Ocean Engineering 160 (2018) 301–310

Contents lists available at ScienceDirect

Ocean Engineering

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

An alternative method for computing hydrostatic performances of a floating body with arbitrary geometrical configurations

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ARTICLE INFO

Keywords:
Hydrostatics and stability
Static pressure integration
Surface triangulation
Trimaran
Floating kuroshio turbine

ABSTRACT

In the fields of naval architecture and ocean engineering applications, floating platforms or multi-hull vessels with very different geometrical appearance have been designed to meet their mission requirements. Many objects were built by composing a number of sub-objects in an arbitrary way because of the high flexibility available for the construction work. Because the composition of the sub-objects normally are not arranged along a certain direction in a fixed sequence, it could be sometimes troublesome for computing the hydrostatic data of such objects. In order to facilitate this computation more easily and flexibly, a method has been developed in this paper, which was derived from the simple principles of an exact pressure integration over triangles for getting the total buoyancy force vector and the static equilibrium condition between the buoyancy force and the weight of the floating object. The triangles thereby were generated by triangulation of the surfaces representing a whole floating object. Finally, applications on a high-speed trimaran hull and a floating Kuroshio current turbine were conducted for demonstrating the merit of this method. The placement of water compartments and free surface effects were further analysed to evaluate the changing ballast conditions for hydrostatic and transitional stabilities.

1. Introduction

Ship terminology defined a hull geometry in three orthogonal directions, bodyplan, waterplan, and sheerplan. These plans are related to stations, waterlines, and buttocks correspondingly, on which an offset table is constructed. It is a common format to define a hull geometry and to analyse its hydrostatics and stability performance. The analysis involves area and volumetric properties and also static properties such as moment, moment of inertia, and centre of buoyancy etc., so that a numerical integration method for processing geometries is needed. Just before the fast development of computer technology in recent decades different integration methods have been widely applied, such as trapezoidal or Simpson's methods, which can be easily founded in a series of well-known naval architecture textbooks such as (Barrass and Derrett, 2006), (Biran and Pulido, 2013), (Dudszus and Danckwardt, 1982), (Kobylinski and Kastner, 2003), (Lewis, 1988) and (Rawson and Tupper, 2001). These methods are applicable to regular shapes, whose geometrical changes along a longitudinal direction are smooth. In addition, the shape has to be presented in a well-structured format. An offset table for ships can meet these requirements. However, the main deficiency of this integration approach is that the volumetric properties are calculated by integrating area properties, which are again by integrating line properties. The double integral operation can accumulate errors from insufficient resolution of the offset table and from the numerical methods. So modern ocean structures involving abrupt geometrical changes, for instance multi-hull vessels and ocean platforms, suffered difficulties to evaluate their performances in the traditional way. Nevertheless, most offshore units are structured by simple mathematical geometries, for example rectangular box, cylinder, sphere and prism. Analytical solutions for area and volumetric properties (Bronshtein et al., 1997) exist for such geometrical components that the whole properties can be calculated by summation or parallel axis theorem (Paul, 1979). But this is not the case for other shapes beyond simple mathematical expressions.

Also in the case of determining the transverse statical stability, an approach by making a distinction of small and large angles of heel is usually given in the aforementioned textbooks. The reason to take the approach is due to the fact that the waterlines with different heel angles may cut the stepwise cross-sections in different manners. If the heel angle

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https://doi.org/10.1016/j.oceaneng.2018.03.036
Received 26 September 2017; Received in revised form 21 January 2018; Accepted 11 March 2018

is small, the resulting intersection point of a waterline and the ship side can be assumed to be vertical wall-sided. In this case, a simplified relationship can be easily derived between the transverse stability and the heeling angle. For large angles of heel, precise results can also be gotten by more elaborately formulated equations. This method shows however a disadvantage with two separate steps, which is kind of annoying. Some analytical formulation for arbitrary 2D shape and implementations in MATLAB (Wu, 2005; Duan et al., 2015) have been done and can provide accurate results, However a more general three-dimensional method with single integrated computing process is inevitable to calculate hydrostatic properties of an arbitrary configuration of geometry.

On the other hand the determination of floating states, for bodies, subject to external loads in some scenarios requires a root finding process. In other words, this process finds the position and orientation of a watertight body, so that all forces and moments are balanced. Usually the matrix methods was used to calculate the floating states (Zhao & Lin, 1985; Kopecky, 2007). For each iteration, the waterplan area, centre of floatation, moment of inertia, displacement volume and centre of buoyancy are calculated and filled in the Jacobian matrix. Not only the computational workload is high but also those geometrical properties might suffer inaccuracies in the traditional approach as described.

