are also mentioned as references although with no guarantee of validity.

### **1.1 Report 2009's DVD**

To assist continuity and to avoid duplication of existing PIANC material the former 1986 PIANC Report on Locks is included on the DVD attached to the 2009 report (Directory A3). In addition, the former Table of Contents is given in Annex I of the new report. These documents should be used as support to this report and as a baseline of standard practice.

Due to publishing constraints the number of pages of the InCom-WG29's hardcopy report was limited. Therefore additional information has been saved on a companion DVD (attached to this PIANC hardcopy report). Care should always be taken to use the current versions of standards and other publications that might supersede the versions on the DVD.

This DVD includes the following directories:

- A1: The Project Reviews of 56 lock projects.
- A2: PIANC'2009 Lock Report, n°106
- A3: PIANC'1986 Lock Report – in French and English
- A4: PIANC Dictionary on Locks & Waterways
- A5: LIST of LOCKS (Worldwide list)
  
- Additional information to various sections of this report (Directories B) such as:
  - o B4.6.1: Salt Water Intrusion
  - o B4.6.5: 3D Video Modelling of Construction Process
  - o B5.2: Hydraulic (Manoeuvring, Fendering, ...)
  - o B5.5: Gates and Valves
  - o B5.7: Lock Equipment
  - o B5.8.5: Lubricants and Bio Oils
  
- Various technical guidelines (Directories C) :
  - o C1- Estoril'2006 - PIANC Congress Papers
  - o C2- Beijing'2008 - AGA-2008 Papers.
  - o C3- Navigation Lock - Ecluse de Navigation (by N.M Dehousse, 1985) in French
  - o C4- Corps of Engineering, USA - Reports on Innovation
  - o C5- Chinese Codes
  - o C6- French Guidelines - Lubaqua (CETMEF)
  - o C7- Fish Passage In Lock
  - o C8- Corrosion Protection
  - o C9- Planning of Lock Maintenance (example)
  - o C10- European Code For Inland Waterways (CEVNI)
  - o C11- Ship Impact
  - o C12- Seismic Impact of Lock Gates
  - o C13- ISPS Code 2003 - IMO (Safety and Security of Ship and Port)
  - o C14- Panama Third Lock Lane
  - o C15- Seine Nord Europe Canal (France)

- C16- Three Gorges Locks, China
- C17- Specifications for Lock Design (Lanaye Lock, Belgium)

## 2. Project reviews

An important feature of Report 106 is the availability of many detailed project reviews in which the practical use of innovations are presented (Figure 1 to Figure 7).



*Figure 1. Example of Project reviews – Sevilla (Spain),*

Representative samples of each lock type are summarized in Chapter 2 of the report. Case studies (56 in total) of each of these locks are included on the attached WG 106-CD-Rom (Directory A1).

The case studies include a complete description of the locks, foundations, gate types, hydraulic systems, construction methods and, where available, cost. Photographs and selected engineering drawings are also presented for many of the locks (Figure 2).



*Figure 2. Examples of Project reviews – Panama (left), Rhone in France (right)*

Each project was reviewed and the innovative features applied to that project are described.



Figure 3. Examples of Project reviews – Turucui Brazil (Left), Hohenwarthe Germany (right)  
 Source: Luftbild & Pressefoto)

These innovative features were ranked into five general classifications. Those innovations and their classifications are shown in Table 2.1 in the report (see Table 1).

Table 1. Layout of Table 2.1 in the report

|                        |                                   | Hydraulics                   |  | O & M             |                 |             |
|------------------------|-----------------------------------|------------------------------|--|-------------------|-----------------|-------------|
|                        |                                   | Filling and Emptying Systems | Water Management (Water Saving Basins) | Energy Management | Life Cycle Cost | Maintenance |
| <b>Project Reviews</b> |                                   |                              |  |                   |                 |             |
| 1                      | 1-01 Kallø Sea Lock               |                              |  |                   |                 | PT          |
| 2                      | 1-03 Self-Propelled Floating Lock |                              |  |                   |                 |             |
| 3                      | 1-04 High-Rise Navigation Lock    | AC                           |  |                   |                 |             |
| 4                      | 1-05 Van Cauwelaert Lock          |                              |  |                   |                 |             |
| 5                      | 2-01 Tucuruí Lock                 |                              | PT                                     |                   |                 |             |

The selected project reviews do not exhaustively cover all aspects, but are representative for the innovations currently in use or currently in the phase of research or design.

Members of WG 106 selected projects for which they or their associates have experience in the lock design or construction. Many of the projects fall under multiple categories in their areas of innovation (Figure 4).



*Figure 4. Project reviews – Naviduct-NL (Left), Float in Segment - Braddock-USA(right)*

In order to show what these areas are in a systematic way, five major categories and appropriate subcategories were created as follows:

- Hydraulics
- Operation and Maintenance (Figure 5)
- Environmental
- Design / Construction
- Miscellaneous



*Figure 5. Examples of Project reviews – Mooring System (Left), Folded plate miter gate and capsulated hydraulic actuator (right)*

Each project summary enhances few innovative concepts. These innovations were categorized to indicate the status of the innovations. The following definitions were used.

- A PROVEN INNOVATION is one which has been researched, designed and constructed. It is been in service for a number of years and has possibly been constructed at multiple locations.
- An UNPROVEN CONCEPT is one that has been recently constructed and as such the viability of the concept has not been validated by time and sufficient use for potential shortcomings or needed modifications to become apparent.

- A NEW CONCEPT is a concept that has been validated by a client and is in design. Construction is currently scheduled or will be as funding becomes available.
- An ADVANCED CONCEPT is one that is currently in research. A prototype may have been built to establish proof of the concept but it has not yet been accepted for construction or for regular operations.



*Figure 6. Project reviews: Falkirk Wheel - UK (left), Floating Pontoon and lock in the rock – Finland (right)*

Because each review may represent multiple innovations the project reviews have not been categorized by innovation. They are organized alphabetically by country.

Short summaries of each project review are included in Section 2.3 of the PIANC report. Detailed reviews and contact information for each project are included on the WG 106-CD-Rom.



