Flanders
State of
the Art

19_084_2
FH reports

Development of a new measurement tool for validating lock levellings

DEPARTMENT
MOBILITY &
PUBLIC
WORKS

www.flandershydraulics.be

Development of a new measurement tool for validating lock levellings

Vercruysse, J.; Verelst, K.; Schrijvers, S.

Flanders Hydraulics
Flanders State of the Art

Legal notice

Copyright and citation

D/2024/3241/291

This publication should be cited as follows:

Vercruysse, J.; Verelst, K.; Schrijvers, S. (2024). Development of a new measurement tool for validating lock levellings. Version 4.0. FH Reports, 19_084_2. Flanders Hydraulics: Antwerp

Document identification

Customer:	Flanders Hydraulics	Ref.:	WL2024R19_084_2
Keywords (3-5):	navigation lock, measurements, validation, hawser forces		
Knowledge domains:	Locks > Filling and emptying system> In-situ measurements		
Text (p.):	34	Appendices (p.):	/
Confidential:	☒ No	☒ Available online	

Author(s):	Vercruysse, J.; Verelst, K.; Schrijvers, S.

Control

	Name	Signature
Reviser(s):	Verelst, K.	Getekend door:Kristof Verelst (Signature) Getekend op:2024-12-02 10:21:11 +01:0 Reden:Ik keur dit document goed Vlaamse overheid
Project leader:	Vercruysse, J.;	Getekend door:Jeroen Vercruysse (Signa Getekend op:2024-11-28 11:36:25 +01:0 Reden:Ik keur dit document goed Vlaamse overheid

Approval

Head of Division:	Bellafkih, K.	Getekend door:Abdelkarim Bellafkih (Sign Getekend op:2024-11-28 15:12:54 +01:0 Reden:Ik keur dit document goed Vlaamse overheid

Abstract

Both the Flemish as the Walloon region of Belgium have dense inland waterway networks, in which navigation locks are key elements. Flanders Hydraulics executes optimization studies of the levelling process of both inland and sea locks. The goal of this optimizations studies is to find a compromise between levelling time and cost. Due to the water exchange during levelling hydraulic forces will act on the ships in the lock chamber. To guarantee a safe levelling the forces on the ship and hereby the forces in the mooring lines must be kept below certain criteria.

Flander Hydraulics has a vast experience with in situ measurement of lock levelling processes. From this experience it was concluded that all present techniques have some major drawbacks. Due to this limitations Flanders Hydraulics identified the need for a new technique to validate lock levelling in an accurate, safe and efficient way. Given its innovative nature and potential impact the project was supported by the Programme for Innovation Procurement, a Flemish Government initiative launched in 2016 to stimulate public sector organisations to buy innovative solutions.

A preliminary study concluded that there is no off-the-shelf solution available but pointed out some possible techniques. Two different techniques have been explored in a Proof of Concept. Apixa explored a technique based on stereovision. Iv-Infra explored a technique based on tachymeters tracking prism's positioned by drones. Both PoCs were executed in autumn 2023 in the lock of Viersel in cooperation with the waterway administrator, the Flemish waterway. Together with the General Technical Support Division of the Department Mobility and Public Works Flanders Hydraulics carried out reference measurements. The execution of both PoCs went well and the comparison with the reference measurements demonstrated the quality of both set-ups. Both proof of Concepts proved that technology is mature enough to develop an operational set-up.

Contents

List of tables

List of figures

1 Introduction

Navigation locks are key elements in navigable waterways facilitating the movement of ships between two adjacent parts of a waterway or harbour with different water levels. During the lockage process the water level in the lock chamber is adjusted and causes hydraulic forces acting on the ships in the lock chamber. These hydraulic forces are transferred to the mooring lines. To provide a safe locking process the forces on the ship and therefore the forces in the mooring lines must be kept below certain criteria.

During hydraulic design of a new or renovated lock, the allowable force on a ship during levelling is one of the design conditions. The hydraulic design of navigation locks includes mainly physical modelling, numerical modelling, ranging from simplified 1D models to 3D Computational Fluid Dynamics models, or a combination of those. After construction or renovation of the lock, commissioning tests are organised. Commissioning tests and field hydraulic measurements are discussed in the PIANC report related to the design of navigation locks (WG206, in preparation). Details on ship movement in the lock chamber can be found in the PIANC report related to ship behaviour in locks and lock approaches (InCom Working Group 155, 2015).

Currently, and for most locks, commissioning tests mainly involve the comparison of measured and designed levelling curve and the appreciation of the captains using the lock. Within the aim of a further professionalization of the Flemish navigation locks Flanders Hydraulics (FH) identified the need to include also forces as one of the parameters during commissioning tests. Therefore, a measurement technique is needed to assess on efficiently, safely and accurately forces acting on a ship during levelling. Such measurement technique is not only applicable during commissioning but can also be used for optimisation and validation of hydraulic design of filling and emptying systems of locks, general safety assessments of locks and provide an update of the criteria for forces in the mooring lines.

For the development of such a new measurement technique Flanders Hydraulics started a trajectory in cooperation with the Programme for Innovation Procurement (PIO) of the Flemish Government. Within the first phase of this trajectory a need analysis, tech scouting and market consultation was performed. In the second phase an assignment was launched to perform Proof of Concepts (PoC's) with different possible measurement techniques. Following PoC's where assigned:

- a technique based on photogrammetry, executed by Apixa,
- a technique based on tachymeters tracking prisms positioned by drones, executed by Iv Infra.

For both PoC's the assignment consisted of a fixed and a conditional part. Within the fixed part both Apixa and Iv-Infra demonstrated the quality of their measurement technique. The conditional part contained the actual PoC and consisted of measuring the so called six degree of freedom of an inland vessel during levelling in the ECMT class IV lock of Viersel. Flanders Hydraulics assisted by the General Technical Support Division conducted reference measurements during both PoC's.

The results of the trajectory and both PoC's are reported in Dutch in Vercruysse *et al.* (2024b). Even before the results of the PoCs were known, a paper was written and presented at the PIANC World Congress 2024 .

The present paper restates, summarizes and supplements the insights from that earlier English paper.

This report is structured as follows. Section 2 presents an overview of some experiences with the existing techniques used for validation of lock levelling. The requirements for the new measurement technique are described in section 3. The pathway prior to the proof of concept is explained in section 4. The lock, ship and the reference measurements for both PoC's are presented in section 5. The tested techniques during the PoC's are presented together with the results in the following sections. The first PoC based on a photogrammetric technique is handled in section 6. The second PoC based on tachymeters tracking prism's mounted on drones is handled in section 7. The conclusions are presented in section 8.

2 Experiences with current validation techniques

Between 2008 and 2022 FH performed measurements of the water level slope during levelling in a number of locks in Flanders. During these measurements the water level was measured at some locations in the lock chamber using autonomous logging water level sensors of the type Divers weighted with ballast and attached to a cable within the ladder recesses. From these water level measurements the water level slope in the lock chamber is deduced. These measurements rely on the assumption that the water level slope is a good proxy for the slope of the vessel, which on its turn is a good proxy of the hydrodynamic force acting on a vessel in the lock, as described in the PIANC report related to ship behaviour in locks and lock approaches (InCom Working Group 155, 2015). The set-up is presented in Figure 1 and the results in Figure 2. These measurements were executed both in sea locks and in inland navigation locks. The results of these measurements seem often to be trustworthy, but the theoretical accuracy is limited. Due to the longer distance between the measurement points, the accuracy is higher for the measured longitudinal water level slopes, but very low for measured transversal water level slopes. Also, the risk that one of the ropes or the sensors would be sucked into the propellors of a ship is a major concern and drawback.

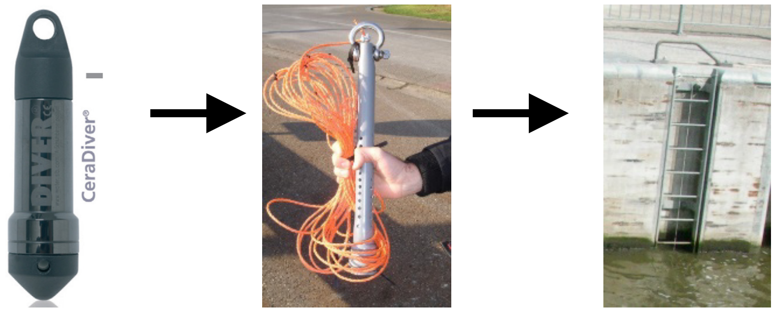


Figure 1 - Measurement set-up with Divers applied by FH

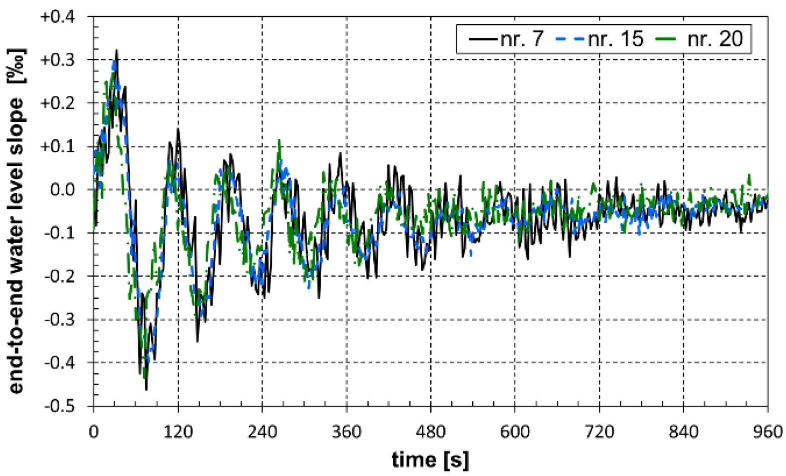


Figure 2 - Measurement end-to-end water level slope in the Vandamme Lock in the port of Zeebrugge by FH

In March 2010 a joint measurement campaign in the lock of Roselies (Belgium) was organised between FH and the hydraulic research lab of the Walloon administration (Service Public de Wallonie, SPW). SPW measured the water level slope with highly accurate and synchronized pressure sensors and the movements of the ship with tachymeters, RTK GPS and a dual axis inclinometer. At the same time FH measured the water level slope with the above-described measurement set-up. This joint measurement campaign let conclude that the amplitude of the water level slopes measured by FH and SPW were comparable but not exactly the same, most probably caused by a synchronization issue with the Divers of FH. The measurements of the RTK GPS and those of the tachymeter were similar and performant, the measurements from the inclinometers were less representative due to their inappropriate dynamic response. The measured pitch of the ship, even if bigger due to inertia effects, proved to be comparable with the longitudinal water level slope, indicating that the water level slope is a good proxy for the slope of the vessel.

