Transport analysis of solid sediments in a ballast water flow

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Abstract. The ballast waters, necessary for the stabilization of the ships, move with it and are often discharged into marine environments sensitive to non-native organisms and transport polluting sediments capable of altering the balance of the local ecosystem. In this work, the transportability of particles smaller than 1 mm in size is studied by experimental analysis and the velocity field, generated by the flow, is detected by means of an image acquisition system. The work is developed with an experimental method using a variable flow rate hydraulic circuit equipped with a transparent duct capable of allowing optical access. The measurements of the motion of the particles, acquired by means of the fast photography system, along a section of the transparent duct are analyzed near the sedimentation area. By means of an image processing the frequency of the particles, crossing through the reference section is detected. The data processing by FFT provides the average flow rate of the sediments and allows quantizing the particles transport according to the different hydrodynamic conditions imposed.

1. Introduction

It is widely assumed that more than 90% of goods in international exchange are safely transported by ships throughout the world, and that the ballast water plays an essential role in guaranteeing the safe navigation and operation of ships [1],[2]. When a ship is not fully loaded, additional weight is required to compensate for the increased buoyancy that can result for example in the lack of propeller immersion, inadequate trim or static and dynamic transversal and longitudinal instability [1]. At the same time the ballast waters, when discharged in a different ocean causes an environmental threat by serving as a vehicle to transport sediments and live unwanted species across the oceans. In addition to emissions of NOX, SOX, CO2 and other gaseous pollutants, ballast water is also an emission source from vessels, directly influence the sea ecosystem[3],[4],[5],[6]. According to [7] the first event associated with the use of ballast water was observed in 1903 when the tropical algae Biddulphia sinensis were found in the North Sea. Nevertheless, the transfer of non-indigenous species (NIS) was not considered as a serious problem until the late in the past century [8]. According to some research activities, up to 10 billion tonnes of ballast water is transported by ships annually, and several thousands of microbial, plant and animal species may be carried globally in this water. When these species are discharged into new environments, they may become invasive and can generate an alteration of the local ecosystems. According to Le et al., 2021[2], worldwide commercial shipping contributes to travel more than 50% of all marine invasive species, and ballast water is estimated to transport around 10,000. Several studies indicate that intrusive species have harmful effects on the environment, economic activities as well as human health [9], [10]. Ballast water can also contain heavy metals and non-biodegradable waste [11], [12].

The International Maritime Organization (IMO), the United Nations’ specialized agency responsible for the safety and security of shipping and the prevention of marine pollution by ships, first responded to this issue by developing guidelines and recommendations aimed at minimizing the transfer of live...
organisms and pathogens by exchanging ballast water at sea, since experience had shown that ballast water exchange in deep waters reduces the risk of species transfers [13]. Consequently, IMO developed the globally applicable International Convention for the Control and Management of Ships’ Ballast Water and Sediments (BWM Convention), adopted in February 2004 and ratified in December 2013 (by 30.38% of the world merchant shipping gross tonnage) [13]. IMO has also joined forces with the Global Environment Facility and the United Nations Development Programme (UNDP) to implement the Global Ballast Water Management Programme (GloBallast) [14]. The aim of these programme is to provide assistance for the implementation of the BWM Convention. Recently some studies have approached the problem form a computational and experimental point of view: Liu et al., 2022, for example, has developed an experimentally validated computational model that can be used to study flow phenomena in ballast tanks and to evaluate the drainage efficiency for a design optimization [15].

The aim of this paper is to report the result obtained after a post-processings of an acquisitions campaign realize on a scale model of a two-phase flow in a ballast duct (pump, duct, and tanks). The experimental set, the acquisition methodology, and the characteristics of the granulometry-known sands used to simulate the ballast sediments has been detailed in [16] and [17]. By means of an image processing the frequency of the particles, crossing trough the reference section is detected. The data processing by FFT provides the average flow rate of the sediments and allows quantizing the particles transport according to the different hydrodynamic conditions imposed.

2. Experimental setup

IMAT (Italian Maritime Academy Technologies) is the first Academy in Italy for number of seafarers trained every year. Since 2006, the academy goal is to train maritime crew following international standards and improve safety in the world of shipping. Thanks to the availability of advanced technologies, and the knowledge gained by our instructors, is able to offer complete crew training, from mandatory STCW courses to IMO recommended training (https://www.imat2006.it/home/en/about-us/). In the field of training and scientific research, it has equipped laboratories such as inertial platform for ship steering, fire-fighting systems and on-board hydraulic plant. The scheme of the hydraulic system used for the measurements is shown in Figure 1. The experimental system, Figure 1 have a tool for the circulation of water in steel pipes and two inspectable sections in plexiglass, a water tank for storage and discharge, a radial blades pump that is connected via a double cardan joint to an electric three-phase motor (two-pole asynchronous).

The motor, placed on a free base support, is connected to a dynamometric cell. Through the deformations of the elastic cell system, force and torque can be measured. The energy dissipation phenomena related to the pump can be obtained from the value of these stresses. The principal components of the scheme are: a centrifugal pump (A), a motorized valve (B), a volumetric flow meter (C), a FAST CMOS Camera (D) and a Pc (E). The rolling valve B, in Figure 1 and the by-pass valve H, in Figure 1 allowing the adjustment of the flow passing through the pump. There are two strain gauge pressure transducers (G) located respectively in the suction tube (upstream of the impeller) and in the upper part of the auger (downstream of the impeller). Finally, the Plexiglas parts allow to see and film inside of the impellers and in the duct with the fast camera.

