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A New Method for Precise Computation of Vessel Hydrostatic Performances

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Abstract: Hydrostatic curve is one important technical data for vessel design, vessel building, marine transportation and other related business. With hydrostatic curve, parameters about performance of vessel navigation can be computed, which can improve navigation safety and complete scientific cargo distribution. Compared to traditional conversion from 3D vessel hull to 2D plane computation methods, this study, by applying affine transformation theory, presents water-line plane equation determined by floating parameter, calculates precisely vessel hydrostatic properties under arbitrary floating condition by using the intersection algorithm of the plane and the surface as well as the universal algorithm for arbitrary sealed polygon and arbitrary sealed polyhedron. Hydrostatic performance computation results of sample real vessels including cargo arrangement and stability curve under given loading condition confirm the validity of these proposed algorithms.

Key words: Affine transformation, geometric properties, vessel hull performance, vessel floating state

INTRODUCTION

With rapid development of CAD technology and modeling technology of curve and surface, mathematical methods has become main tool for vessel hull representation and performance computation. For triangular mesh generation of vessel hull surface and reconstruction of three dimensional vessel hull surfaces, we have discussed in our previous studies (Shi and Jia, 2006; Shi *et al.*, 2013). Based on 3D vessel representation based on NURBS, we put forward a new method for precise calculation of vessel hydrostatic performances.

Hydrostatic curves are defined as a set of curves which plot the hydrostatic quantities such as displacement, centre of flotation, centre of buoyancy, transverse metacentre, etc. against the draft; these curves are useful for quick assessment of the drafts and the initial stability in various loading conditions. Parameters of hydrostatic characteristics include buoyancy parameters, stability parameters and coefficients of vessel type parameters. Hydrostatic curve can be represented as relation curve of mathematical function for corresponding parameters and draft.

To improve propulsive efficiency of vessel propeller, loading distribution must be heeling longitudinally at the initial stage in order to restrict the bow wave. When vessel breaking occurs, it needs to right the vessel adjusting floating state based on hydrostatic characteristics parameters for breakage of floating state. In one word, computation of vessel hydrostatic performances is to compute displacement volume, buoyancy center, volume and geometric centroid of the damaged cabin under water line. All other computations are based on these computations (Adrian, 2003; Cai *et al.*, 1995; Wu, 2005). For example, hydrostatic curve refers to computing volume, buoyancy center when vessel in upright state changing with draft. And floating computation means volume and geometric centroid computation when balancing the vessel in loading conditions.

Unlike traditional computation methods of hydrostatic characteristics which only focus on vessel upright state with limitations of two dimensional representation. Some researchers put forward three dimensional computation methods. For example, Wang presented an algorithm for computing quantities involving integration of NURBS curves (Wang, 1996). For cubic NURBS curves, he gave an approximation method but with some errors. Zhang proposed a method to compute geometrical properties of free-form surface based on NURBS and Gauss theorem and parametric surface

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integral theory (Zhang *et al*., 2002), only processing vertexes within computation bounding area. For a more precise calculation of a vessel's performance, Lu presented a new algorithm that calculates the 2D or 3D geometric properties based on surface representation (Lu *et al*., 2005). After the represented surface was partitioned into quadrangular or triangular elements, the geometric properties of the limited plane, curve surface and volume were calculated respectively combining the ones of quadrangles, triangles and generalized prisms. Applying this method, the properties of the sectional area, partial surface area and volume bounded by analytical surface were calculated based on NURBS representation of them with the result coming close to the analytical solution. A drawback of Lu's method is that it is only fit for computation when vessel in upright floating state or longitudinal heeling state.

This study, by applying affine transformation theory, presents water-line plane equation determined by floating parameter, calculates precisely vessel hydrostatic properties under arbitrary floating condition by using the intersection algorithm of the plane and the surface as well as the universal algorithm for arbitrary sealed polygon and arbitrary sealed polyhedron and confirms the validity of these algorithms through real vessel computation.

