Submarine water flow characterization using particle image velocimetry.

Caracterización de flujos hídricos submarinos usando velocimetría de imágenes de partículas.

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Abstract— **The study of velocity characteristics in an hydric flow represents a valuable tool for evaluating the potential for renewable electric generation through hydrokinetic turbines. Although there are instruments available for measuring flow velocity, most of them are devices that give measurements in a single point and provide little information about the overall characteristics of the flow. The purpose of this work is to present a practical option for measuring the velocity of a water current in the field using image processing and analysis algorithms with the intention of facilitating the study of energy generation potential through hydrokinetic generators. A variation of the Particle Image Velocimetry (PIV) technique is implemented on videos of marine currents captured using commercial underwater action cameras, obtaining results that allow for both qualitative and quantitative assessment of the energy potential of a given water current. Videos obtained in Punta Cancún, in the state of Quintana Roo, were analyzed, and it was confirmed that it is possible to obtain non-surface velocity vector fields that can contribute to the evaluation of generation potential in hydrokinetic turbines.**

Keywords—Particle velocimetry, PIV, Hydrokinetic Turbine, Digital Image Processing.

I. INTRODUCTION

The widespread use of renewable energy has presented a great opportunity to replace fossil fuel-based energy sources in recent years. Although obtaining energy through hydrokinetic turbines is a viable option in places with available water resources [1], it is important to consider that determining the hydropower potential plays a crucial role in the choice of location, dimensions, and characteristics of the turbine, complicating and increasing the cost of its deployment [2].

One of the essential processes for determining hydropower potential is the characterization of water flow velocities, which is typically carried out through monitoring and measuring with instruments known as flow meters.

There is a good number of flow meter devices that use different physical properties such as pressure or kinetic energy transferred to a rotating element to carry out the indirect measurement of fluid velocity. However, most of them have the disadvantage of only being able to classify the flow in one or a few specific directions, which does not facilitate a more qualitative analysis of the fluid's movement characteristics (such as vortices, eddies, etc.). These characteristics can significantly affect the operating conditions and generation capacity of a hydrokinetic turbine [3]. Furthermore, knowing the detailed characteristics of a water flow allows for better design parameters for the turbine and more informed decisions about its location, details that are typically only possible to analyze through computational simulations.

Particle Image Velocimetry (PIV) is an experimental method that allows for the estimation of the velocity vector field of a fluid through digital image processing, obtaining the relative movement of the particles between two consecutive images. It usually involves a planar projection of laser light and particles with high reflectance at the wavelength of this light to achieve greater contrast. However, it is also possible to analyze images without the requirement of the planar light source, mainly when the particles are large or have high contrast with the fluid in which they are immersed [4].

While the PIV technique has been used to determine water flow velocity in rivers, this process is typically carried out by capturing images with the camera located outside the fluid, which mainly allows for understanding the surface flow characteristics, usually with the aim of estimating river discharge.

For example, in [5]and [6], satellite images were used to approximate the discharge of the Yukon River in Alaska, which exhibits observable sediment presence through the PIV technique. In [7]the same technique is used along with a complex system of pulsed lasers and tracer particles to obtain the turbulence profile on the seabed.

Sediment transport is the movement of organic and inorganic particles through water. Suspended load refers to the proportion of sediment transported by the water column rather than settling. The proportion of sediment that becomes suspended load depends on the fluid velocity and particle size. In general, the higher the flow velocity, the greater the amount of sediment and the higher the proportion of suspended load, making this effect, particularly noticeable in river flows or currents near the seabed [8]. These high flow conditions and sediment presence provide the natural environment for the operation of hydrokinetic turbines for electricity generation.

Unlike the previously cited documents, this work will implement the PIV technique without the use of complex experimental setups requiring pulsed lasers and tracer particles, taking advantage of the natural presence of sediments and suspended loads to obtain flow characteristics near a hydrokinetic turbine as a means to evaluate its generation potential. This methodology offers flexibility and ease of implementation, which is important in remote or hard-to-access areas, facilitating both design adaptation and decision-making regarding the installation of a hydrokinetic turbine.