The scheme of the experimental system and the system specifications are reported in Figure 1 and in Table 1.
Table 1. Hydraulic circuit characteristics.

| Component                | Characteristics          |
|--------------------------|--------------------------|
| motor                    | P = 9 [kW]               |
|                          | n = 2890 [rpm]           |
|                          | 380 [V]                  |
|                          | 50 [Hz]                  |
| Centrifugal pump         | Qmax = 15 [m3/h]         |
|                          | Hmax = 19.5 [m]          |
|                          | nmax = 2850 [rpm]        |
| Plexiglass suction tube  | L = 500 [mm]             |
|                          | D = 50 [mm]              |

Figure 1. Experimental setup

A CMOS MINI FASTCAM AX100 camera has been used to obtain the frames. The camera provides a 1.3 megapixel resolution (1280 x 1024 pixels) with frame rates up to 4,000 fps. The memory is up to 32 GB; this opportunity offer extended recording times and activation flexibility. In order to have an adequate record of the experimental tests, the measurement space was highlighted by a halogen HLX 64627 - OSRAM 12 V 100 W to cut low frequencies which would modify the distribution of grey tones in the frame. This lamp provides light with a wavelength of about 650 nm, where the fastcam sensor is particularly stable and sensitive. To assist the method, a standard 50mm Canon lens was used; this lens 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/ Active Pixel Sensor, consisting of an integrated circuit, a Bayer filter, a pixel matrix, a digital controller and an A/D converter. In addition, an analogic converter and a digital controller are part of the same integrated circuit. For a further detailed description of the system, see [18]. The particles added in the circuit to simulate those present in the double bottom of a ship were obviously classified and catalogued before the test. Calibrated in series sieves have been used to carry out a particle size analysis to determine the distribution of the particles. Four diametrical classes were identified: d1 = 0.8 mm, d2 = 0.7 mm, d3 = 0.6 mm, d4 = 0.4 mm

Subsequently, fig 2, the granules were weighed on an analytical balance with a capacity of 120 g and sensitivity 0.1 mg. (Gibertini E42 scale was used).
3. Tests

According to GEF-UNDP-IMO 2017 the composition of ballast sediments varies among ships, depending greatly on the sediment content of the ballast water taken up and the condition of the tank itself [8], [14]. In table the principal contents [8]:

| Type                  | Dimensions                      |
|-----------------------|---------------------------------|
| Clay                  | 2 μm or less                    |
| Silt                  | 2–63 μm                         |
| Sand                  | 63 μm – 2 mm                    |
| Larger sediment particles | Over 2 mm                      |
| Others                | Parts of protective coatings, Product of corrosion process in the tanks, Non-living organic material |

Tests were performed varying the pump rotation speed from 900, to 990 and 1300 rpm, corresponding to three water flowrates and three average water velocity inside the pipe (0.27, 0.31 and 0.4 m/s). In this first approach only a few water velocity were realized, in order to test the procedure and verify if it led to reliable results.

Figure 2. Average weight of granules

Figure 3. Reconstruction of particles motion by image analysis.

The analysis technique is based on the identification of a vertical array of pixels (see fig.3) that cuts the flow area where the passage of solid particles carried by the current is located. The analysis over time of the intensity of each pixel detects the frequency of passage of the particles. In this analysis it is essential to compare the frequency of image acquisition with that detected by the
passage of the particle. The frequency of image acquisition must be at least double the frequency of passage of the particle, so as not to lose any passages between one acquisition instant and the next. In these conditions the frequency analysis is effective and avoids counting the same particle several times.

4. Results
By means of a Fast Fourier Transform (FFT) it has been possible to detect a mean particle passage frequency, as reported in fig. 4, which allows to deduce the particle velocity, as well.

![FFT of a single pixel light intensity](image)

**Figure 4.** FFT of a single pixel light intensity

By combining the information relating to the frequency of image acquisition and the FFT, it is possible to trace the frequency of passage of the single particle. To obtain cumulative information on the flow rate of entrained sediments, it is possible to process the data relating to the entire vertical array of pixels. By the integration of pixel intensity variation along the whole array, this technique allows to quantify the rate of sediments passing throw the vertical line. The size of the particle has been compared with the area corresponding to each pixel of the array. This comparison is necessary to avoid a multiple counting of particles when they are greater than a pixel and the passage of a single particle could interest two or more pixels simultaneously. In the next steps the image analysis software will be implemented for detecting this occurrence, counting the right number of particles passing through the virtual surface.

5. Conclusions
This work is configured as a first step towards the definition and improvement of an analysis technique for images acquired by fast camera, for the characterization of the transposition of sediments in water streams. The aim is to study the transport of sediments inside the ballast water, in order to optimize some components of this system and avoid accumulations or clogging. Thanks to this first analysis, a little step for a further level of knowledge of particle transport phenomena has been done. A new image analysis technique for the detection of solid particle motion in water flow has been defined and tested. By means of this procedure, the frequency of single particles passing through a virtual surface has been identified. Starting from this information and integrating the frequency values along the virtual surface, a particle rate can be evaluated, in terms of number of particle vs time. Coupling this data with particle size and weight, a particle mass rate can be derived. Future work has to be done about cluster of particles also taking into account cohesion forces which have been neglected in this first approach. Such forces alter the behavior of the single particle and are therefore fundamental in the study of the motion of sediments composed of a large number of particles very close to each other during the transport phenomenon.
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