To gain insight in the relation between the water level slope and the pitch of a ship FH performed a number of comparative measurements during which longitudinal water level slope, movements and pitch of the vessel were measured. These measurements were carried out in the Lock of Lembeek on the canal Brussels-Charleroi and in the old lock of Sint-Baafs-Vijve on the river Lys. An example of the variation in time of the water level slope and pitch of the ship measured in the old lock of Sint-Baafs-Vijve is presented in Figure 3. The measurements let conclude that the measured longitudinal water level slope and the pitch of the vessel were similar but not directly comparable. The differences can either be explained by some measurement errors of the slope of the ship due to RTK GPS connection problems or by a misalignment between the position of the ship and the position of the measured water level slopes.

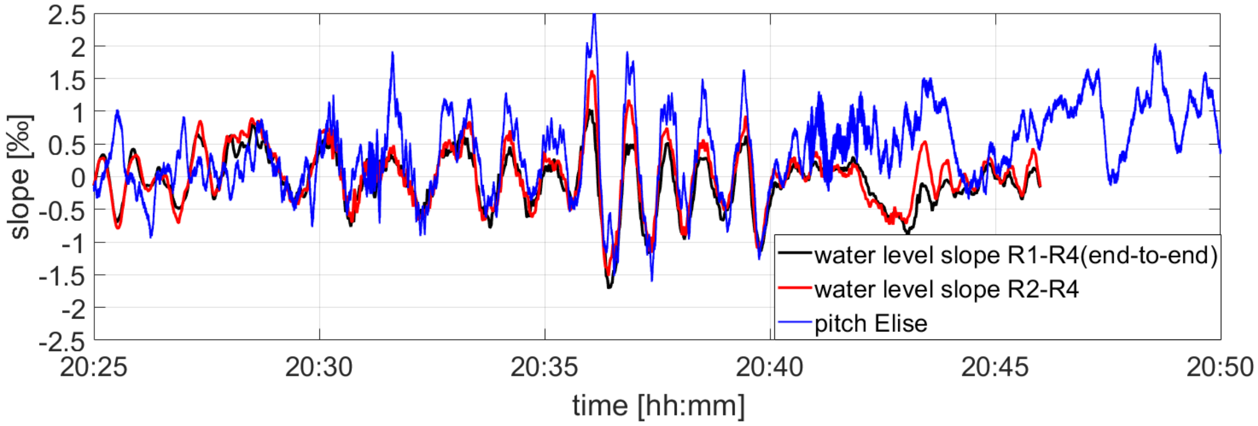


Figure 3 - Comparison of water level slope and pitch of a ship in the lock of Sint-Baafs-Vijve

During measurements in the sea locks of Ijmuiden and Terneuzen (Schouten, 2019) in the Netherlands experience was gained with direct measuring of the force in the mooring lines during levelling. In 2023 The Flemish Waterway together with FH also gained some experience with measuring forces in mooring lines on the locks of the canal Leuven-Dijle in Belgium. However, during design phase of a lock levelling system, the longitudinal force or the transversal force acting on a ship are calculated and compared with corresponding force criteria. To be able to compare the measured force in the mooring lines with the design values it is therefore necessary to convert the tension in the mooring lines into a longitudinal, transversal and vertical component, taking into account the exact course of the mooring line, which also has to be assessed or measured.

Additionally, a sensor has to be installed between the mooring line and the bollard the ship is moored at. This implies safety issues, and the installation of the sensors hinder the normal mooring operation of the ship in the lock chamber reducing the efficiency.

The measurement techniques presented in this chapter show all some major drawbacks when applying for the validation of the levelling system of navigation locks. The current technique with Divers deployed by FH is considered efficient but less accurate and comes with an important safety concern. The other techniques imply either boarding of the ship or influencing the mooring of the ship in the lock chamber. Boarding and deboarding a ship safely before and after a levelling or attaching sensors to mooring lines is difficult to plan and time consuming, which reduces the efficiency of the validation measurement. Due to the limitation of the current techniques, FH identified the need for a new measurement technique to validate a lock levelling.

3 Requirements new measurement technique

The pitch and roll of the ship are considered as a reliable measure for the longitudinal and transversal hydrodynamic force acting on a ship during levelling. Taking this into account, the requirement for the new measurement technique was identified by FH as follows: a remote and mobile measuring technology allowing to measure efficiently, safely and accurately, from the quay, the movements of a ship in a lock chamber during a levelling process. The aim is to perform one day assessments of levelling systems of navigation locks with a mobilisation and demobilisation time being limited to less than two hours.

The frequency of the measurements was set at 1 Hz or better. Because the movement and the slope of the ship are measured on top of an ascending or descending mean lock water level synchronization is very important and the duration of an individual measurement is consequently limited to 0.1 s. The output of the measurement system should be the movements and rotations of the ship around each of the three axes.

For the stage of the PoC's, the accuracy is defined based on the pitch of the vessel. For inland navigation locks the allowable force on the ship is presented relative to the underwater displacement volume of the vessel. For different ECMT classes of inland navigation ships, the relative force criterion is presented in Table 1. The relative allowable force reduces with increasing ECMT class of the ship. The aimed accuracy of the measurement system is for the different ship types considered assessed from the relative force criteria taking into account the pitch of the ship being a good proxy for the relative hydrodynamic force acting on a ship, assuming the measurements being carried out at bow and stern of the ship and assuming an overall accuracy of 5 %. Table 1 shows that the measurement accuracy varies between +/- 0.3 cm and +/- 0.7 cm.

Table 1 - Calculation of the accuracy of the measurement system based on relative force criteria

ECMT class ship	Length [m]	Criterion [‰]*	Difference bow–stern [cm]	Accuracy [cm]
Vb	185	0.75	13.9	+/- 0.70
Va	110	0.85	9.4	+/- 0.47
IV	85	1.1	9.4	+/- 0.47
III	80	1.5	12	+/- 0.60
II	55	1.5	8.3	+/- 0.42
I	38.5	1.5	5.8	+/- 0.29

* (Beem *et al.*, 2000), allowable force on the ship relative to the underwater displacement volume

4 Pathway prior to the Proof of Concept

Because of the innovative nature of the new measurement system, the project was supported by the Programme for Innovation Procurement (PIO) of the Flemish Government. With this programme the Government of Flanders wishes to stimulate all public sector organisations in Flanders to use their substantial purchasing power strategically as a catalyst for innovation by buying innovative solutions matching their needs.

With the support of PIO, the consultancy company Verhaert first executed a requirement analysis followed by a technological scouting. The technological scouting indicated a set of A-type solutions, being completely remote, and a set of B-type solutions, allowing limited non-human contact with the ship. For the A-type solutions photogrammetry and Lidar were considered, for the B-type solutions tracking of prisms by tachymeters, the use of inertial measurement units and some ideas with local GPS sensors were considered. Consequently, Verhaert performed a market analysis and consultation. The technological scouting and the market consultation showed the lack of an off-the-shelf solution and indicated that solutions using photogrammetry, LiDAR and a set-up with non-human contact seemed to be technologically possible but still challenging.

Together with the PIO office, it was decided to continue the project by organising Proof of Concepts to compare the possibilities of different techniques. After a tendering process a PoC with a photogrammetric solution was awarded to Apixa and a PoC with limited non-human contact was awarded to Iv-Infra. Prior to the real PoC's, both Apixa and Iv-Infra demonstrated that their set-up meets the aforementioned requirements. This test was organized by the participants themselves in conditions representative to those in the lock used for the PoC. The accuracy was proven by an independent measurement technique acting as ground truth.

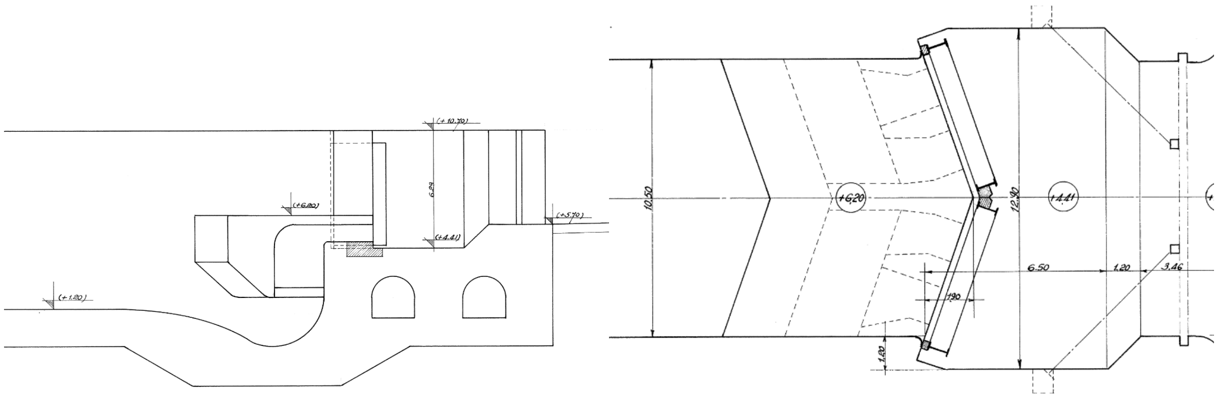
5 Proof of Concept

Both the PoC with the photogrammetric technique as the PoC with the technique based on tachymeters were carried out in the Lock of Viersel, see par. 5.1. For both PoC's a similar inland navigation vessel was chartered by FH, see par 5.2. During both PoC FH assisted by The General Technical Support Division carried out reference measurements, see par 5.3.