*Figure 7. The Three Gorges Project (China)*

### **3. Live Cycle Cost And Lock Design Objectives**

The comprehensive 1986 PIANC report on Locks (PIANC, 1986) provides a mass of detailed data and recommendations for the planning and design of locks. But it also focuses on new areas of design objectives that have become more important since 1986, like the live cycle cost of navigation locks.

### **3.1 General Project Objectives**

The objectives and priorities of planning and design a lock vary depending on the viewpoint of the assessor, but they can usually be grouped into financial, economic and environmental categories. Safety is a theme running through all these categories. They all require detailed evaluation to allow logical decisions when selecting optimum solutions or deciding whether to proceed with a proposed project.

### **3.2 Economic and Financial Objectives**

There can be more than one reason for constructing a new lock or waterway. It might be to reduce maintenance costs, or to allow larger ships to reduce overall transport costs and to increase capacity of a canal. Alternatively a waterway project may be justified because it brings increased economic activity in the form of tourism and leisure, both on the waterway and in the surrounding waterfront land areas.

Financial objectives depend on the type of developer. While a public sector developer might not need to raise revenue directly from users, a private sector project such as a marina may require revenues from users to fund the project directly.

### **3.3 Environmental Objectives**

This issue has become of overriding importance since the 1986 PIANC report, and often governs the decision whether a project should go ahead. Local and regional environmental impacts of all aspects of construction and operation now have to be evaluated, to assess whether the project complies with statutory requirements.

### **3.4 Priorities**

The design approach can have four different priorities:

- Design for lowest initial (construction) cost
- Design for minimum maintenance.
- Lowest whole life cost, which is a logical combination of the two previous approaches
- Best performance (fastest operation, least down-time).

The selection of priorities depends on the objectives of the owner/developer of a project.

### **3.5 Main Design Objectives**

The following are the main design objectives for lock design, and many of these were relatively low priority at the time of the PIANC1986 report (numbered as in the PIANC2009's report)

3.2 *Reliability and proven technology*

3.3 *Reliable lock operations*

3.4 *Life Cycle Management*

3.5 *Lock navigation cycle*

3.6 *Water motions inducing ship displacement and mooring forces*

3.7 *Water resource problems:*

- *Water shortage*
- *Saltwater intrusion*

3.8 *Minimizing energy use*

3.9 *Environmental impacts*

3.10 *Minimizing impacts of construction*

3.11 *Security and Safety*

Of course the first point “*Proven Technology*” does not match with the use of innovation, and a major reason for adopting innovative concepts and materials is to achieve improved performance, reliable design or reduced costs.

### **3.6 Life Cycle Management (LCM)**

LCM is a management approach to infrastructure construction to achieve optimum quality and minimum Whole Life Cost (WLC). For locks, a reduced WLC should imply optimum levels of reliability (which must be determined specifically for each project), and more efficient maintenance. This does not mean less inspection and survey or less maintenance.

### **3.7 Safety**

Safety has become another increasingly important aspect of design for locks. As well as highlighting many areas of design that can lead to increased safety (e.g. mooring, lighting, signs, channel design and gate protection), the report (PIANC, 2009) also provides a classification of different types of water edge structure and gives guidelines for suitable safety treatment for each type.

## **4. Innovations in Traditional Filling and Emptying Systems**

Hydraulic systems for filling and emptying locks can be divided into two main types. One is the filling and emptying “through the heads”; and the other is the “through longitudinal culverts” system. Within these filling and emptying systems, the “In Chamber Longitudinal Culvert System” (ILCS) and “Pressure Chamber under the Floor System” are new types developed after 1986.

In recent years some locks in Germany have been equipped with a filling system which uses a pressure chamber beneath the floor. This type of filling system has proven to be very efficient especially in combination with water saving basins.

In general the ILCS system could be used for intermediate lift locks. Under specific conditions, such as in rock, a large saving in lock wall construction costs could be realized if the lock filling and emptying culverts were located inside the lock chamber rather than within the lock walls. The WG29 report reviews these systems, previous implementations, guidelines for the selection of a system, utilization in combination with other methods such as water saving basins, and optimization of the systems.

The objectives to choose a proper filling and emptying system are to get a proper filling/emptying time (not as short as possible) and to get a lower cost with the proper filling time. In general the simpler the filling and emptying system is, the lower the lock cost as shown in Table 2.



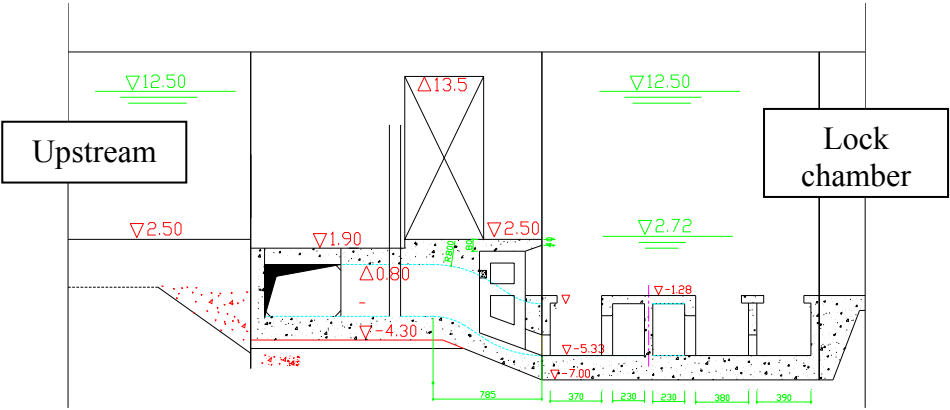
**Table 2. Complexity categories of hydraulic systems**

| Complexity              | Hydraulic systems   | Lock cost |
|-------------------------|---|-----------|
| 1. Simple systems       | - Through the head system<br>- Wall culvert side port system<br>- In Chamber longitudinal culvert system (ILCS)   | Low       |
| 2. More complex systems | - Wall culvert bottom lateral system<br>- Longitudinal culverts under the lock floor<br>- Wall culvert bottom longitudinal system<br>- Longitudinal culverts under the lock floor | Higher    |
| 3. Very complex systems | - Dynamically balanced lock filling system<br>- Pressure chamber under the floor  | Highest   |

Energy dissipation is a major problem in filling and emptying systems. For a specific filling and emptying system, you can raise the hydraulic efficiency of the system (or shorten the filling time) by optimizing the energy dissipation measures. Following are some examples to improve the efficiency of filling and emptying systems (studied in China).

