Ocean Engineering 111 (2016) 439–448

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

An experimental technique to track mooring cables in small scale models using image processing

Guilherme Moura Paredes *, Francisco Taveira-Pinto

Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Received 14 October 2014
Accepted 16 November 2015

Keywords:
Mooring cable
Motion tracking
Image processing
Experimental technique
Physical model

ABSTRACT

Obtaining information about the motion of mooring cables in small scale models in laboratories can be difficult. To help mend this limitation we present a proof of concept of an experimental technique to track mooring cables. Our technique records underwater videos of cables and then applies image processing to extract the coordinates of the complete medial axis of the cables. Using video acquisition has little interference in the experiments and the processing algorithm performs well even under sub-optimal contrast conditions. All the experimental steps are executed underwater, avoiding the need to simplify complex physical models due to visibility or access constraints. Since the whole length of the cable is fully captured on video, any singularity or quick motion (such as those caused by wave energy converters) is adequately detected. Also, the technique yields an acceptable error when compared to directly measured values. With this technique it is possible to acquire important information about the dynamics of mooring cables.

1. Introduction

The use of physical models is, sometimes, required to study the dynamics of mooring cables because of their complex interaction with water. Due to the role that mooring systems play in wave energy converters, we wanted to develop a tool that could provide information about the shape or profile of mooring cables in small scale models with minimal interference in the experiments.

As mooring cables in laboratory models are submerged in a dense fluid (water), the information that can be obtained about them is limited. The application of technologies developed to be used in air will either limit the scope of the research or interfere in the phenomena studied. For example, Howell and Triantafyllou (1993) used ball markers on a cable to study its dynamics in air, but this technique could not be applied underwater: bulky ball makers would change the buoyancy and cross section of the cables, changing their dynamics.

Improving the technique of Howell and Triantafyllou (1993), Yang (2007) developed an algorithm and an experimental procedure that can be used in experiments with submerged cables and applied it to study the dynamics of mooring cables. Like Howell and Triantafyllou (1993), Yang (2007) tracked selected points on the cable (marked with white tape instead of using ball markers) and used interpolation to compute the shape of the cable between the tracked points. The motion of the cables was recorded through windows in the walls of the tank. This technique could possibly be used for cables that are outside of the field of view of the windows, but this is not described nor exemplified. Imaging through windows limits the application of the technique to two-dimensional experiments that can be assembled in the field of view of those windows. For it to be advantageous in complex physical models, a tracking technique needs to be able to track cables that are not visible through side windows and to have the possibility of being used or adapted to track three-dimensional motion.

In wave energy converters, the mooring cables affect the power performance of the device (Fitzgerald and Bergdahl, 2008) and may be subjected to extreme motions and loads (Johanning et al., 2006). Additionally, some types of devices are expected to be installed near each other (Johanning et al., 2005), increasing the possibility of moorings of adjacent devices to interact. The cables may undergo large and fast deformations and interpolating between a discrete number of points on the cable might not capture the geometry with enough resolution, missing singularities. In such situations, it is important to track the complete length of the cable. When studying the dynamics of a falling chain in air, Tomaszewski et al. (2006) used a technique that was able to capture the entire length of a cable. Unfortunately, the method used is not fully described.

To bridge these gaps we developed a tracking technique to capture the geometry of mooring cables moving with frequencies in the range of the exciting waves. Our technique records videos of underwater cables, which are processed to extract the coordinates

* Corresponding author.
E-mail address: moura.paredes@fe.up.pt (G.M. Paredes).

http://dx.doi.org/10.1016/j.oceaneng.2015.11.014

of the whole medial axis of those cables, therefore capturing any singularity. The technique couples a processing algorithm (developed to determine the medial axis of the cables from the videos) to standard photogrammetric methods (that convert the processed data into physical values). By using video capture we are able to obtain information from a distance with little interference in the experimental set-up.

Since the technique captures the complete medial axis of mooring cables, there is no need to use interpolation to retrieve the shape of the cables at any instant. Also, as all the experimental steps are performed underwater (linearization, calibration and video acquisition), the technique can be applied to a broad range of situations.

We will demonstrate that our technique is feasible and robust, performing well even when contrast conditions are far from optimal. We will also provide simple error estimates to illustrate that the error in the measurements is acceptable, in spite of the prototype nature of this proof of concept: around 1.2% or 0.08 m in the horizontal direction and 0.04% or 0.0005 m in the vertical direction, in the large experimental set-up used.