5.1 Lock Viersel

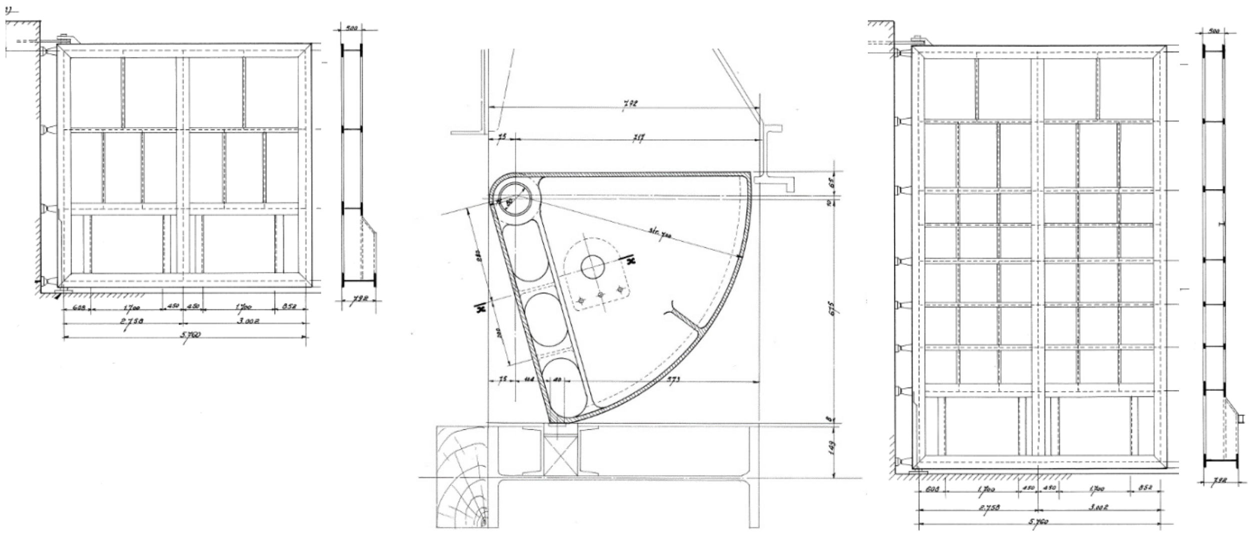
The PoC's were executed in the inland navigation lock of Viersel, being an ECMT class IV lock connecting the Nete Canal with the Albert Canal in Belgium. The lock has a useful length of 81.3 m and a width of 10.5 m. The head difference equals approximately 5.15 m.

The lock chamber is filled trough the upper head by segment valves positioned near the bottom of the mitre gates. After passing the segment valves the inflow is directed into a stilling chamber before entering the lock chamber. To empty the lock, the mitre gates in the lower head are equipped with four rectangular openings sealed by segment valves. Figure 4 presents a side and plan view of the levelling system in the upper head. Figure 5 shows a front view of the upper and lower mitre gate and a side view of the segment valve.



(Ministerie van Openbare Werken - Bruggen en Wegen - Dienst der Zeeschelde, 1962)

Figure 4 - Side and plan view upper had lock Viersel



left: gate upper head / middle: cross section segment valve upper head / right: gate lower head
(Ministerie van Openbare Werken - Bruggen en Wegen - Dienst der Zeeschelde, 1962)

Figure 5 - Gate upper and lower head lock Viersel

5.2 Ship

During both PoC's a ship from Blue Line Logistics was chartered, the Zulu 2 for the PoC of Apixa and the Zulu 1 for the PoC of Iv-Infra. Both ships are so-called pallet ships, characterised by a flat deck and a small steering cabin, see Figure 4. The ships are catamarans with hulls consisting of two wig-shaped floaters. By adjusting the water level in the ballast tanks the deck level is controlled to facilitate the loading and unloading of the pallets. Due to their design, the underwater volume of both ships is very limited. The characteristics of both ships are presented in Table 2.

Table 2 - Ship characteristics for the executed PoC's

PoC	Ship name	Ship dimensions	Condition	Underwater Volume
Apixa	Zulu 2	50 m x 6.6 m	No Cargo, partly ballasted	83 m³
Iv-Infra	Zulu 1	50 m x 6.6 m	No Cargo, not ballasted	47 m³

During the PoC's the ship was moored in the lock chamber by a bow and stern spring without the usage of propulsion. During the PoC of Apixa the mooring line at the stern was controlled by a winch. During the PoC of Iv-Infra the mooring line at the stern was handled manually.

Figure 6 - Zulu 1 positioned in lock chamber during PoC Iv-Infra

Before the start of the PoC the ship was moored at a waiting area on the Nete Canal. After installing the reference measurement set-up the ship sailed into the lock chamber with the bow pointing upstream. The ship orientation was maintained during the PoC's. For both PoC's the ship was moored at the right lock wall. After the ship temporally sailed out to clear the lock for passing traffic the ship was repositioned in the lock chamber with the same orientation and moored at the right lock wall. During the PoC of Apixa the ships position was optimized for the camera set-up. During the PoC of Iv-Infra two positions were tested : one with the ship located towards the upper head and the other with the ship in a central position.

An illustration of the mooring lines configuration during both PoC's is presented in Figure 7. At the bow, one mooring line is attached to a bollard located upstream and at the stern one mooring line is attached to a bollard located downstream. The mooring line at the stern was controlled by a winch during the PoC of Apixa and manually during the PoC of Iv-Infra. The mooring line at the bow was not controlled during either PoC. During the PoC of Iv-Infra, the ship was positioned towards the upper head during the first two levellings and moved to a central position in the lock during the third and fourth levellings. A view of the mooring line during the first two levellings is presented in Figure 7 upper right. During the third and fourth levelling of the Iv-Infra PoC the bollard near the upper head was maintained and the mooring line was lengthened. Note that due to the limited under water volume, the ship tended to hang in its mooring lines during emptying, see Figure 7 lower right.

Upper left: PoC Apixa / Upper right : PoC Iv-Infra positioned upstream
Lower left: PoC Apixa mooring line controlled by winch / Lower right : PoC Iv-Infra mooring manually controlled

Figure 7 - Mooring line configuration during both PoC’s

5.3 Reference measurements

Together with the General Technical Support Division of the Department Mobility and Public Works FH carried out reference measurements, see Figure 5.

Three prism were mounted on the deck of the ship. Each prism was tracked in time by a tachymeter. The set-up of the tachymeters is presented in Figure 8. Note that this is a similar measurement technique to that applied by Iv-Infra.

Left : Set-up tachymeters tracking each a prism
Upper right: prism / lower right: tachymeter

Figure 8 - Set-up tachymeters

A highly accurate dual axis inclinometer (type Sherborne T233 with range +/- 3°) was positioned approximately at the center of the ship. The measurement frequency of the inclinometer was set at 10 Hz. The specifications of the inclinometer are provided in Table 3 and an image of the inclinometer mounted on the deck is shown in Figure 9.

Table 3 - Specifications Sherborne T233

	angle	Tan (angle)
	[°]	[‰]
reach +/-	3.00	52.41
resolution	0.00006	0.001
Non-linearity	0.0030	0.052
Non-Repeatability	0.0012	0.021

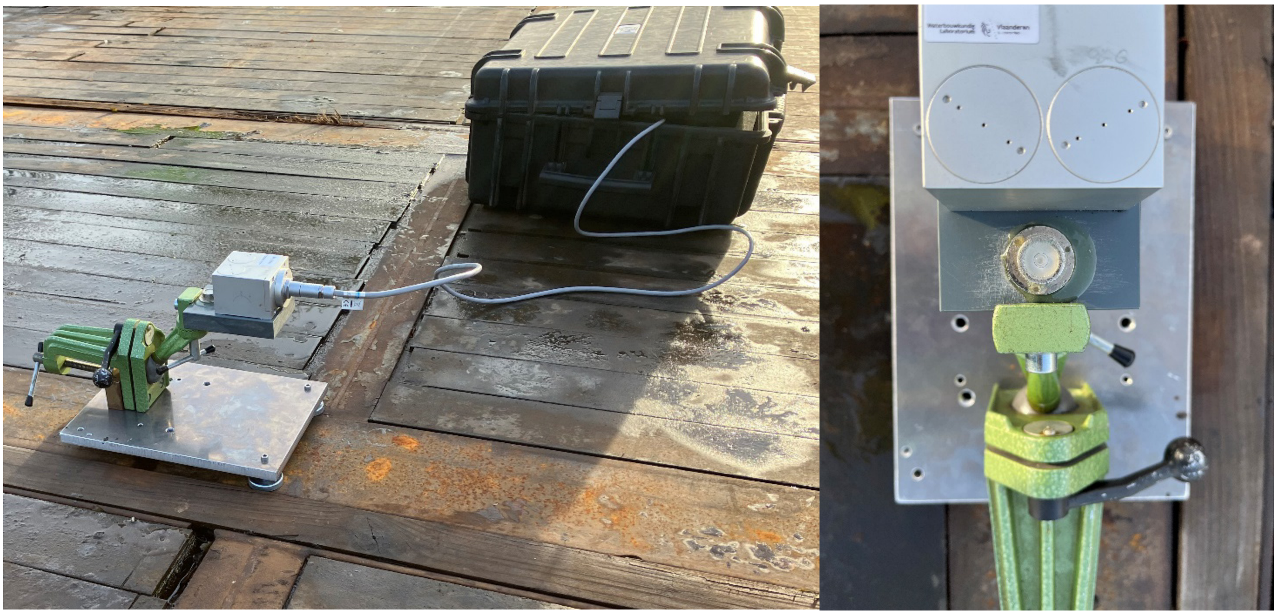
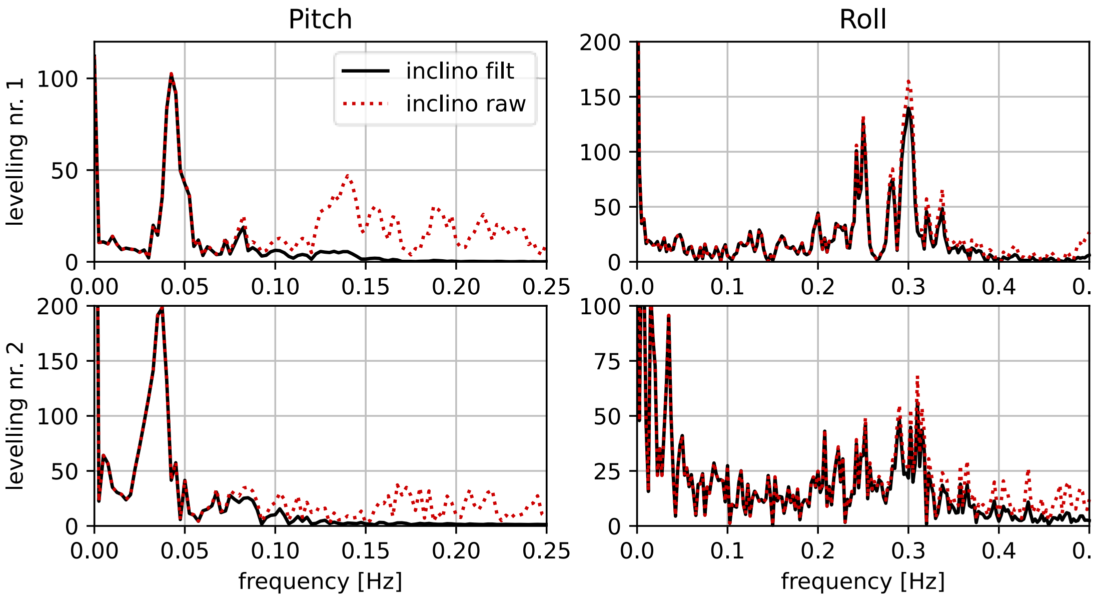