**4.1 Partial Distributed System**

Through the head system is a very simple and low cost system. But it can be only used for locks with very low lift height. Based on the principle that distributed (longitudinal culvert) filling and emptying system could improve the operation efficiency of locks, a partial distributed system could be used to raise the efficiency and reduce the cost. The short culverts of the system were extended into chamber walls with bottom lateral branch culverts (Figure 8).



*Figure 8. Partial distributed filling system*

**4.2 Double Ditches Energy Dissipation System**

To avoid dangerous currents at the outlets of filling and emptying system, measures should be taken for energy dissipation. Double ditches are effective system for energy dissipation. Figure 9 shows the double ditches used in bottom lateral system and Figure 10 used in In-chamber Longitudinal Culvert System (ILCS). Compared with one ditch system the filling time was shortened.

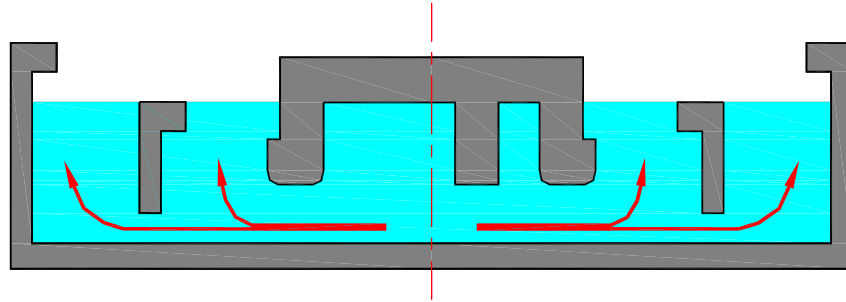


Figure 9. Double ditches used in bottom lateral system

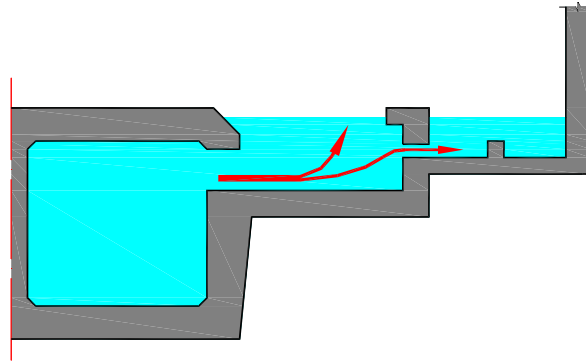


Figure 10. Double ditches used in ILCS system

### 4.3 Energy Dissipation For Side Port System

For side port system enough submergence is required to prevent direct action of the port jets against the bottom of the vessel. But in many cases a little more submergence will lead to much cost.

Tests have shown that if port deflectors were arranged in chamber (Figure 11) the jet into the chamber was spread by the deflectors evenly and the hydraulic condition was improved. So the minimum submergence could be reduced.

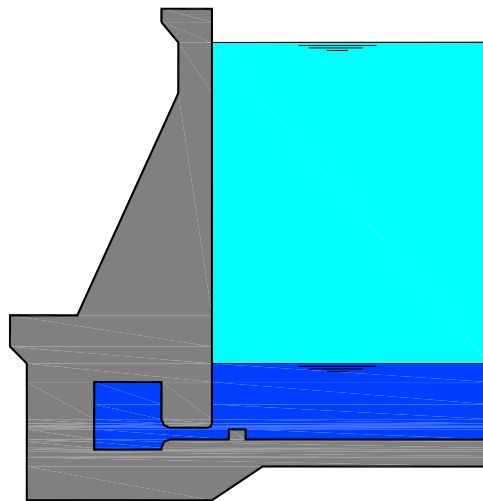


Figure 11. Side Port System with Port Deflectors

### 5. Mooring Forces and Ship Behaviour in Navigation Locks

The hydraulic design of a lock filling/emptying system aims at (among other issues) minimization of the filling/emptying time, constrained by the so-called hawser force criterion (De Mulder 2009). The latter criterion is meant to guarantee a certain degree of safety and comfort to a moored vessel during lockage.

The hawser force criterion attempts to quantify the necessary limitation of ‘turbulence’ (in the wide sense) generated by the lock filling/emptying, in order to limit the displacement of the vessel and the associated forces in the vessel-positioning system (e.g. mooring lines). Notice that the water flow, the lock (chamber and filling/emptying system), the vessel and its positioning system mutually interact, (see Figure 12).

The appreciation of safety and comfort during a lockage contains both objective (e.g. forces on the vessel, forces in the mooring lines, slope of the water surface, slope of the vessel, displacement of the vessel) and subjective elements (e.g. feeling of the captain, pilot, lockmaster).

The hawser force criterion sets an upper bound (i.e. a threshold) to an objective element (i.e. definition of the criterion). To assess whether a given filling/emptying system meets the defined criterion, a verification tool should be available. In order to assess that the adopted definition and its associated verification tool lead to both safe and comfortable as well as economic lockage’s, validation efforts should be carried out.

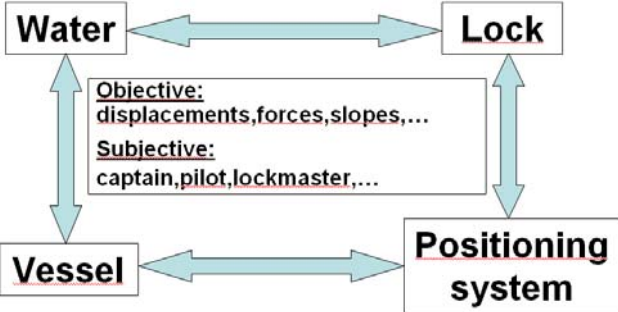


Figure 12. Constituting elements of a hawser force criterion

### 6. Construction Methods

The in-the-wet method has recently been applied to the construction of locks and weirs. This innovative method demonstrates several advantages over the conventional construction method, because the prefabrication can be performed in a well-controlled environment, the quality of the construction can be better ensured with this method than with cast-in-place concrete construction. This technique can also provide greater flexibility to the construction process to adapt to varying needs of the site and the community, such as accommodation of off-season work and easy access of personnel and materials. As a result it can substantially reduce the construction time, helps to reduce adverse environmental impacts and construction risks. In general, this method reduces impact to existing navigation, and can provide considerable cost savings. The WG29 report presents these methods, their respective advantages and disadvantages in comparison with conventional methods, and case studies (Yao and Clarkson 2009).