Apart from the gradient-based solver, another method of nonlinear programming used to calculate the floating state of ships was proposed (Ma et al., 2003, 2007). It established the absolute value of the total recovery arm as the objective function to ensure that the displacement is equal to the weight as the constraint condition, and the optimization of the mathematical model for the design variables is the draft. Compared with the traditional matrix method, the method in each iteration does not need to calculate the surface properties, instead just calculating the tilts of displacement volume and centre of buoyancy, and hence reducing amount of calculation greatly, but the nonlinearity of hydrostatic properties requires some remeshing techniques (Lee & Lee, 2016). Others treated this optimization problem by the genetic arithmetic (Lu et al., 2005, 2006; Jin et al., 2007), in which the free float calculation is summed up as a multi-objective constraint optimization problem. According to the free floating condition of ships, since it is based on the calculation of surface expression, it does not need a given initial iteration point, only the total weight and centre of gravity of the ship are need. In addition, it uses the draught, pitch angle and roll angle as the design variables directly without the calculation of the tangent value of the dip angle. Compared with other iterative methods, it is more accurate than the methods based on two-dimensional representation.

To summarize the drawbacks of current geometrical process for hydrostatics are the erroneous double integration of offset tables and limited analytical solutions for mathematical shapes. The former further reduces the performance of determining floating states. The present method derives the analytical solution to hydrostatic pressure for triangulated surfaces, which avoids numerical integration and breaks the limitation of mathematical shapes. The overhead of the proposed method is the additional triangulation operation which is another topic about surface grid preparing, and to present large numbers of triangles of a body requires relatively larger files to store and also higher memory usage.

2. Methodology

2.1. Surface triangulation and intersection

In computer-aided geometry modelling, a surface is usually presented in parametric form, i.e. u and v direction in unit domains (Piegl and Tiller, 2013), (Gallier, 2000). Isoparametric curves are easy to extract from a surface by holding one parameter constant. Simply interleave the isoparametric curves in u and v directions a structure grid can be obtained. Triangulating the structured grid into triangle panels is connecting diagonal vertexes of each cell, as shown in Fig. 1. Advanced controls such as aspect ratio, maximum edge length, and maximum deviation from surface are on demand. The closed hull surface and compartment geometry are triangulated with normal directions point into fluids.

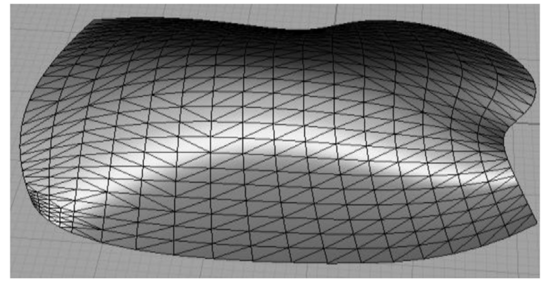

Fig. 1. Surface triangulation.

Geometrically speaking, the waterplans of a floating body and the free surface inside a compartment in calm water are intersections of a flat plane and 3D closed surfaces. Since these surfaces are triangulated, it is the problem that intersects triangles with a plane. Four conditions is illustrated in Fig. 2 and an intersection exist in case II and case III, where h represents the immersed or above depth in/out of water. An intersected segment must be a straight line starts and ends on the edges of the triangle, which are also straight lines. So the calculation of the end points of this line is simply by calculating an intersection of a plane and line segments of the triangle edges. After obtaining the end points on the edges in case III, the immersed triangle is a special case of case I that one edge lies on the plane. For case II the immersed part is a quadrilateral, which can be further divided into two sub-triangles, both reduced to case I. So the immersed part of a triangulated surface can be represented as a set of triangles, which will be resolved hydrostatic pressures. A special case that a triangle lies perfectly on the plane, the case V in Fig. 2, and generate a jump of waterplan change will be specifically treated in the following section. This condition does not effect on the pressure since its water head is zero.

The outcome of the intersection of a plane and a closed meshed surface is one or several planar polygons, as shown in Fig. 3. The polygon contour is constructed by N vertices and N linear segments, and the x and y are the coordinates of vertices. The area properties, including enclosing area A, centre of polygon C_x and C_y, and moments of inertia about the polygon centre in X and Y directions I_x and I_y, are analytically calculated by Eqs. (1)–(3). The values in Y direction are obtained by swapping the terms in the first parenthesis: x to y in Eq. (2) and y to x in Eq. (3). These equations are derived from 2D triangle properties, which constitutes the basic element of a polygon.

$$A = \frac{1}{2}\left|\sum_{i=0}^{N-1}(x_i y_{i+1} - x_{i+1} y_i)\right| \tag{1}$$

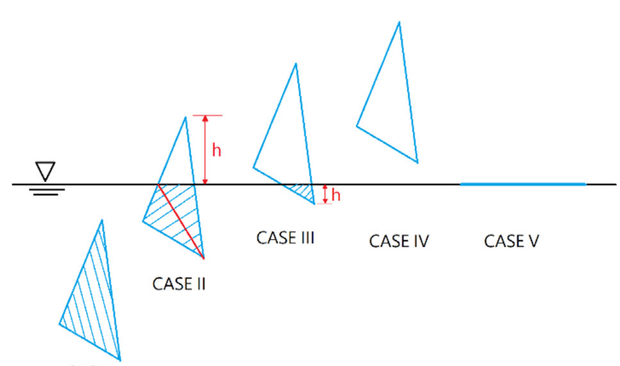

Fig. 2. Triangle-plane intersection.