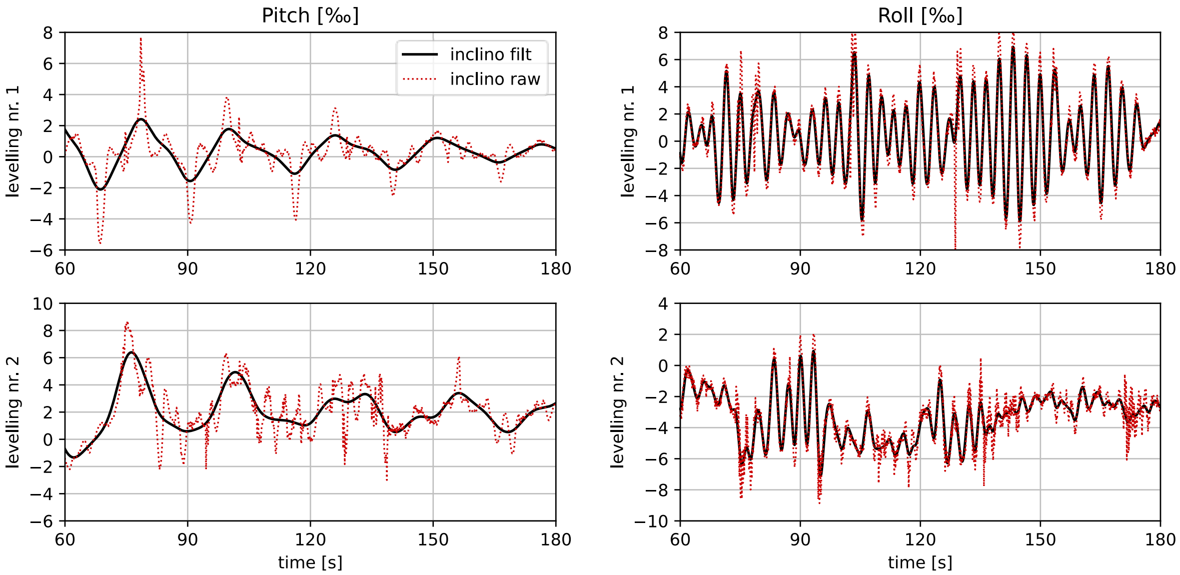
Figure 9 - Inclinometer mounted on deck Zulu I during PoC Iv-Infra

During processing it was found that the inclinometer measurements exhibited a higher order frequency compared to the reference tachymeter and the PoC measurement. The occurrence of a higher order frequency was notably stronger during the emptyings. Although an inclinometer designed for environments with vibrations was deliberately chosen, the measurements appeared to be disturbed by sudden impacts and/or friction. Based on the power density spectrum it was decided to filter out the frequencies not occurring in the reference tachymeter and PoC measurement using a low pass filter, more specific a second-order Butterworthfilter. For pitch, the cutoff frequency was set at 0.1 Hz and for roll the cutoff frequency was set at 0.4 Hz. To illustrate this for the first two levelling processes during the photogrammetric PoC the power density spectrum and the filtered and non-filtered measurements are presented in Figure 10 and Figure 11.



First and second levelling PoC Apixa

Figure 10 - Processing inclinometer measuremetns – illustration low pass filter on the frequency domain



First and second levelling PoC Apixa

Figure 11 - Processing inclinometer measuremetns – illustration low pass filter in the time domain

Two S-type load cells from Zemic, each with a maximum load of 100 kN, were used to measure the forces in the mooring lines. The load cell's were positioned between the mooring lines and the bollards on the lock platform as illustrated in Figure 12. The measurement frequency of the load cells was set at 1 Hz. The load cells had an accuracy +/- 0.5 kN. According to the calibration certificate, the deviation ranges from -0.6 kN to +0.16 kN over the full range and reduces till -0.04 kN at 5% of the full range. Table 4 presents the measurement accuracy with respect to the underwater displacement.

Table 4 - Measurement accuracy with respect to expected force

/	PoC Apixa	PoC Iv-Infra
Full Scale	100000 N	100000 N
5% Full Scale	5000 N	5000 N
1‰ force with respect to ships under water volume	814 N	461 N
Measurement error at 5% FS	40 N	40 N
Measurement error with respect to 1‰ under water displacement = measurement accuracy	0.05	0.09

Figure 12 - Load cell mounted in between mooring line and lock platform bollard

For the synchronization of the PoC measurement of Apixa with the reference inclinometer measurement a local WIFI network with an NTP server was established. The synchronization between the tachymeters was established by a GNSS connecting.

During the POC of Iv-Infra the tachymeters were synchronized before installation. During this synchronization exercise both the Iv-Infra tachymeters as the tachymeters for the reference measurements tracked the gradually movements of the same prism over time. During this exercise the inclinometer was also connected to this prism.

6 PoC photogrammetric technique

The PoC of Apixa with the photogrammetric technique was conducted on the 11th October 2023. The set-up is discussed in paragraph 6.1 and the results are presented in paragraph 6.2.

6.1 Set-up

Vision++ (tradename 'Apixa') specializes in resolving challenging computer vision problems, including photogrammetry systems and measuring the 6 degrees of freedom rigid body motion. A novel multi-camera system has been developed to fulfil the challenging requirements. The proposed design incorporates two stereo-camera systems, each observing the front and rear sides of the vessel. This approach provides a less biased estimate of the overall vessel motion compared to a single stereo system.

The chosen design strategy involves tracking a multitude of naturally occurring points on the vessel surface, departing from conventional marker-based designs. Leveraging the law of large numbers in probability theory and imposing inherent rigidity constraints on the ship's structure throughout the motion track, the system anticipates achieving significantly lower errors compared to single-point stereo triangulation. After a successful initial phase demonstrating accurate tracking in controlled conditions, the current phase extends to assessing the system's ability to track a ships motion in a lock, in real-world conditions.

The system configuration comprises two stereo pairs of cameras mounted on rigid aluminium profiles, with custom-built mounting plates for stability and rigidity, see Figure 13. The 150 cm separation between the two cameras within each stereo pair ensures accurate stereo depth calculations. The cameras are synchronized using a central trigger box, enabling coordinated recording at 1-second intervals.

Individual stereo calibration is a crucial step, and a Charuco board-based procedure is employed, offering advantages over classical checkerboards in terms of visibility requirements. This step can be done before the measurement campaigns and needs only be repeated in case decalibration of the systems is detected. The challenge of co-calibrating two stereo pairs separated by 80 meters is addressed through two methods involving markers and a Leica X4 Disto distance measurement device, see Figure 13.

The co-calibration enables the registration of the two stereo pairs in the same referential. While the marker-based approach involves precise marker positioning, a free-moving markers approach is also developed, enhancing precision by collecting a significant number of points. These marker positions are crucial for aligning the Apixa coordinate system with the reference FH system, facilitating accurate comparisons.

The synchronization of all systems is crucial, and a local NTP server ensures temporal alignment.

Feature detection and tracking for both stereo systems are conducted independently, focusing on local ship surface visual features. A manual step involves selecting highly textured feature areas, and mostly automatic subsequent processes, including corner detection, matching, and tracking, contribute to the overall precision. The Bundle Adjustment (BA) technique is applied for global error minimization, providing a statistically sound averaging of all observations.

Left: stereo pair; upper right: fixed marker; lower right: free moving-marker

Figure 13 - PoC photogrammetric technique – stereovision set-up and markers

Figure 14 - PoC photogrammetric technique – example images

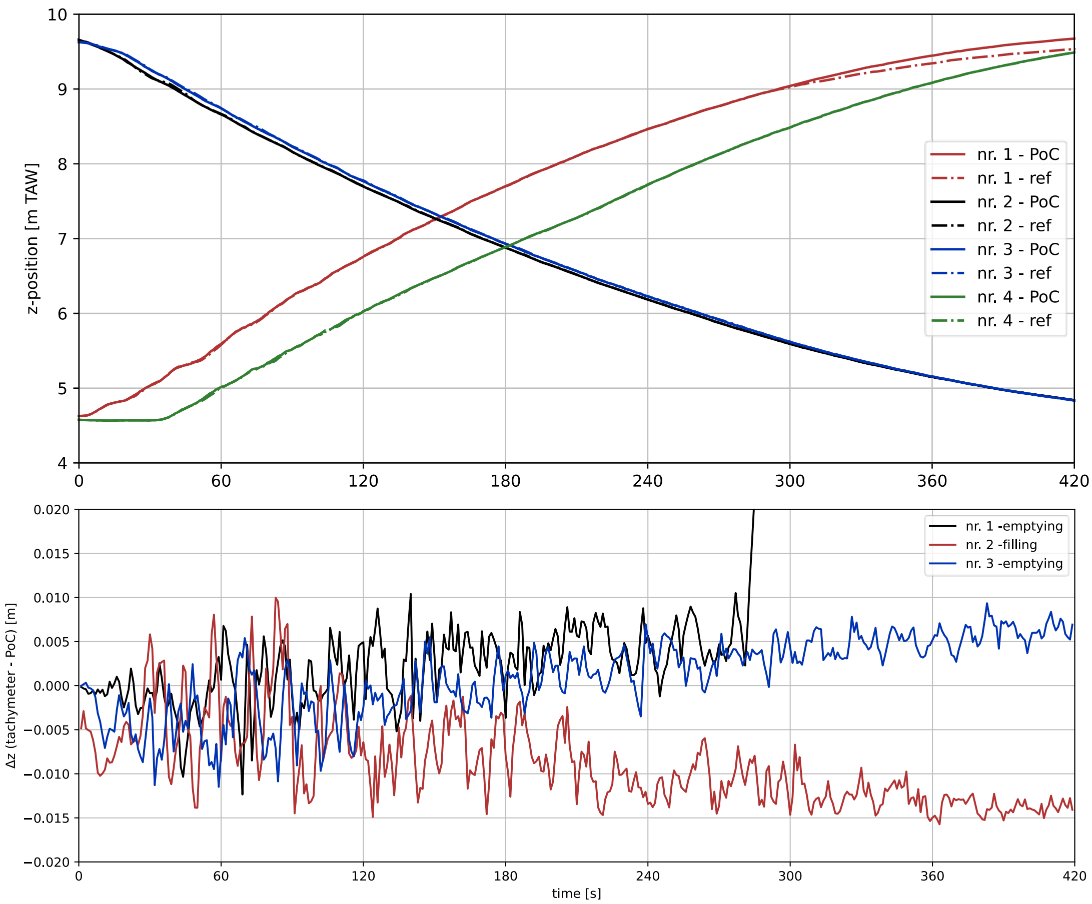
6.2 Results

Apixa processed two lock emptyings and one lock filling, see Table 5.

