Analysis of particles transportation applied to a ship's ballast system by using fastcam recorded images

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Abstract. High-performance imaging techniques represent the present of academic and industrial research. The use of these technologies in the maritime sector sees different applications in different phases of the life of a ship: photogrammetry in the design phase and the use of Lidar sensors to measure emissions are just a few examples. The novelty of this study is the application of these acquisition techniques to ship ballast systems. The new ballast water management regulations aimed at limiting the alteration of the marine ecosystem has overturned the canonical use of the ballast systems. In recent years, studies have shown how the spillage of ballast water has generated the proliferation of invasive species in seas all over the world. For this reason, the IMO has tried to regulate these operations. In this work, transportation phenomena of sediments through the duct, suctioned by a pump have been analysed. The inspected duct has been exposed to a CMOS MINI FASTCAM AX100. This camera was used to acquire images that allow studying the behaviour of the particles. With the use of a Matlab toolbox, a post processing of the images has been realized in order to estimate the speed and accelerations of the particles.

1. Introduction

Ballast water (BW) is required for safe and efficient ship's operation during the voyage, so preserving maneuvering capabilities and transverse stability of cargo. In addition, with the use of BW, the seaworthiness and maneuvering capabilities of the ship are preserved and variations in weight distribution caused by fuel consumption are well balanced.

However, BW involves both economic crises, due to damage in marine fauna, and ecological problem owing to several plant and animal species transported through the BW with destruction of biodiversity, also affecting human health. In fact, waters in the ports are often contaminated by an array of chemicals due to industrial activities. Hence many problems are caused by the presence in BW of harmful aquatic organisms and pathogens (HAOP), aquatic invasive alien species (IAS), and sediments. Really, different non-indigenous species (NIS) are introduced through the BW, like cysts and larvae, bacteria, microorganisms, and several viruses [1]. In this regard, amongst the different aquatic species transported through the BW, the most dangerous and potentially toxic NIS which can affect human health are the following [2]: Cercopagis pengoi, Carcinus maenas, Vibrio cholerae (bacteria cholerae), Mnemiopsis leidyi, Neogobius melanostomus, Eriocheir sinensis, Asterias amurensis (North pacific starfish), and Dreissena polymorpha. The abundant presence of non-indigenous species and toxic dinoflagellate species was found [3] in BW tanks of 65 cargo ships arriving to the East Coast of Canada between 2007 and 2009. This study reported that potentially viable dinoflagellate cysts were introduced in ballast sediments, with 14 non-indigenous dinoflagellate cyst species representing a severe risk of
new potentially harmful species. Based on this study, it was stated that the introductions of such toxic NIS could involve several problems for the marine ecosystems due to destruction of biodiversity, also involving human health and with potentially devastating effects on aquaculture, tourism, and fishing.

Figure 1. Ballast exchange

The IMO (International Maritime Organization) convention on the management of ship’s BW [4], which has entered in force since September 2017, correctly deals with the control of HAOP and IAS through appropriate treatments of BW, but unfortunately the ecological and health problems related to sediments in BW are not suitably treated. In fact, the national regulations defining procedures for sediment control and management are not totally established yet. Consequently, procedures and requirements for sediment treatment facilities are missing at national levels [6]. However, regulation B-5 Sediment Management for Ships, in agreement with the Ballast Water Management Plan (BWMP), establishes that new ships should provide safe access for sediment sampling and reduce the undesirable entrapment of sediments [7]. Besides, the IMO BMW Convention [4] states that ports and terminals must be able to acquire suitable equipment and facilities for the reception of sediments; besides, the IMO BMW Convention also states that terminals must be prepared to eliminate all organisms present in BW and to clean ballast tanks. Hence, recently an increased interest has been observed in ballast tank sediments. The size of sediments in the tanks depends deeply on both the characteristics of the tank (so varying amongst ships) and the sediment composition of the ballast water itself. Generally, ballast sediments can be grouped on the base of size, as in the following classification [8]: clay, particles lower than 2 μm; silt, particles lower than 65 μm; sand, particles lower than 2 mm; sediment, particles greater than 2 mm; higher sediment products resulting from corrosion processes. The accumulated volume of sediments in the tanks depends on the ship’s ballast management procedures and can reach a thickness of more than 30 cm [9]. In this regard, the sediments must be removed from the BW tanks and such sediment removal typically occurs during the usual dry-dock maintenance; this process takes place usually every 30 months [10]. Besides, it must be taken into consideration that appropriate systems for the treatments of BW are based on UV irradiation [11], but abundant presence of sediments in BW reduces the efficiency of these techniques that cannot eliminate all harmful aquatic organisms and pathogens present in BW. In effect, the presence of sediments in BW significantly decreases the efficacy of such techniques because the ballast sediments protect small organisms and aquatic invasive alien species from exposure to UV irradiation, so inhibiting the delivery of a durable lethal dose to HAOP and IAS.