In-the-wet construction techniques were first used in the offshore oil industry before evolving into the immersed tunnel and bridge building industry and are a recent development in the construction of locks and dams. This innovative method prefabricates precast concrete or steel

modules on land and places them in rivers as the in-situ form into which underwater concrete and mass concrete are then placed directly. The tremie and mass concrete is designed to work in composite structural action with the prefabricated modules. Therefore, a lock or a dam may be constructed without use of a cofferdam.

Selection of a proper erection method for transporting and placing prefabricated modules is an important design decision. The erection method can be generally categorized into the float-in method and the lift-in method. Each method has its special implications on project cost, construction schedules, river traffic, and level of construction risks. In general, a thorough evaluation of the erection method is preferably made in the early design phase, because it affects the structural concept and layout.

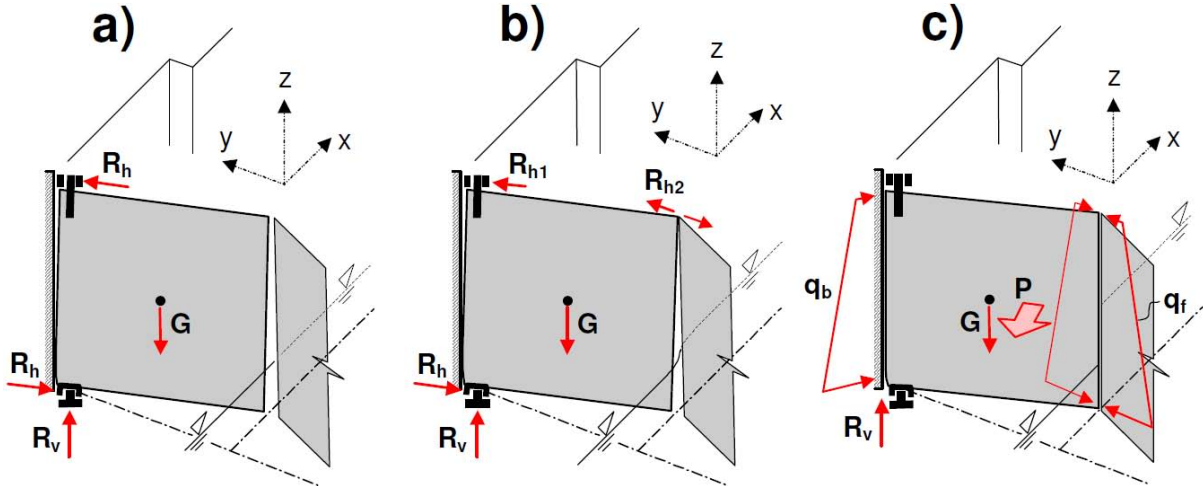
**7. Innovative Approach to Gate Contact Aspects**

This section introduces some innovative concepts related to gates identified by R. Daniel, co-author of this paper, who was not a formal WG29 INCOM member. The material of this section does not belong to the PIANC Report 106 (2009).

**7.1 Lock gate contact problems - Introduction**

Until now, the innovative concepts in navigation locks have been presented in global terms. This is understandable considering the large area of this subject and the diversity of technical disciplines involved. As an example, one issue will now be discussed in more details. This issue is the lock gate contact aspects.

This choice does not indicate that other issues are less important, but it is also not incidental. Movable hydraulic gates – whether in a lock, a weir or e.g. a harbour or shipyard dock – are structures which assume different support conditions and, therefore, different systems during operation. This is a property which does not often appear in other structures.



*Figure 13. Mitre gate changing support conditions during operation*

Consider a mitre gate as an example (Fig. 13). During the closing, different structural systems become activated. In the open position (a), the gate is basically a ‘flat shell’ loaded only in its plane. This begins to change when the two gate leaves meet (b) and the water head grows. At first the top hinge becomes released, then the bottom hinge and then the gate starts passing its loads to the heel posts (c). Moreover, it carries not only in-plane loads but also perpendicular loads. It works as a plate, which is a different system than a shell.

## 7.2 Significance of innovations in gate contacts

Having realized this, one must conclude that the behavior of gate contact areas codetermines the system functioning. This is more serious than only a matter of smooth motion or leakage. Consequently, every effort must be made to correctly design those contact areas. Therefore, intelligent innovations in this field are very welcome. An example is the innovative solution to the vertical lift gate guiding system, introduced in the middle of 1990's on the Hartel Canal Barrier near Rotterdam (Daniel 1996). The conventional solution to that detail included large and complex wheel units with expanding devices, like in the storm surge barrier in Krimpen a/d IJssel. Observe (Fig. 14 left) that this requires extensive additional structure in the gate support areas, wide guide slots in the lifting towers and piers, complex machinery and sealing systems. Replacing this by sliding line contacts (Fig. 14 right) allowed for narrow guide slots, practically no additional structure, no machinery and no seal around the gate support posts. These posts are now self-sealing thanks to the application of high-tech contact materials: ultra high molecular polyethylene (UHMPE) and stainless steel (316L). Moreover, the guides are practically maintenance free and require no lubrication, which spares the environment.



Figure 14. Vertical lift gate guides in Krimpen a/d IJssel (left) and in Hartel Canaal Barrier (right)

Another target of gate contact innovations is the service life of both the contact components and the entire gates. A worn or in another way malfunctioning gate hinge, guide or seal has a tremendous influence on the condition and service life of the gate as a whole. The successful innovative solutions in this field often result from a combination of theoretical and empirical knowledge, sometimes in a trial and error process. This will be shown in the next sections.