Table 5 - Proccesed levellings PoC Apixa

Levelling number	start time	type
nr. 1	13:23:50	Emptying
nr. 2	13:44:10	Filling
nr. 3	13:58:58	Emptying

The variation of the z position over time during the three levellings is presented in Figure 15. Note that at 285 s during the first levelling one of the three tachymeters lost connection with its prism. The lower figure presents the deviation between the reference measurement and the PoC measurement. Note that the deviation between both measurement stays within the range -0.015 m till + 0.010 m.



upper : variation of z-position over time / lower: variation of deviation over time

Figure 15 - PoC Apixa – comparison z position ship center

The variation of the pitch over time is presented in Figure 7. During both emptyings the extrema of the pitch reach 1 till 2 ‰. For a ship with a length 50 m this corresponds to a height difference over bow and stern of 0.05 m till 0.10 m. During filling the extrema of the pitch reaches 4 till 6 ‰, corresponding to a difference in height between bow and stern of 0.20 m till 0.30 m. The variation over time is similar for the three different measurements. A very good agreement was achieved between the PoC measurement and the tachymeter reference measurement. Only the second negative peak during emptying is noticeably higher for the PoC measurement compared to the tachymeter measurement. The pitch measured by the inclinometer seemed to be affected by acceleration and deacceleration effects, which appeared to be stronger during emptying.

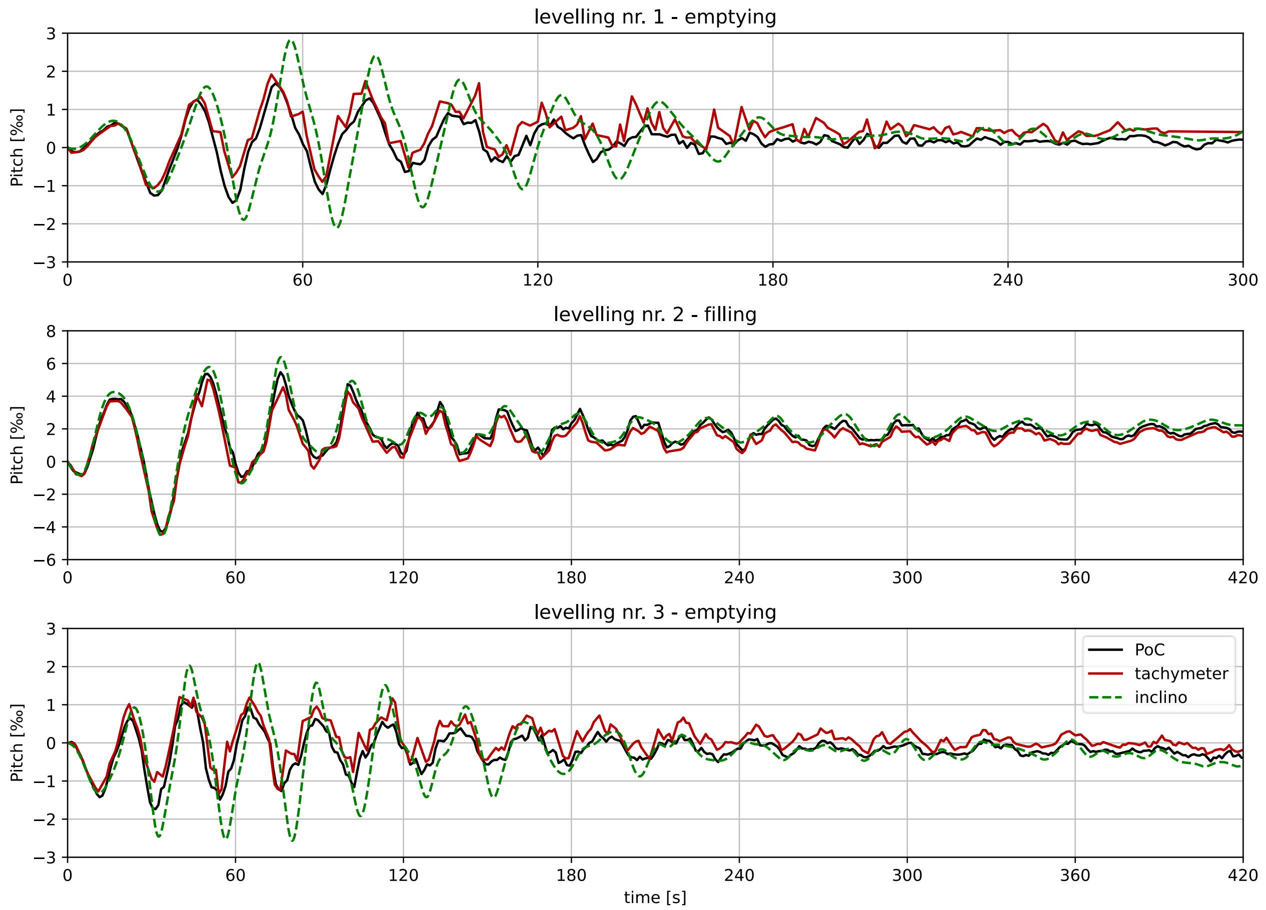


Figure 16 - PoC Apixa – comparison pitch ship

For each of the three processed levellings the value of the first 10 consecutive peaks were derived for the PoC measurements and the tachymeter reference measurement. The peak values were converted to a height difference between bow and stern, and consequently, the deviation in height between both measurement techniques was calculated. Figure 13 presents a probability density distribution of the calculated deviation. For comparison the normal distribution is also plotted in the figure. The median difference between both measurements is limited to -0.006 m with a standard deviation of 0.021 m. The 95 % confidence interval ranges from -0.050 m till 0.044 m.

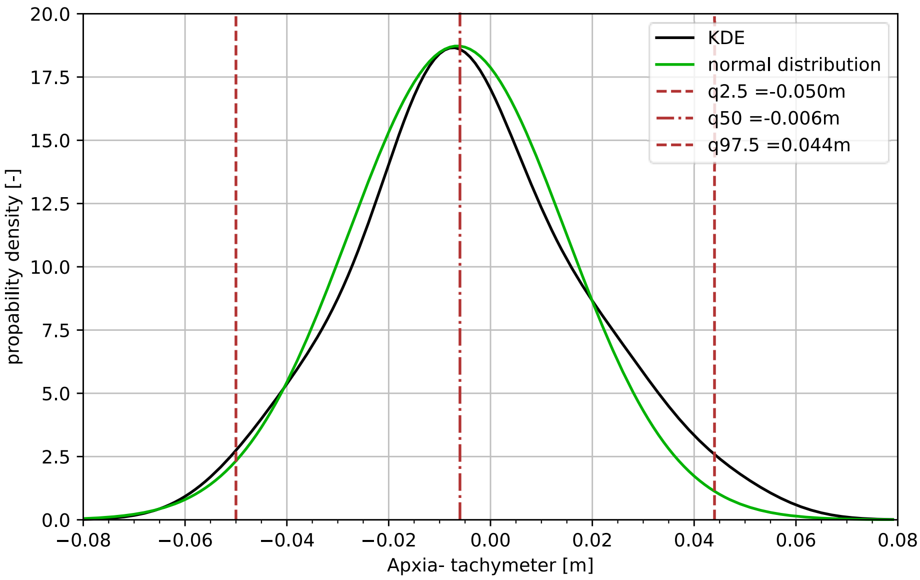


Figure 17 - PoC Apixa – probibility density distribution height difference between bow and stern

The variation in time of the measured roll is presented in Figure 18. he amplitude reaches 6 ‰, which corresponds to a difference of +/- 4 cm between port and starboard for a ship with a width of 6.6 m. During both emptyings the roll is limited to oscillations around zero. For the filling however there is a clear negative trend corresponding to an uprise of the starboard side with respect to the port side. The roll has a period of 3 s to 4 s. Note that the measurement frequency from the tachymeter, set at 1 Hz, is too slow to measure the roll movement. The agreement between the PoC measurement and the inclinometer reference measurement is quite good.”

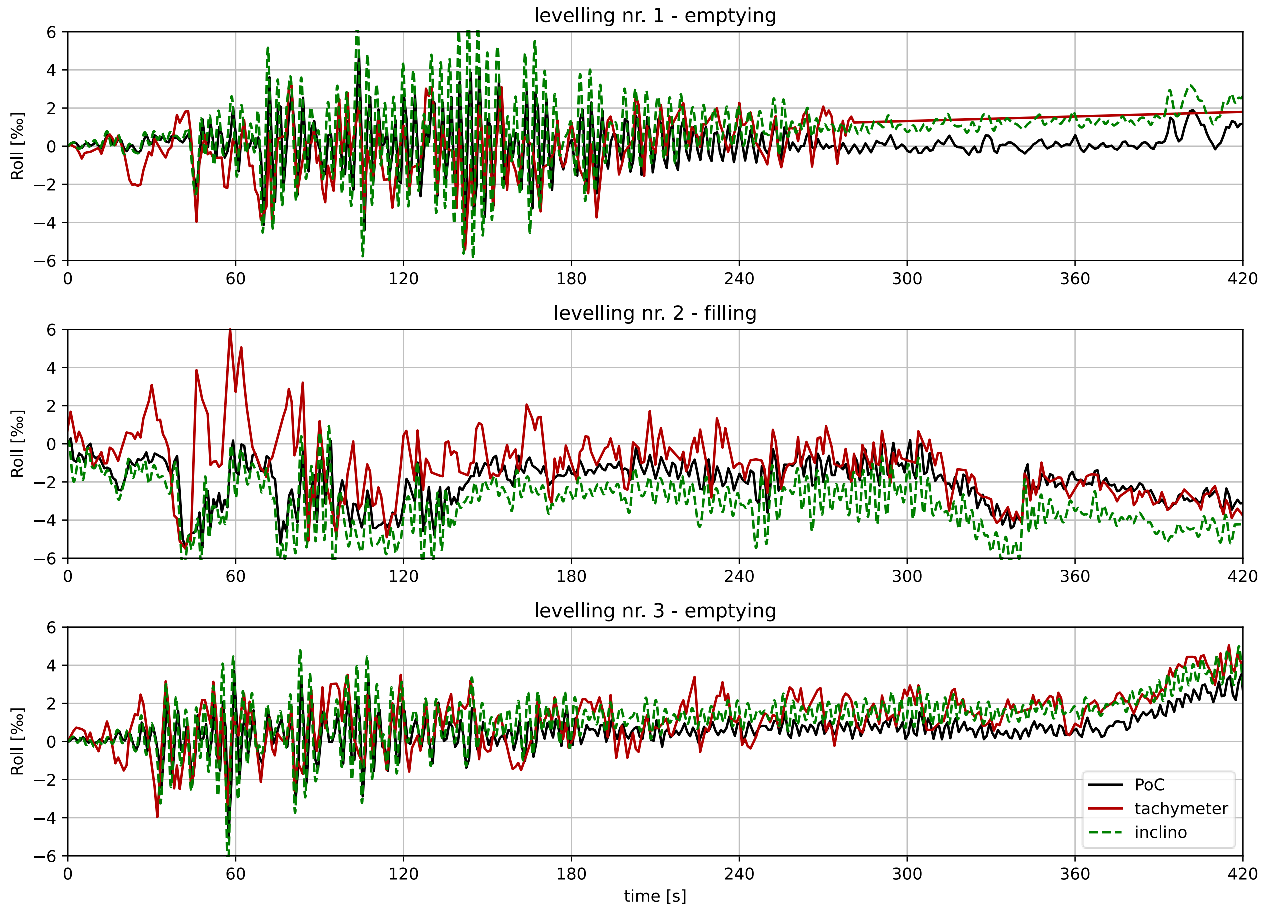


Figure 18 - PoC Apixa – comparison roll ship

The frequency spectra for the pitch and roll is presented in Figure 19. Note that on pitch the agreement is very good with exception of the higher amplitude for the inclinometer during both emptyings of the lock. For the roll the tachymeter reference measurement deviates from the PoC-measurement and the inclinometer measurement.