Considering the above, the purpose of this work is to leverage the described characteristics of sediment presence in water flows where a hydrokinetic turbine operates to carry out the analysis and processing of underwater images of the current using the PIV algorithm without the need for complex experimental setups such as pulsed lasers or tracer particles, demonstrating its utility in analyzing the energy potential of a hydrokinetic turbine.

II. Processing Methodology

The PIV technique involves performing a "cross-correlation" in the spatial domain of two images with a known time difference Δt. This time difference should be as small as possible to obtain a better estimation of the instantaneous velocity of the particles.

Cross correlation $(f * g)[n]$ of two discrete time functions as shown in (1).

$$(f * g)[n] = \sum_{m=-\infty}^{\infty} f[m]g[m+n] \tag{1}$$

When this process is performed on images, it becomes necessary to translate the previous definition for two dimensional functions (vertical and horizontal) with coordinates m and n as shown in (2), where f corresponds with the first photogram, and g with the second photogram in a sequence [4].

$$f[m,n] * g[m,n] = \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} f[i,j]g[m+i,n+j] \tag{2}$$

It is possible to create a detailed visualization of the velocity in each region of an image by dividing it into a grid. This allows us to obtain the relative displacement between successive images for each region of interest, thus obtaining a vector field whose resolution will depend on the chosen grid size. Common options for the region size are 32 x 32 and 64 x 64 pixels, considering that higher resolution will require more processing time [4].

The process of performing the cross-correlation operation in each grid element results in a correlation matrix in the [m,n] domain for each region. The maximum point in this matrix indicates the most probable displacement of the image elements (particles) in that region. Ideally, the correlation matrix should present a single peak with a high signal-to-noise ratio to ensure greater certainty about the calculated displacement. The algorithm for the cross-correlation process, as well as the correlation matrix obtained for each region of the grid, is illustrated in "Fig. 1".

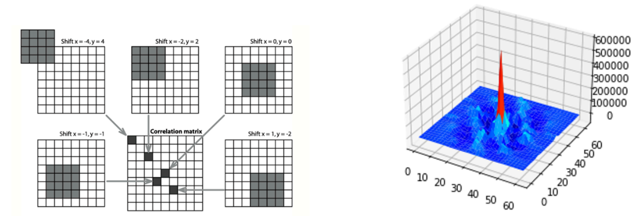

Fig. 1. Cross correlation and correlation matrix

If the image resolution in pixels per unit area or length is known, as well as the video capture speed in frames per second (fps), it is possible to extrapolate the obtained displacement to real velocities of the dissolved particles and, consequently, of the fluid in question.

Finally, considering the convolution theorem, it is possible to perform the above calculation in the frequency domain using the fast Fourier transform, a widely used algorithm with implementations available in most scientific computing packages such as MATLAB and SciPy [9].

III. Results.

Short-duration videos were taken using GoPro action cameras to test the dynamic performance of a hydrokinetic turbine. The videos were captured in one of the submarine currents near the land protrusion known as Punta Cancún in the state of Quintana Roo, on the eastern coast of the Yucatán Peninsula along the Caribbean Sea.

In the videos, the presence of sandy-type particles dissolved in the fluid can be observed with the naked eye. These particles can be considered to meet the requirement of having a small lag or velocity difference relative to the fluid in question according to Stokes' drag equation as expressed in (3).

$$U_s = U_s - U = {d_p}^2 \frac{\rho_p - \rho}{18\mu} \alpha \tag{3}$$

Where d_p is the particle diameter, ρ_p is the particle density, ρ is the fluid density, μ is the fluid viscosity, and α is acceleration.

While it is possible to analytically quantify the velocity lag between dissolved particles, this determination has been experimentally carried out for liquids in several studies. These studies have found that particles smaller than 0.5 mm exhibit velocities very close to those of the surrounding liquid [10]. This fact has been used in experimental setups using the PIV technique for fluid velocity measurement [4].

As a preliminary step to evaluation using the PIV algorithm, it is advisable to perform image preprocessing to enhance the contrast of the particles against the background as well as to stabilize the image. This is particularly important considering the adverse capture conditions, either due to unintentional movement of the person recording or because the camera is mounted on a boat subject to waves. Nowadays, there are several tools available that allow us to perform this preprocessing easily, some even supported by artificial intelligence algorithms [11].In this work, preprocessing was done using Davinci Resolve software.