## 7.3 Gate contact levels

A precondition of such an innovation success is the knowledge of contact mechanics (e.g. Johnson 2003). This is a different discipline than structural mechanics that civil engineers are familiar with. Contact mechanics analyses the contact behavior of solids and the resulting phenomena like local deformation, creep, friction, wear, warmth generation, surface fatigue etc. under various conditions. Such analyses are performed on different so-called levels of contact. With regard to hydraulic (e.g. lock, weir, dock) gates, it is advisable to distinguish the four contact levels (Daniel 2005), as shown in Fig. 15 for a mitre gate hinge.

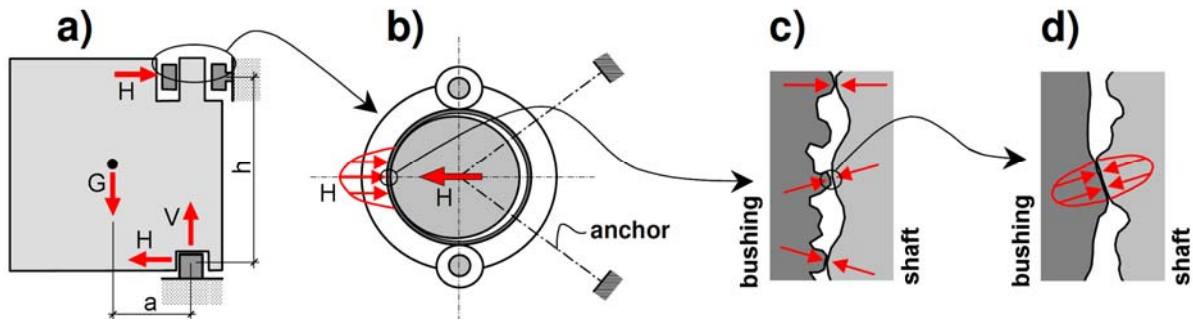


Figure 15. Levels of contact in a gate hinge: a) system, b) component, c) segment, d) asperity

In tribological literature (e.g. Van Beek 2001), the levels (b) and (c) are also referred to as, respectively, “macroscopic” and “microscopic” contacts. In this paper, however, contact issues are seen wider than only in tribological sense. Our attention is focused on the impact of contact solutions on the performances of entire gate systems. Therefore, the contact levels are referred to in an object-orientated way rather than a view-orientated way.

One can see that the size and character of contact loads are different when seen on different levels. What seemed to be a concentrated force on the system level becomes distributed on the component level. Then – seen under microscope on the segment level – it turns out to be a set of concentrated forces, not necessarily in the direction of the system force. Finally, also these forces appear to be distributed loads by a focus on a single asperity. The case becomes still more complex when the gate comes in motion. Obviously, these qualitatively different contact loads generate different contact phenomena. It is, therefore, important that engineers correctly recognize appropriate contact levels to analyse those phenomena.

#### 7.4 Case of a mitre gate bottom hinge

In this paper, it is impossible to demonstrate the significance of contact analysis for a wide range of gate contacts. As an example, one case is discussed: the mitre gate bottom hinge. This component (down in Fig. 15a) presents problems in the Dutch navigation locks and it shortens their maintenance cycle. In the Born and Maasbracht lock complexes on the Juliana Canal, e.g., the gate hinges are exchanged every 8 years which drives the maintenance costs up and obstructs the navigation. The main cause of the problems is an excessive bottom hinge wear (Fig. 16) in a so-called “free hinged” gate that operates as shown in Fig. 13.

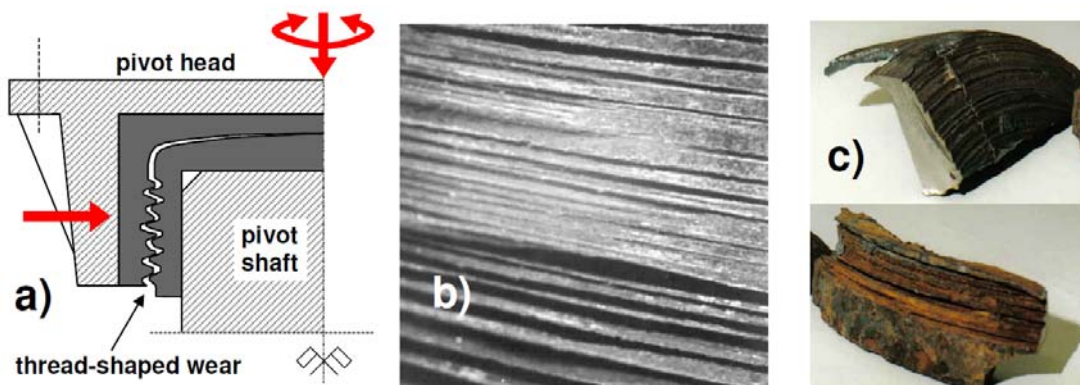


Figure 16. Thread-shaped wear in the bottom pivots of the Born and Maasbracht locks: a) cross-section, b) worn surface in natural size, c) pieces of worn manganese steel caps

The manganese steel caps used in this hinge were introduced in the 1950's as standard in the Dutch navigation locks. This material proved earlier to be wear-resistant in coal mining and quarry machines. For the lock gate hinges, this choice was a big mistake. If the engineers of 1950-1990 analysed the hinge behaviour on asperity level, they would probably not use the same steel on both sides of the contact – and certainly not that particular alloy. Manganese steel shows a strong strain-hardening behaviour giving inhomogeneous contact surfaces in which the hard asperity tops cut grooves in parent material. This is good in quarry machines, where whole surfaces become hardened by the energy of (predominately) impact loads, but it works disadvantageous by very slow and regular traction loads, like in gate hinges.