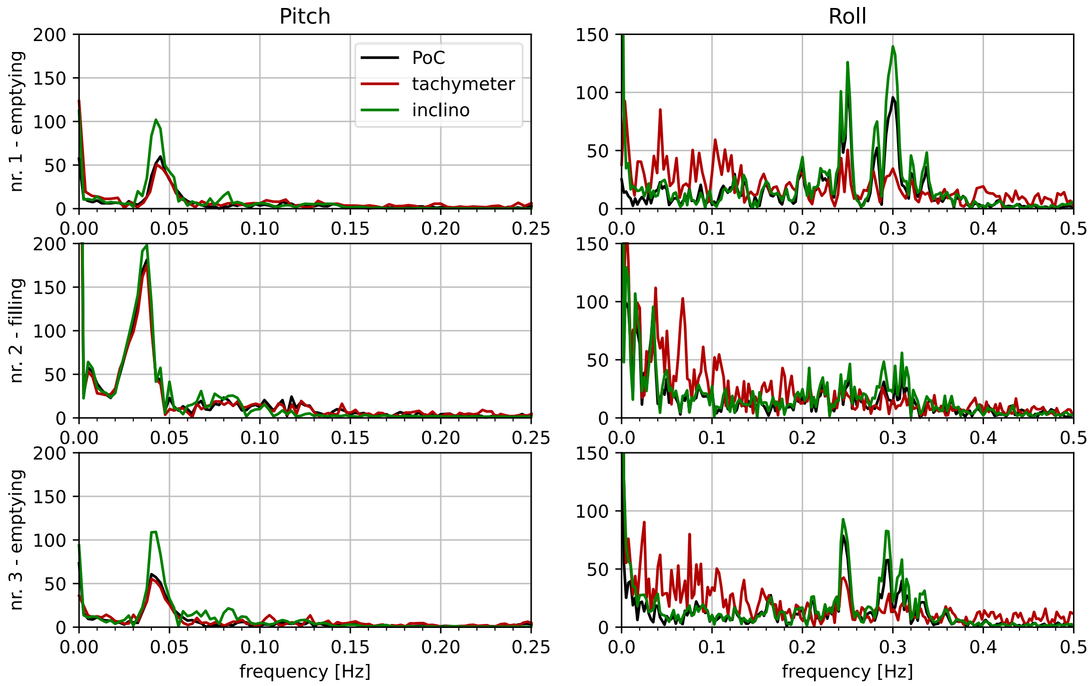


Figure 19 - PoC Apixa- comparison frequency spectra pitch and roll

7 PoC technique with limited non human contact

The PoC of Iv-Infra with the technique based on tachymeters tracking prims positioned by drones was conducted on 8th November 2023. The set-up is discussed in paragraph 7.1 and the results are presented in paragraph 7.2.

7.1 Set-up

Iv-Infra developed a measurement set-up consisting of four tachymeters tracking prisms on the ship positioned by drones. The measurement set-up was developed based on the extensive experience of Iv-Infra with continuous measurement of moving objects by multiple synchronous measuring tachymeters,. The four tachymeters during the PoC are positioned, two by two, on both sides of the lock platform, see Figure 20. By positioning the tachymeters on a measurement portal at approximately 2.5 m above the lock platform the prisms are kept in sight during the full levelling process. By using four prisms instead of the required three the measurement system is over determined. This over-determination provides the flexibility to build controls into the calculations, resulting in improved accuracy and reliability of the final results. Based on the experience of Iv-Infra and demonstrated by the preceding test an accuracy of +/- 1 mm is expected in the three directions for all measured values.

One of the mayor challenges of performing measurements by tachymeters is synchronization, as it is not possible to have a continuous synchronization of tachymeters by a NTP server. Also, a sync pulse is not possible for the deployed tachymeters. To accomplish the synchronization a test is performed by measuring the movements of a common prism by the four tachymeters. To also synchronize with the reference measurements also the inclinometer and a second prism for the tachymeters of the reference measurements were attached to the first prism during this test. The synchronization measurement is repeated during the Proof of Concept measurements because each 0.1 second interval is essential for accurate data processing.

Before the measurements a local coordinate system of the lock was defined and the location of each tachymeter is expressed in this coordinate system. After positioning of the drones on the ship the contours are measured, with respect to the position of the drones in order to determine the local coordinate system of the ship in post processing.

Upper: portal with tachymeters
Lower: portals positioned at both sides of the lock platform

Figure 20 - PoC Iv-Infra – setup tachymeters

Upper left: 360° mini prims mounted on drone / upper right: landing area drones
lower: positioning drones on the ship deck indicated by green circles

Figure 21 - PoC Iv_infra – drones

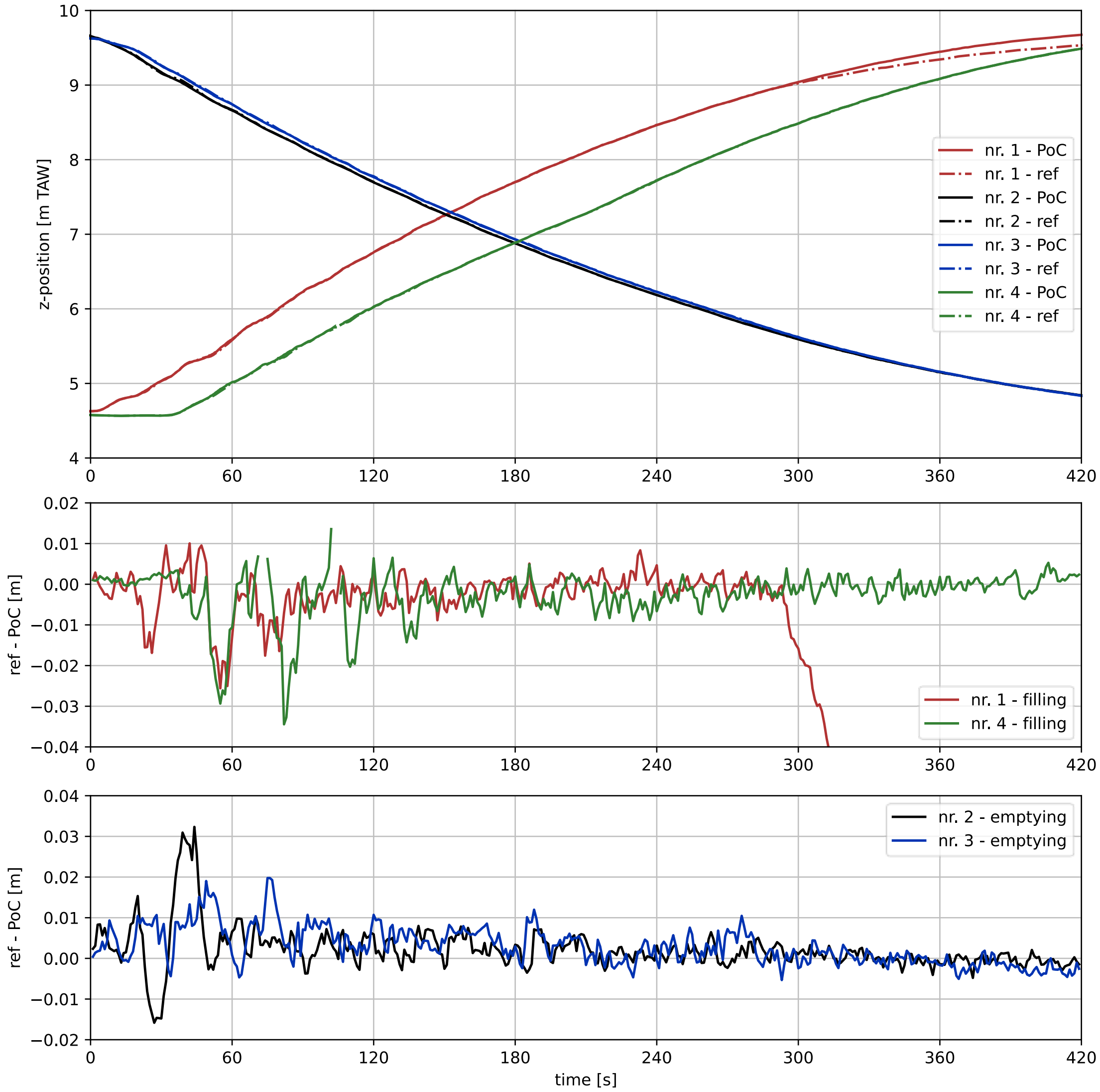
7.2 Results

Iv-Infra processed four levellings. For each lock levelling the type and start time is given in Table 6.

Table 6 - Proccesed levellings PoC Apixa

Levelling number	start time	type
nr. 1	11:00:48	Emptying Emptying
nr. 2	11:29:00	Emptying
nr. 3	12:13:28	Emptying
nr. 4	12:22:05	Emptying

The variation of the z-position over time during the four levellings is presented in Figure 20. The agreement between the reference and the PoC measurement is good. For the first levelling the reference measurement starts to deviate from 292 s onward. The deviation between the two measurements increases to 3 cm at the start of the leveling and subsequently reduces to approximately +/- 1 cm.