Starting from all these considerations, the purpose of this study is to contribute to the development of an experimental study of transport phenomena. In this regard, it is important to stress that ballast sediment is an extremely heterogeneous material so that its characterization involves a testing plan in response to the sediment accumulation in the tanks.

This paper presents the first results of an experimental campaign carried out thanks to the collaboration of the Naval and Mechanical Engineering departments of the University of Naples Federico II with the IMAT training center. The experimental campaign aimed at weighing the feasibility of experimental tests of this kind, aimed at studying the behavior of sedimentary residues in ballast
waters. In fact, several studies approach this problem by taking into consideration only the tanks; in this case, instead, the work focuses on the pipelines.

2. Experimental setup

The experimental equipment was designed with the intention of creating a system capable of visualizing the motion of solid sediments carried by a liquid stream, with the varying of the size of the particles and of the speed of the liquid stream. To carry out the tests, an equipment for visualizing the flow field in the rotor of a centrifugal pump was upgraded. The system consists of a partially transparent hydraulic circuit, consisting of a centrifugal pump, a circulation ring with plexiglass pipes, a bypass valve and a motorized lamination valve. The pump is driven by an electric motor powered by an inverter. A volumetric flow meter allows to view the water flow rate values as the number of revolutions of the pump and the position of the control valves vary. The possibility of varying the speed of the pump, thanks to the inverter, and the availability of a bypass valve on the circuit, allow for a wide range of variation in the flow rate and therefore in the water velocity in the circuit. The inspection area is located in the suction duct at a distance from the pump that is not influenced by the fluid dynamic phenomena occurring in the rotor.

![Figure 2](image2.png)

**Figure 2.** Layout of experimental set-up. A - Centrifugal Pump. B - Motorized Valve. C - Volumetric Flow meter. D - Camera. E – PC for plant control and image acquisition. F – Inverter electric motor.

As shown in Figure 3, both the intake duct and part of the rotor case are made of transparent plexiglass. This allows one to film the motion of the particles and analyze it offline with appropriate software.

![Figure 3](image3.png)

**Figure 3.** Transparent suction pipe and pump flange  
Main characteristics of electric motor and pump are summarized in Table 1.
The characteristics of the pumping system are as follows:

| Component                          | Characteristics   |
|------------------------------------|-------------------|
| Single-phase asynchronous motor:   | P = 9 [kW]        |
| Rpm                                | n = 2890 [rpm]    |
| Voltage                            | 380 [V]           |
| Frequency                          | 50 [Hz]           |
| Centrifugal pump: flow             | Qmax = 5.0 [m^3/h]|
| Pump head                          | Hmax = 19.5 [m]   |
| Rpm (max)                          | nmax = 2850 [rpm] |
| Plexiglass suction tube: length    | L = 500 [mm]      |
| diameter                           | D = 50 [mm]       |