As this work describes a proof of concept, the photogrammetric methods have not been optimized yet. The technique has only been tested for cables without any floaters or sinkers attached. Additionally, because there was only one camera available, three-dimensional motion could not be determined, so the technique is only demonstrated for cables with two dimensional motion. However, the procedures and algorithms described can be easily expanded to determine three dimensional motions if the proper equipment is available.

2. Background on image processing

In this section, some background concepts and operations used in image processing are presented. Readers familiar with image processing may skip this section. The explanations are provided for ease of reading and, for compactness, will be brief. For a deeper understanding, the readers are referred to Gonzales et al. (2004).

2.1. Optical effects

To some degree, all video and photo cameras have imaging distortions, caused by their optical components. These distortions are usually represented and corrected using the Conrady–Brown polynomial model (Brown, 1971, 1966). In this paper, the term *linearization* will be adopted for the procedure of correcting optical distortions, because it allows the camera to be treated as a linear component. There are several codes that can determine the distortion parameters of a camera and correct the distortions. These linearization codes might also determine other optical parameters and the relative position between the camera and a specified target.

A photograph is a projection of a three-dimensional object onto a plane. The result of the projection depends on the relative position between the camera and the object. This is illustrated in Fig. 1. On the left image, when a square pattern is viewed from the front, the squares retain their shape in the projection. On the right image, when the same pattern is viewed from an oblique angle, the squares look distorted, shrinking in size with the distance to the projection plane. The perspective from which an object is viewed has an effect on the image that is created.

If the optical specifications of the camera and the relative position between the camera and the object are known, it is possible to process a photograph (a projection) from one position to obtain a photograph (another projection) taken from a different position. This process is called *homography* and can be applied to

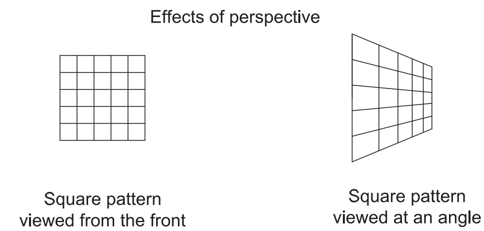

Fig. 1. The effect of perspective on a projection.

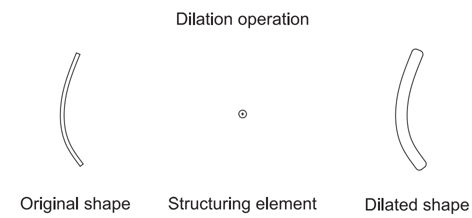

Fig. 2. Dilation. *On the left*: the original shape. *In the center*: the structuring element. *On the right*: the structuring element is added around each pixel of the original shape, enlarging it. The final object acquires a rounded look around the corners, because of the circular shape of the structuring element.

correct the effects caused by the viewing angle, described in the preceding paragraph. An image that is transformed in order to achieve geometric similarity between shapes in the image and in the real object is said to be *rectified*.

In order to obtain accurate measurements of objects using images, any deformations in those images must be eliminated. Therefore, both the distortions caused by the optical system and the perspective effects must be corrected before any measure is estimated.

2.2. Processing operations

A digital image is a discrete function of two coordinates that assigns to each pair of coordinates (a pixel) a numeric value. In a black and white image, the function usually takes the value 0 for black and 1 for white; in a grey-scale image (and its derivatives) the function usually takes an integer value from 0 (black) to 255 (white), with the values in-between representing various shades of grey. Several operations can be performed on these images and the most relevant for this work are *dilation*, *thinning*, *edge detection* and the *top-hat transform*.

In black and white images, *dilation* enlarges objects or shapes by adding around each white pixel the shape of a structuring element, centered at the element's origin. This operation is represented in Fig. 2. A structuring element is a shape (e.g. a circle, square, etc.), with a specified origin, that is used in some operations in image processing. A detailed mathematical explanation is given in Gonzales et al. (2004).

Thinning is an operation in which a shape or an object in an image is shrunk by reducing its thickness by one or two pixels (Gonzales et al., 2004). When executed repeatedly, this operation reduces objects to strokes that are only one pixel thick, without breaking the object into smaller ones, Fig. 3. For simple shapes, the remaining stroke is located approximately in the position of the medial axis of the shape.

Edge detection is an operation that detects discontinuities in the intensity within an image (Gonzales et al., 2004). These discontinuities are usually associated with the edges of objects in the image, although they may be caused by other phenomena such as variations in light or even noise.

The *top-hat transform* singles out the regions in an image that are both brighter than the surroundings and smaller than the size of a specified structuring element. Representing the image as a