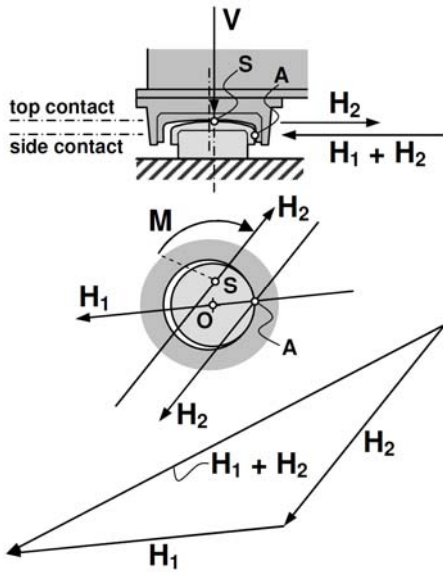
“Innovation” can also be defined as correcting mistakes. In this sense, another innovation that can be introduced using the four contact levels model, is the improved definition of contact loads. In the design of gate bottom hinges, these loads are usually determined from the static equilibrium conditions which give the following simple expressions (see Fig. 15a):

$$V = G \quad \text{and} \quad H = G \frac{a}{h} \tag{1}$$

This is correct on the system level, but not on the (b), (c) and (d) levels. To begin with the vertical hinge load  $V$ , it appears that it also has a component generated by gate rotation and tending to push the two hinges away from each other or to pull them towards each other. This phenomenon, similar to the so-called “shaft floating” (Springer 2009), is particularly strong in not (or poorly) lubricated hydraulic gate hinges. In the Netherlands, it is the empirical design practice to increase the  $V$  load by 10 ÷ 30 % of the  $H$  load (indicative: 10% for soft synthetic bushings like PE, 20% for hard synthetics or composites, 30% for metals). This gives:

$$V = G + (0.1 \div 0.3) \cdot G \frac{a}{h} \tag{2}$$

Also the horizontal contact load is, in fact, larger than from the equilibrium conditions (1). To understand why, one needs to go down to the component level. For the sake of simplicity, we ignore now the load distribution and we picture all acting loads as vectors (Fig. 17).



The “free hinged” gate requires large hinge clearances in order to secure the hydraulic load transfer to the heel posts, see Fig. 13. It also requires that the spherical radii atop the pivot differ very little from each other, because this keeps the contact stresses low. This fact and the hinge wear will always produce an eccentricity of the force  $V$  origin  $S$ . As a result, the gate rotation about  $S$  is not possible without horizontal shifting in this point. With the friction coefficient  $\mu$ , the shift force  $H_2$  is:

$$H_2 = \mu V \tag{3}$$

Figure 17. Loads on a gate bottom pivot

This force is kept in equilibrium in the contact point A on the vertical, cylindrical surface. In fact, it increases the horizontal contact load from the global equilibrium equations (1), marked  $H_i$  in Fig 17. The direction of both  $H_i$  forces will not be exactly the same, but for engineering purposes it is fair to assume the contact load as follows:

$$H = \vec{H}_1 + \vec{H}_2 \approx G \frac{a}{h} + \mu V \quad (4)$$

If we considered the segment level, we would have noticed that the friction atop the pivot is of a “nasty” kind, making the  $\mu V$  component very high. This, however, goes beyond the scope of the paper. The conclusion to be drawn now is that especially in heavy gates with metallic hinge bushings the contact loads are much higher than from the system level approach. It is no wondering that gate hinges induce many problems in navigation locks.

### 7.5 Time for innovations

Having analysed the problem and completed proper material investigations, one can step up to the solutions. In case of gate hinges, the approach called “morphologic survey” (Pahl & Beitz 1977) was applied for generating and assessing potential solutions. For the sake of space, we shall only present some realized solutions from the author’s engineering practice.

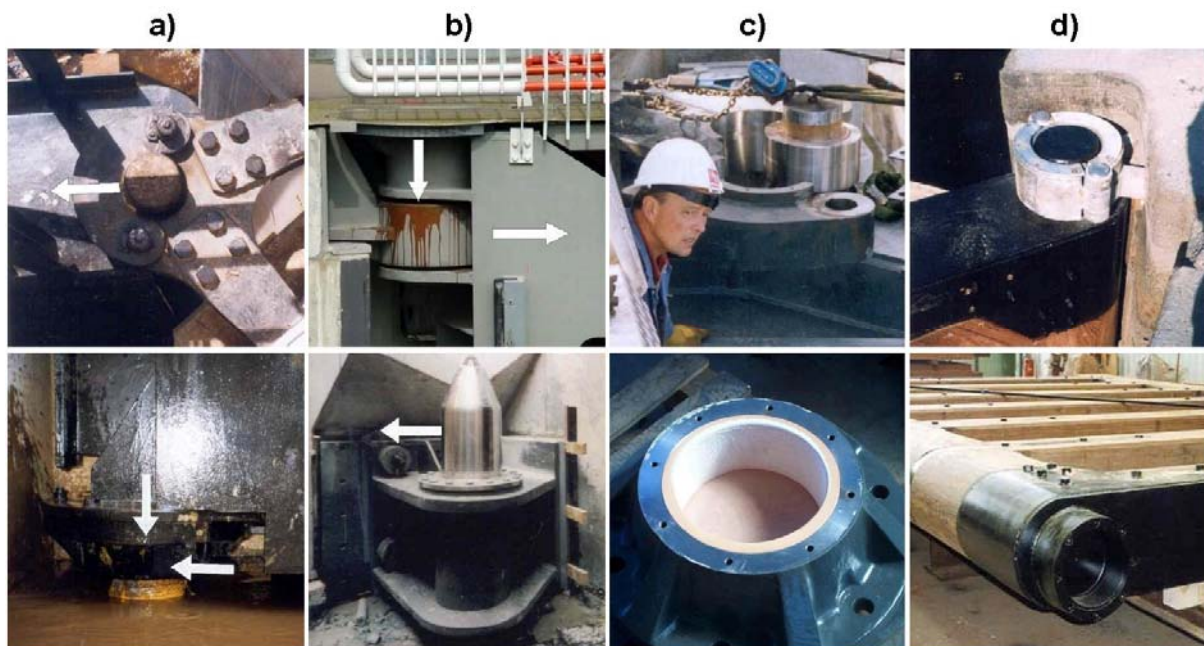


Figure 18. Some innovative solutions of the top and bottom gate hinges, examples

These solutions are shown in Fig. 18 (Daniel & Dembicki 2008). Photos in the top row show the top hinges; in the bottom row – the bottom hinges of gates in the four new or renovated navigation locks. Below is a short description of these solutions:

a) Princes Maximá Lock on the Meuse in Lith:

**up:** shaft of 42CrMo4 refined steel, bushing of aluminum-bronze CuAl10Ni5Fe4;

**down:** pivot cap of 34CrNiMo6 refined steel, heel cap of GX120Mn12 manganese steel.

Here, different steel alloys have been applied as bottom hinge contact materials. The choice for these alloys was supported by laboratory tests. It gives 1½ - 2 times less wear than in double-sided manganese steel contacts. Other details are still conventional.



b) Orange Locks complex in Amsterdam:

**up:** shaft of 42CrMo4 refined steel, bushing of reinforced polyamide (SKF bearing);

**down:** shaft of 316L stainless steel, heel bushing of Tenmat T814 composite.

These gates pass their vertical loads not to the bottom but to the top hinges. This does not solve the wear problem, but it makes it accessible and better manageable. The SKF polyamide bearings appeared to wear faster than originally specified, and were replaced by bearings with synthetic composite bushings after 6 years of operation.

c) Lock on an aqueduct ('Naviduct') in Enkhuizen:

**up:** shaft of 42CrMo4 refined steel, bushing of Tenmat T814 composite ('Feroball');

**down:** shaft with 316L stainless steel cap, heel bushing of Tenmat T814 composite.

Tenmat T814 is a phenolic resin reinforced by polyester fibers. The choice for it resulted from a series of laboratory tests in which various materials were included.

d) Lock on the Wilhelmina Canal in Tilburg:

**up:** shaft of 316L stainless steel pipe, bushing of polyethylene (UHMPE);

**down:** old shaft with a new 316L stainless steel cap, heel cap of polyethylene (UHMPE).

This gate was high, narrow and light (timber), which kept the hinge loads low. Therefore a 'soft', low friction synthetic (UHMPE) appeared to be a feasible option.

A solution that structurally solves the problem of large bottom hinge wear is the so-called "suspension gate" (Daniel 2005), e.g. as presented in Fig. 19. In that solution, there is no  $H_2$  load because the hinges do not carry the vertical load  $V$ . This concept has not been realized yet, but it is currently considered for some lock projects in the Netherlands.

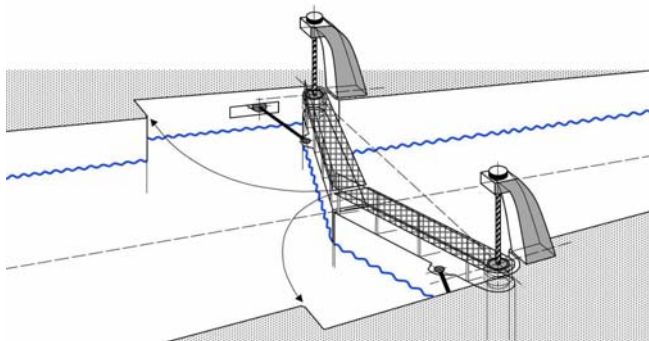


Figure 19. Concept of the "suspension gate" that reduces gate hinge loads

## 8. Lock Structures and Foundations

In third part (Section 5) of the PIANC report 106, many issues including new structural concepts, technical aspects and foundations issues are reviewed, focussing on changes and innovations occurring since 1986.

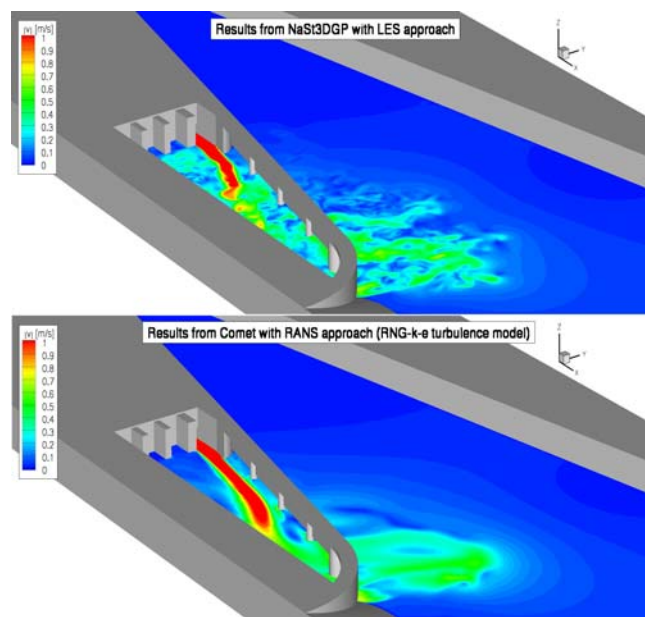
## 9. Computational Fluid Dynamics (CFD) in Lock Design

A main change since 1986 concerns the arrival of the CFD (Thorenz 2009). The recent developments in computational methods and the tremendous rise in available computing power have shifted the regions of applicability of numerical models in the last years (Figure 20). Still it must be stated that the filling and emptying of a lock is a complex process, which is not easily replicated in computational models.

The development of computers and numerical models has shifted the range of applicability largely in the last years. Many aspects of fluid flow in locks can be described with computer

models. But it must be stated that the most accurate and complete way to predict the behavior of a lock is still a physical model. On the other hand, numerical models can be very helpful for many aspects of lock design. If a new design is based on an older design for which data is available, it can be sufficient to use numerical models to extrapolate this know-how to the new design. In conjunction with physical models, they can be helpful to eliminate unnecessary variants or to model aspects of the fluid flow which are difficult to see or measure in physical models.

Nowadays, Computational Fluid Dynamics (CFD) software is available “from the shelf”. Additionally, computing resources have increased substantially, so that many people start to do CFD simulations. If the person who is doing the simulations is not very well trained and/or of good will to produce quality results, there is a significant danger that only nice pictures will be rendered. For external parties, only looking at the resulting pictures, it is impossible to judge the quality of the results. Especially commercial packages have a tendency to produce results under any circumstances, even if for example the grid resolution is not sufficient for the problem. This is triggered by the tendency that only models of higher dimensionality are “accepted”, so that three dimensional models are being used, even if the available computing resources are not sufficient for quality results. As a result “colored fluid dynamics” pictures are produced, which have nothing in common with real CFD.