The PIV algorithm was run on regions with a size of 32 x 32 pixels, with a discrimination of vectors having an SNR lower than 1.2.

During the initial selection and analysis of the images, the presence of sandy-type particles dissolved in the water flow was confirmed, with some of them visible to the naked eye, as shown in "Fig. 2". A careful inspection of these images (magnification) makes it evident that the presence of the particles is not localized and random, but rather that particles smaller than 500 microns are present throughout almost the entire image. This reinforces the previous assumption that the dimensions of the dissolved particles are small enough to consider their displacement as representative of the displacement of the fluid in question.

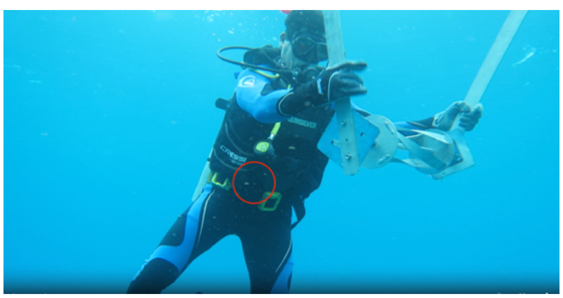

Fig. 2. Photogram of captured video before processing. Dissolved particles are present inside the region marked in red.

The processing was carried out using an open-source implementation of the PIV algorithm called OpenPIV, which is executed in the Python programming language. Several frames of the obtained video were processed, clearly showing the formation of the water's vector field as in "Fig. 3". Additionally, disturbances in the flow can be observed as it comes into contact with elements and people present in the image frame. It is of particular interest to note the vortex formed by the arrows of the vector field near the test hydrokinetic turbine.

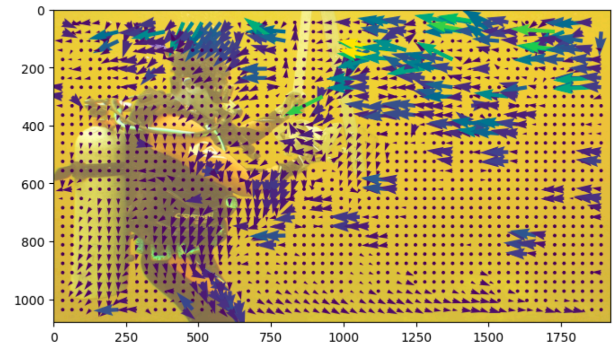

Fig. 3. Velocity vector field obtained after processing.

A speed histogram of the flow is shown in figure "Fig. 4" where we can observe that flow speeds up to 2 m/s are present in the photogram.

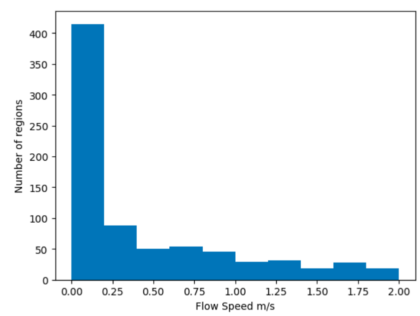

Fig. 3. Velocity vector field obtained after processing.

One important thing to notice is that the velocity vector field generated only considers a two dimensional displacement of the flow, so a measurement of the overall direction of the flow can help improve the accuracy of the absolute speed values.

IV. DISCUSSION.

It is observed that a qualitative analysis and a quantitative estimation of the vector field present in a water flow can be performed using commercial underwater cameras. This can be a useful tool for understanding, analyzing, and evaluating the water potential of an area identified as potentially viable for the deployment of a hydrokinetic turbine. This technique, along with other direct measurements and computer simulations, allows for a more informed decision regarding the design of the turbines, their location, orientation, and other important parameters.

While the implementation of the technique does not replace high-precision experimental setups, it is feasible even in unfavorable situations where traditional measurement instruments would only provide information about the flow rate at a single point, without informing about its characteristics and evolution, as is the case with the vector field obtained through the PIV technique.

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