The CMOS MINI FASTCAM AX100 is Photron’s high performance model within the FASTCAM Mini series of high-speed cameras. The Mini AX delivers exceptional light sensitivity, excellent image quality and flexible region of interest (ROI) features. Three performance level models - Mini AX50, AX100 and AX200 - deliver 1-megapixel image resolution (1024 x 1024 pixels) at frame rates up to 4,000fps. The AX100 Mini AX models offer a minimum exposure duration of 1μs as standard with recording memory options up to 32GB, providing extended recording times and triggering flexibility. Subject to export approval the Mini AX100 can be offered with maximum frame rates up to 540,000fps with a minimum exposure time of 260 nanoseconds. Standard operational features of the FASTCAM Mini AX include a mechanical shutter to allow remote system calibration, Gigabit Ethernet Interface for reliable system control with high-speed data transfer to PC, and the ability to remote switch off cooling fans to eliminate vibration when recording at high magnifications. With the combination of high frame rates, high image quality and exceptional light sensitivity contained within a 120mm x 120mm x 94mm rugged camera body weighing just 1.5kg, the FASTCAM Mini AX is suited for use in a wide range of demanding scientific and industrial applications including combustion imaging, and microfluidics. The camera (Figure 3) was used to register the motion of sediments inside the suction transparent pipe. The minimum exposure time is of 1.05μs selectable independent of frame rate. The region of interest is selectable in steps of 128 (horizontal) x 16 (vertical) pixels, the dynamic Range is of 12-bit monochrome and 36-bit color.

Below, in Table 2, some typical record duration (in frames) as function of image resolution and memory.

| Image Resolution | 4GB Memory | 8GB Memory | 16GB Memory | 32GB Memory |
|------------------|------------|------------|-------------|-------------|
| (hxv pixels)     | 2,726      | 5,457      | 10,918      | 21,841      |
| 1024x1024        | 10,906     | 21,829     | 43,674      | 87,365      |
| 512x512          | 43,626     | 87,317     | 174,698     | 349,461     |
| 256x256          | 174,506    | 349,269    | 698,794     | 1397,845    |

Photron CMOS CAMERA AX-100 installed on the inspection zone, see Figure 4. The inspection zone was highlighted by using a halogen HLX 64627 - OSRAM 12 V 100 W, to have a high quality image shooting. A strong light intensity was required due to the reduction of light because of the shutter exposure time decreasing with increasing the frame rate of the image acquisition. This choice was made to cut frequencies, especially low frequencies that would alter the distribution of gray tones in the image. The light emitted by Xenon lamp has a wavelength of approximately 650 nm, for which the Fastcam Photron UX100 sensor is particularly stable and sensitive. A standard 50mm Canon lens was used to
facilitate the image acquisition. This choice does not allow a good magnification ratio but supplies a stable image with a shallow depth of field.

The image sensor used is the active C-MOS, or Active Pixel Sensor, consisting of an integrated circuit, a Bayer filter, a pixel matrix, a digital controller and an A/D converter.

Each of these components contains a light sensor and a signal amplifier. In addition, an analog converter and a digital controller are part of the same integrated circuit.

The light comes through the lens and it is processed by the color filter before reaching the pixel array. Once the filtered light reaches the matrix, each individual pixel converts the light into an amplified voltage, which will be processed by the rest of the sensor.

Photron Software Package (v 4.0.3.4), which was used for image processing, allows to extract individual frames from the video. Photron FASTCAM Viewer software (PFV) provides a comprehensive and integrated imaging software trusted by professionals in a diverse range of industrial and scientific high-speed imaging environments.

The particles used for the tests are grains of silica sand with dimensions ranging between 0.4 and 0.8 mm. The raw sand was subjected to a separation process through calibrated sieves (see Figure 5), made of a woven mesh fabric, which were arranged in series of decreasing mesh dimension, fixed to the base of an open cylindrical container.

Four diametrical classes were identified through the sieving operation: $d_1 = 0.8 \text{ mm}$, $d_2 = 0.7 \text{ mm}$, $d_3 = 0.6 \text{ mm}$, $d_4 = 0.4 \text{ mm}$. This operation made it possible to carry out tests with fixed particle size particles in a well-defined range, see Table 2. Moreover the granules were weighed on an analytical balance with a capacity of 120 g and sensitivity 0.1 mg (Gibertini E42 scale was used), see Figure 6.
3. Measures and results

After setting the acquisition systems, the pump has been set on 1900 rps with a constant flow rate in the pipeline equal to 1960 l/h. Given a water section of 50.8 mm and the flow rate, the average flow velocity obtained is of 0.27 m/s. The high-resolution images acquired by the camera allow to detect, instant by instant, the positions, speed, and acceleration of a single particle, Figure 7 and Figure 8.