Upper figure: variation of Z position over time; middle figure: deviation between measurement Iv-infra and reference measurement during filling / lower figure: deviation between measurement Iv-infra and reference measurement during emptying

Figure 22 - PoC Iv-Infra – Comparison of the variation in time of the Z position of the center of the ship

The variation over time of the measured pitch is presented in Figure 21. Note that the agreement between the PoC and the tachymeter-based reference measurements is good. The reference measurements are slightly smoother, which can be explained by the higher frequency of the PoC measurement (5 Hz compared to 1 Hz). Due to an issue with the synchronization of the reference tachymeter measurement the time series were interpolated from 1 Hz to 5 Hz. This interpolation could also result in a smoothing of the reference tachymeter measurements. The quality of the inclinometer varies, possibly due to the manual handling of the mooring lines, which results in a less fluent process compared to the winch-controlled operation during the first PoC.

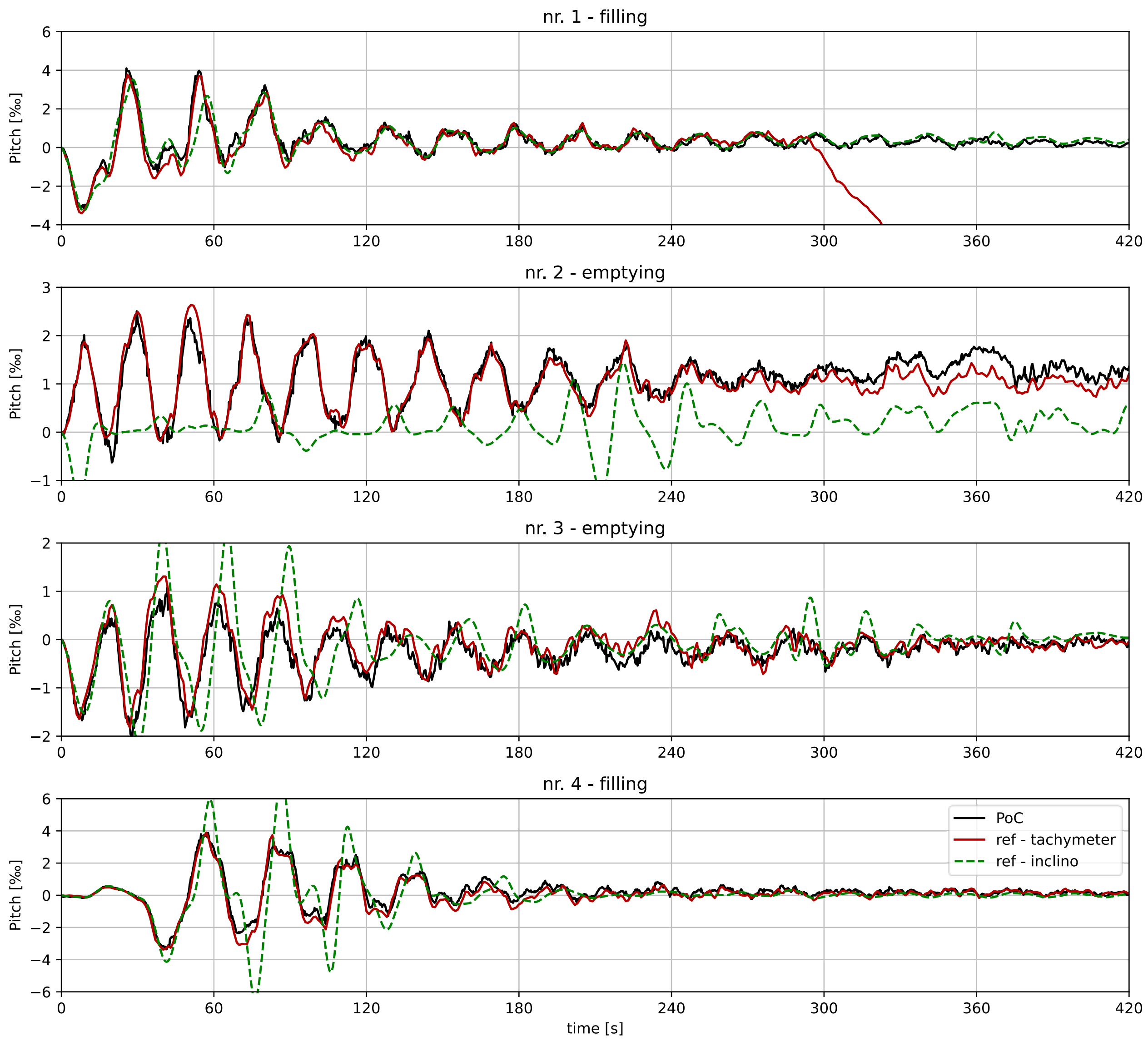


Figure 23 - PoC IV-Infra – Comparison of variation in time of the pitch of the ship

For each of the four processed levelings the value of the first 10 consecutive peaks were derived from the PoC measurement and the tachymeter reference measurement. These peak values were converted to a difference in height between bow and stern and consequently the deviation in height between both measurement techniques was determined. Figure 13 presents the probability density function of these calculated deviations. For reasons of comparison the normal distribution is also plotted in the figure. The median difference between both measurement is limited to 0 mm, with a standard deviation of 0.014 m. The 95 % confidence interval ranges from -0.028 m till 0.032 m.

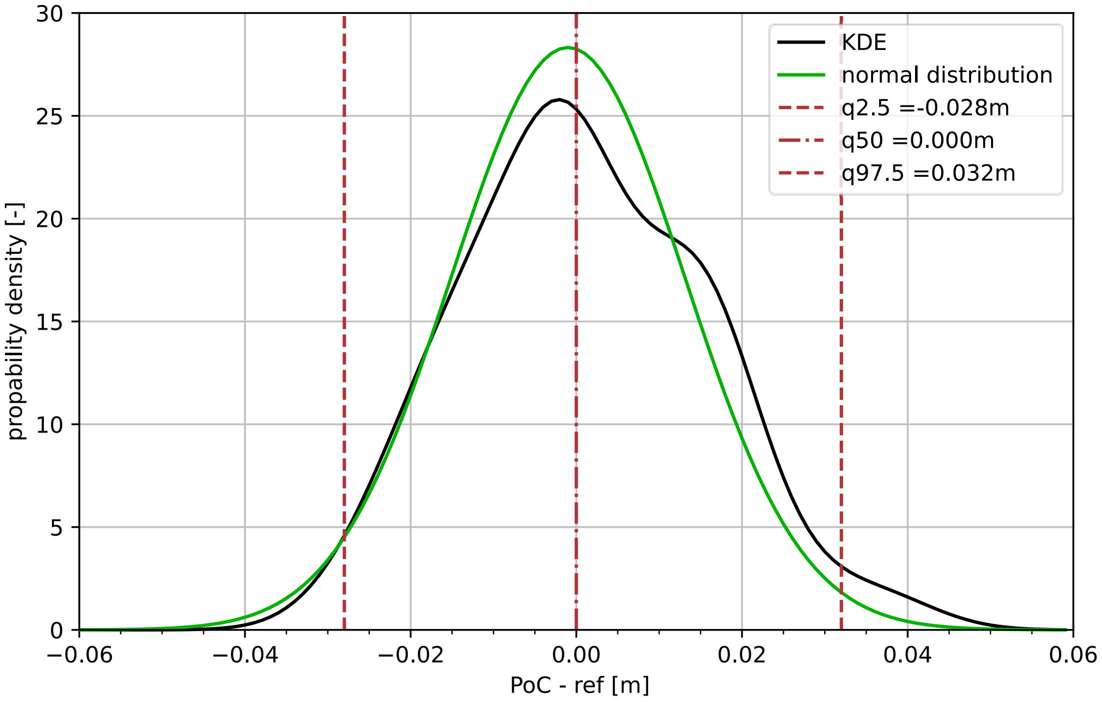


Figure 24 - PoC Iv-Infra – probibility density estimation height difference between bow and stern

The variation in time of the measured roll is presented in Figure 23. Note that the reference tachymeter measurement is not included. Due to the applied time synchronization with sub-second accuracy the measurement of the roll with a period of approx. 3 s becomes unreliable. For the first two levellings, there is a good agreement between the PoC measurements and the inclinometer measurement. However, for the third and fourth measurements, the roll measured by the inclinometer is noticeably lower compared to the PoC measurement, presumably due to a malfunction of the inclinometer. Note that at the end of the second levelling the ship was hanging in its mooring lines.