*Figure 20: Detail of computed flow field in the lower approach area of a lock, computed with LES and RANS turbulence models (Thorenz 2009)*

## **10. Numerical Simulations and Experimental Models: How to Choose?**

Since Leonardo da Vinci the experiment has attained a leading and continuously growing role in fluid mechanics research. It is a prime merit of some scientists at the beginning of 20<sup>th</sup> century that they developed experimental methods for the solution of hydraulic engineering problems and they succeeded in convincing the profession of the usefulness and validity of this approach. Hydraulic physical modelling developed rapidly into engineering tool of a general recognition for the solution of hydraulic engineering problems.

## 10.1 Numerical Modelling

During the second part of the 20<sup>th</sup> century, there is fundamental research concerning the development of some mathematical tools to describe the flow evolution. In parallel, the progress in numerical and algorithmic increases considerably.

Then more numerical models have been applied in some areas of technical hydromechanics with great success. The greater flexibility of numerical models is often compensated by the more convincing intuitive power of the physical model. The market shares of the numerical models have increased in the last century against the physical models.

## 10.2 Comparison between Approaches, Limitations

Scale model studies have proven a cost-effective means of investigating performance of a proposed structure, provided requirements for hydraulic similitude are met. Idealistically, this requires matching the ratio of appropriate pairs of forces in both scaled model and prototype that play significant roles in the physical being examined.

The effort in constructing a hydraulic physical model is comparable to the effort of working out a solution scheme for the numerical model. Both methods must make use of certain simplifications and approximations and have to be adapted to the real situation in nature – in the one case by adapting the empirical coefficients, in the other case by changing the model roughness.

In numerical models, the decisive limitation is the fact that the majority of flows processes are complex and no closed system of equations can be formulated (incomplete set of equations, turbulence hypothesis,...). Another practical limitation is given by the resolution of the model, which is determined by the choice of the grid size for the solution scheme.

For the credibility of a model, it is important to know on the one hand, which experiences are already available with similar types of models, and on the other hand to know the extend of possible feedback between nature and model.

Thus, the results of both physical and numerical models should be carefully examined. For physical models, the model set-up is not very error-prone, but the measuring and interpretation process can be lead to errors. In numerical models, most errors are introduced in the conception and set-up phase of the model.

## 11. Conclusions

PIANC decided in 2006 to launch a new Working Group to update the 1986 report on locks. The new report (n°106) focuses on new design techniques and concepts that were not reported in the former report. It covers all the design aspects of a lock. Innovations and changes since 1986 are the main target of the present report. One area, the gate contact aspects, is discussed here by way of example.

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## References

- PIANC (1986). *Final Report of the International Commission for the Study of Locks*, PIANC, Brussels.
- PIANC (2009). *Innovations in Navigation Lock Design*, PIANC Report No.106, Brussels (\*)
- Beek, A. van (2001) *Tribology – Service Life and Performance* (in Dutch), published on author's own, first printing, Delft-Eindhoven.
- Daniel, R.A. (1996) 'Hartel Canal Barrier – Shifting the possibilities' (in Dutch), *Bouwen met Staal*, no. 130, pp. 38-45.
- Daniel, R.A. (2005) *Contact Problems in Lock Gates and Other Hydraulic Closures*, doctoral thesis, Gdansk University of Technology, Civil & Environmental Eng. Faculty, Gdansk.
- Daniel, R.A., Dembicki, E. (2008) 'Hydraulic Gate Contact Areas in View of Investigation and Field Experience', *proceedings of the PIANC International Navigation Seminar*, Beijing.
- Daniel, R., Vrijburcht, A. (2004). Design of Lock Gate, *PIANC Bulletin*, n°117, Brussels
- De Mulder, T. (2009). Mooring forces and ship behaviour in navigation locks: *Paper 7 of PIANC Workshop*, 15-16 Oct 2009, Brussels. (\*)
- Hiver, J-M (2009) Numerical Simulations And Experimental Models: How To Choose?: *Paper 11 of PIANC Workshop*, 15-16 Oct 2009, Brussels. (\*)
- Hunter, P. (2009), Navigation Locks: Developments In Design Objectives and Methods, *Paper 3 of PIANC Workshop*, 15-16 Oct 2009, Brussels. (\*)
- Johnson, K.L. (2003) *Contact Mechanics*, Cambridge University Press, Cambridge UK, ninth printing.
- Pahl, G., Beitz W. (1977) *Konstruktionslehre – Handbuch für Studium und Praxis*, Springer Verlag, Berlin – Heidelberg.
- Pechtold, E. (2009), Project Reviews, *Paper 3 of PIANC Workshop*, 15-16 Oct 2009, Brussels. (\*)
- Rigo, P.; Gernay T. (2009) Lock Gates – Part A: Innovative Concepts – Part B: Ship Impact, *Paper 9 of PIANC Workshop*, 15-16 Oct 2009, Brussels. (\*)
- Springer (2009) *Springer Handbook of Mechanical Engineering*, eds. Grote & Antonsson, volume 10, Springer Verlag, Berlin – Heidelberg – New York.
- Thorenz, C. (2009) Computational Fluid Dynamics in lock design - State of the art: *Paper 10 of PIANC Workshop*, 15-16 Oct 2009, Brussels. (\*)
- Webb J, Wu Peng (2009) Innovations in Lock Filling and Emptying Systems, *Paper 5 of PIANC Workshop*, 15-16 Oct 2009, Brussels. (\*)
- Yao, S.X.; Clarkson, J. (2009) In the Wet Construction: *Paper 8 of PIANC Workshop*, 15-16 Oct 2009, Brussels (\*)

(\*)

<http://www.anast.ulg.ac.be/index.php/en/news/40-categorynews/94-pianc-workshop-innovations-in-navigation-lock-design>