| Diameter (mm) | Average weights (mg) |
|---------------|----------------------|
| 0.8           | 0.0022               |
| 0.7           | 0.0017               |
| 0.6           | 0.00094              |
| 0.4           | 0.00069              |

Figure 6. Analytical balance (Gibertini E42)

Table 3. Average weight

Figure 7. Transparent duct and particles

Figure 8. Image acquisition
The displacement of the particle every 5 frames were evaluated; therefore it is possible to write a proportion between time and frames, thus it is possible to estimate the time for the particle to move

\[ t = \frac{5\text{fps} \cdot 1s}{250\text{fps}} \text{[s]} \] (1)

\[ \Delta t_1 = 0.02 \text{[s]} \] (2)

\[ \Delta t = \Delta t_{i-1} + 0.02 \text{[s]} \] (3)

Known that 681 pixels correspond to the 50.8 mm duct section, it is possible to estimate the displacement of the single-particle as a function of the pixels through the proportion:

\[ \Delta s = \frac{50.8 \cdot \text{no \ pixel}}{681 \text{ pixel}} \text{[mm]} \] (4)

where \( \Delta s \) is in mm. Known the time and the displacements, speeds are then obtained for each chosen particle. The images recorded as in Figure 8 must be changed so that correct information can be extracted. As shown in Figure 8, the images are digital and have a chromatic interval ranging from 0 to 255 where 0 represents black and 255 represents white. To follow the particles precisely, all the images are binarized following an algorithm that represents a neural network formed by two visible peripheral layers and an incremental number of hidden layers that translate the image into a sequence of partial images until the best image is defined, binarized i.e. formed by only white (255) and black (0) pixels [12]. Figure 9 shows the sequence from gray scale to binary scale.

![Figure 9 Binarization sequence](image)

In this way it is possible to easily distinguish the transported particles, and it is easy to trace the trajectories of the particles correctly and, knowing the frequency of acquisition of the images, it is possible to derive the velocities of the particles.
The measurements have been calculated when the particles position is close to the middle of duct to analyze the interaction between the main undisturbed water stream and the particles. In fact, the behavior of the particles changes totally when they are close to the bed formed by the agglomeration of particles [13]. Graph 10 shows that for particle diameters greater than 0.4 mm, the trend increases for a certain interval of time and then, reached a maximum value, decreases. The behavior of particles with a diameter of 0.4 mm differs in that the local inertias to be overcome for displacement are lower; consequently, the trend of the curve and the absolute values are different with respect to the larger diameters. Basically, the particles with a diameter of 0.4 mm follow the flow. In fact, the figure shows how the particle progressively overcomes the inertias and begins to be affected by the speed of the fluid that develops along the axis, gaining speed. The maximum point represents the equilibrium position; immediately afterwards, it begins to be affected by the weight force and there is a decrease in speed. What we said above is supported by the fact that the acceleration gradient changes sign at these points. The slopes of the branches increasing in speed for larger diameters are lower and consequently the maximum point of each curve is gradually more advanced as the diameter of the particles increases. This is justified by the increase in the inertia that must be overcome to ensure that the particle follows the flow. To confirm this shift towards times longer than this maximum point, it is sufficient to observe how the section of the decreasing curve is gradually shorter as the diameter of the particle increases.

The Reynolds number is an essential parameter to understand in what motion conditions the pipeline works and it can be calculated by using the following equation. It is function of the diameter of the pipeline 0.05 m, dynamic viscosity (μ) 8.9 x 10^4 Pa · s, fresh water density (ρ) 997 kg/m^3 and of the speed average flow rate. Under these conditions a turbulent motion is obtained with a Reynolds number of 1.55·10^4. The turbulent flow regime thus obtained is in line with the minimum values of the Reynolds number that can be identified in the real ballast systems installed on board of ships. In this application it has been possible to estimate the Reynolds number as a function of the particle diameter (see eq. 5). The formula takes into account a relative velocity between flow and particle.

$$\text{Re_d} = \frac{\rho \cdot v_p \cdot v}{\mu}$$  \hspace{1cm} (5)

Where d is the particle diameter, $v_p$ the average speed of the particles obtained and v is the speed of water. Below the results obtained for each diameters are reported.