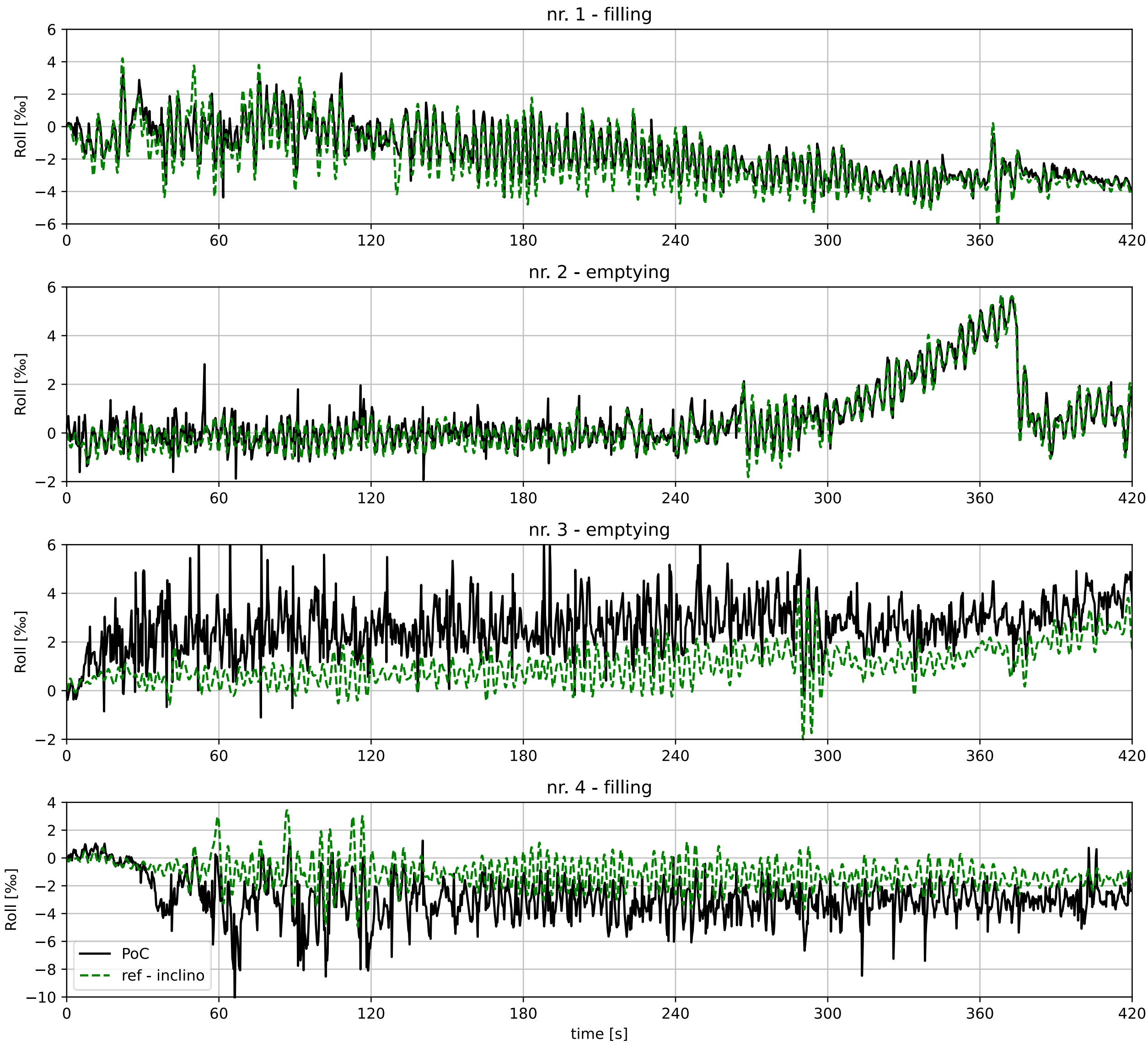


Figure 25 - PoC Iv-Infra – comparison roll ship

For the four measured levellings the frequency spectra of both pitch and roll are presented in Figure 24. For the pitch a clear maximum occurs between 0.037 Hz and 0.045 Hz corresponding to a period of 22 s till 27 s. For the pitch the agreement between the PoC-measurement and the reference measurements is very good for both lock emptyings. For the roll of the ship the agreement between the frequency spectrum derived from the PoC-measurements and the inclinometer measurements is quite good for the first two levellings.

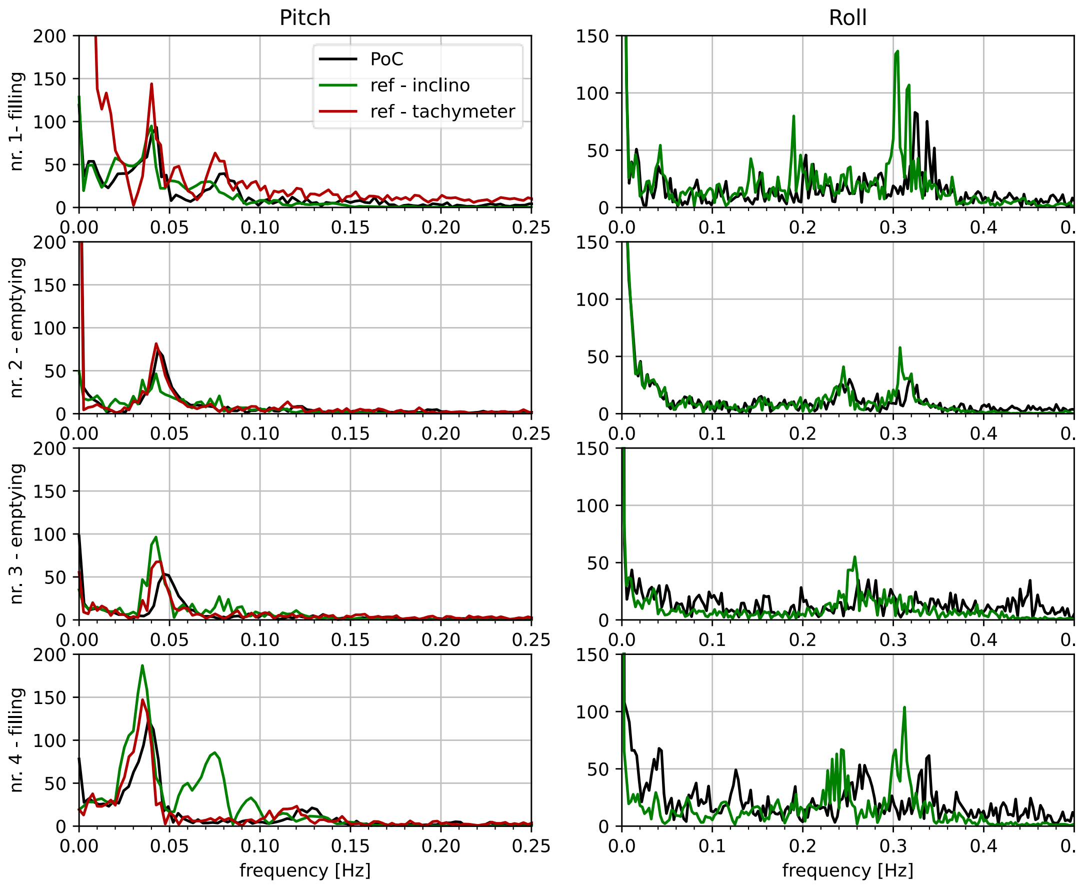


Figure 26 - PoC IV-Infra- comparison frequency spectra pitch and roll

8 Conclusions

Flanders Hydraulics has identified the need of a new measurement technique for performing validation measurements of levelling systems of locks in Flanders. The proposed measurement technique is based on the measurement of the pitch and roll of a ship in the lock, which are considered reliable indicators of the longitudinal and transversal forces acting on a ship during the levelling process of a lock. The set-up of the measurement system must prioritize accuracy, safety, and efficiency, with a limited mobilisation and demobilisation time. To be both safe and efficient the measurements must be completely remote without human contact with the ship or as remote as possible with only minimal non-human contact with the ship in the lock chamber.

Because of the innovative nature of the new measurement system, the project was supported by the Programme for Innovation Procurement (PIO) of the Flemish Government. A preliminary study conducted by the consultancy company Verhaert concluded that no off-the-shelf solution is available and that the requirements for the new measurement technique were identified as technically possible but challenging. Therefore, it was decided to proceed with the execution of Proof of Concepts. The first PoC, being completely contactless, was awarded to Apixa and involved a photogrammetric set-up. The second PoC with non-human contact with the ship was awarded to Iv-Infra and involved a set-up consisting of tachymeters. Both parties demonstrated by a dry test the quality of their set-up first half of 2023. The real Proof-of-concept was conducted in fall 2023 in the lock of Viersel. For both PoCs a commercial vessel was chartered and equipped with a reference measurement set-up. Within the PoC of the photogrammetric technique three levellings were processed (two emptyings and one filling), within the PoC using the tachymeters four levellings were processed (two emptyings and one filling).

Because the pitch is considered as a measure for the longitudinal force that ships encounter during levelling, the evaluation focused mainly on the pitch. Both for the PoC with the photogrammetric technique as for the PoC with the technique with non-human contact the correspondence between the pitch measured by the PoC set-up and the pitch measured by the reference tachymeter set-up was good. The correspondence with the inclinometer measurement varies from levelling to levelling. IUpfront the inclinometer was considered the most accurate and therefore the reference measurement for the pitch. Due to an unexpected inertia sensitivity with the inclinometer, it is not possible to quantify the accuracy of the PoC measurements. Consequently, a comparison between the extrema of the pitch measured during the PoCs and measured using the reference tachymeter is performed. The median value of the difference between the pitch measured during the PoC and the pitch measured with the reference tachymeter was equal to 0.006 m with a standard deviation of 0.021 m for the completely contactless PoC with the photogrammetric technique and equal to 0.000 m with a standard deviation of 0.014 m for the PoC with non-human contact using tachymeters.

Generally, both PoCs are assessed as follows:

1. PoC with photogrammetric measurement:

   The measurement set-up was developed specific for the PoC. From the pre-study a lot of questions and uncertainties arose about the feasibility of processing non--remote measurement techniques within the foreseen budget for the PoC. The PoC of Apixa demonstrated that the state of technology was further than expected by processing three full levellings within the PoC and one during a test beforehand. The developments needed to scale the proof of concepts towards an operational set-up are assessed as feasible.

2. PoC with non-human contact using tachymeters:

   The most important concerns about the applied measurement set-up is the use of three to four tachymeters being cumbersome. Also the positioning of the drones on a conventional inland navigation vessel could become rather difficult.

Both proof of Concepts proved that the technology is sufficiently mature to proceed with the development of an operational system. Flanders Hydraulics considers such a system essential for various purposes, including the validation and optimization of lock levellings, safety assessments, addressing new future challenges such as remote control and uncrewed shipping, redefining force criteria based on simulated and measured forces in mooring lines and the validation of numerical models.

9 References

Beem, R.C.A.; Boogaard, A.; Glerum, A.; de Graaf, M.A.; Henneberque, S.D.; Hiddinga, P.H.; Kranenburg, D.; van der Meer, M.T.J.; Nagtegaal, G.; Van der Paverd, M.; Smink, L.M.C.; Vrijburcht, A.; Weijers, J. (2000). Design of locks. Ministery of Transport, Public Works and Water Management. Civil Engineering Division: Utrecht

InCom Working Group 155. (2015). Ship Behaviour in Locks and Lock Approaches. PIANC

Ministerie van Openbare Werken - Bruggen en Wegen - Dienst der Zeeschelde. (1962). Netekanaal Vierselsluis Herstellingswerken Deuren - c4 3362. 1 pp.

Schouten, M. (2019). Hoge dwarskrachten in de Nieuwe Sluis : wordt het realiteit ? Een onderzoek naar optredende dwarskrachten tijdens het nivelleren in de Wetslsuis: 34

Vercruysse, J.B.; Poitoux, S.; Ozden, E.; Goossens, M.; Aerssens, P.; Van Bastelaere, F.; Verelst, K.; Depreiter, D.; Wolput B., B.; Schrijvers, A. (2024a). Development of a new measurement tool for validating lock levelling, ***in***: (2024a). *Proceedings of the 35TH PIANC WORLD CONGRESS 2024, Cape Town, South Africa, 29 April – 03 May 2024*. PIANC. ISBN 978-2-87223-041-9. pp.1485–1491. Available at: https://documentatiecentrum.watlab.be/owa/imis.php?module=ref&refid=395780

Vercruysse, J.B.; Verelst, K.; Lopez Castaño, S.; Wolput, B.; Schrijvers, S. (2024b). Ontwikkeling meetopstelling voor het opmeten van scheepsbewegingen WL Rapporten, 19_084_1 [CONCEPT]: Antwerpen

DEPARTMENT **MOBILITY & PUBLIC WORKS**
Flanders hydraulics

Berchemlei 115, 2140 Antwerp
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
flanders.hydraulics@vlaanderen.be
www.flandershydraulics.be