**Figure 10** Particles velocity
Figure 11 shows that the Reynolds number grows as the diameter up to increase a maximum of 0.4 mm. The motion speed changes, however, for diameters equal to or less than 0.4 mm. In this case, the flow is in transition regime. Thus, it is possible to state that the particles tend to settle although the pump when it is activated is able to create a turbulent motion.

4. Discussion and conclusions

The environmental impact of the maritime traffic is in the spotlight on a global scale. The problem of ballast water sediments is one of the topics that must be addressed on a large scale to safeguard the marine ecosystem.

The experimental campaign carried out made it possible, with few measures, to calibrate the acquisition system and to plan further tests aimed at studying the transport of sediments. The acquired data can be processed with various image post-processing software, present in the MATLAB environment for example. The instrumentation used proved to be valid coupled to the available system. Further investigations will concern the use of sediments increasingly similar to those taken inside the ballast water tanks. Furthermore, analyzes will see the extension of the study not only to the ducts but also to the ballast tank, which will be able to simulate the ship's motions. The work presented here seeks to understand how the sediments present in the water, which are concentrated in the ballast tanks, respond to the stresses due to the passage of a current of water. It is well known that sediments coalesce inside the ballast tanks and in the pipes, giving rise to very resistant agglomerates but it is also true that the continuous stress of a violent current of water generates tangential forces capable of breaking these agglomerates and transporting the particles that are formed. The study carried out here highlights how the transport of particles is strongly dependent on their size. The analysis was conducted by taking as a reference a very significant range of diameters as it happens inside the pipes. The results showed that truly transportable particles have a diameter of less than 0.6 mm for a stream having a flow rate of about 5000 l/h. Then, by analyzing the Reynolds number trend of the relative velocity between particle and current, it is evident that the mass forces play a very important role in transport. Larger particles have higher mass forces and are poorly carried by the current. On the other hand, particles with a diameter of 0.4 mm have almost the same speed as the current, resulting in their inertia being completely negligible.

References

[1] Gonçalves, Gagnon (2012) Recent technologies for ballast water treatment. Ozone Sci Eng 34:174–195
[2] Carlton, J. T. (1985). Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. Oceanography and Marine Biology, 23, 313-371.
[3] Casas-Monroy, O., Roy, S., & Rochon, A. (2011). Ballast sediment-mediated transport of non-indigenous species of dinoflagellates on the East Coast of Canada. Aquatic Invasions, 6(3), 231-248.
[4] IMO BMW Convention (2004). http://www.imo.org/en/About/.
[5] Conventions/ListOfConventions/Pages/International-Conventionfor-the-Control-and-
Management-of-Ships'-Ballast-Water-andSediments-(BWM).aspx

[6] Maglić, I., Frančić, V., Zec, D., & David, M. (2019). Ballast water sediment management in
ports. Marine pollution bulletin, 147, 237-244.

[7] Resolution MEPC.209(63) (2012) Guidelines on design and construction to facilitate sediment
control on ships (G12)
http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Marine-
EnvironmentProtection-Committee-%28MEPC%29/Documents/MEPC.209%2863%29.pdf

[8] GEF-UNDP-IMO GloBallast Partnerships Programme and Florida. Institute of Technology
(2017) Guidance on best management practices for sediment reception facilities under the
ballast water management convention. GloBallast, Monograph No 23

[9] Leppäkoski, E., Gollasch, S., & Olenin, S. (Eds.). (2013). Invasive aquatic species of Europe.
Distribution, impacts and management. Springer Science & Business Media.

[10] Apostolidis, A., Kokarakis, J., & Merikas, A. (2012). Modeling the Dry-Docking Cost-The Case
of Tankers. Journal of Ship Production & Design, 28(3).

[11] Valkovic V, Kutle A, Obhodas J (2015) Sediments in the ship's ballast water tank. Presentation
at 9th International SedNet Conference. 23–26 Sept. 2015, Cracow, Poland

[12] Amoresano, A., Langella, G., Niola, V., & Quaremba, G. 2014. Advanced image analysis of two-
phase flow inside a centrifugal pump. Advances in Mechanical Engineering, 6, 958320.

[13] Francis, J. R. D. 1973. Experiments on the motion of solitary grains along the bed of a water-
stream. Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences,
332(1591), 443-471.