COMPUTATION OF VESSELS HYDROSTATIC CHARACTERISTIC PARAMETERS

Vessel hydrostatic performances can be categorized to buoyancy parameters, stability parameters, coefficients of vessel type parameters and vessel hull wet-surface area in arbitrary floating condition (Semyonov-Tyan-Shansky, 2004). The vessel state in still water is called the floating state and the vessel floating condition includes upright, heel, trim and heel plus trim of four states and they can be represented by mean draft, horizontal angle and vertical angle. How to determine the waterline hydrostatic equation according to the floating state parameter is a key of calculating vessels hydrostatic characteristic parameters.

Coordinate system of vessel hull and floatation equation: Hull shape is represented by projecting onto three mutually perpendicular basic planes, these three basic projection planes is called main coordinate plane or datum plane, which is shown in Fig. 1.

In Fig. 1, central longitudinal plane is longitudinal vertical plane by Breadth midpoint, which the hull is divided into two parts symmetrical with each other, so the surface is also referred to the vertical plane. The midstation plane is the transverse vertical plane by

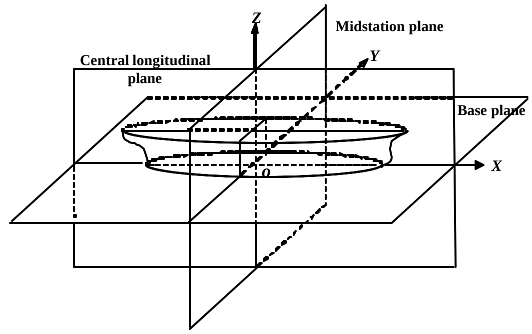

Fig. 1: Coordinate system of vessel hull

Lendth midpoint, which is divided into both parts of the hull. The base plane is perpendicular to central longitudinal, midstation plane and it is parallel to the design waterline by Lendth midpoint and keel line. Three datum planes intersects each other, they constitute the axis of coordinate system of vessel hull. Central longitudinal plane and the base plane intersect at x-axis, x-axis points to the bow, The midstation plane and the base plane intersect at y-axis, y-axis points to the port side. Central longitudinal plane and midstation plane intersects at *z*-axis, ox, oy, oz-axis constitute right-handed coordinate system. The right-handed Cartesian coordinate system is mainly used to calculate curve and surface modeling or related graphics. However, some classical algorithms often use left-handed Cartesian coordinate system in the space vessel floating condition of vessel engineering.

Floating condition of vessel hull is calculated by computing the vessel buoyancy parameters, namely the first parameter Vlasov. In essence, floating condition parameters of vessel depend on the vessel equilibrium equations, the equation includes a force balance equation and two torque balance Eq. 1:

$$\begin{cases} W - \rho V = 0 \\ \rho V Y_b - W Y_g + (\rho V Z_b - W Z_g)\tan\theta = 0 \\ \rho V X_b - W X_g + (\rho V Z_b - W Z_g)\tan\psi = 0 \end{cases} \quad (1)$$

In (1), (X_b, Y_b, Z_b) and (X_g, Y_g, Z_g) are the coordinates of the center of buoyancy and center of gravity in the hull left-hand rule coordinate system. W is the total weight of the vessel and ρ is the density of water, (T_m, θ, ι) is the floating condition parameters of vessel, V is volume under the surface of the hull waterline according to buoyancy parameters. If coordinates of the center of buoyancy and center of gravity in right-hand rule coordinate hull are (x_b, y_b, z_b) and (x_g, y_g, z_g) in Fig. 1, the transformation and the simplified equation of state floatation can be represented as in (2):

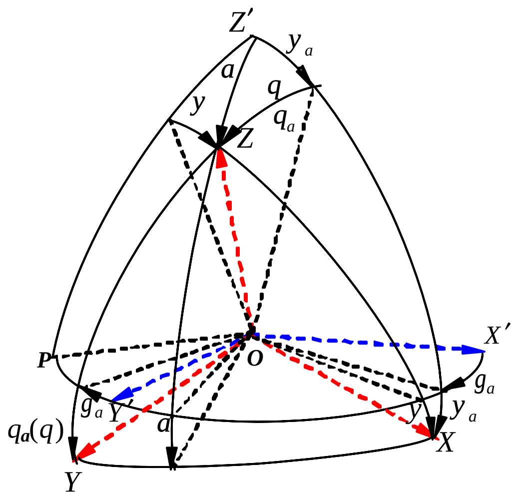

Fig. 2: Parameter of vessel floatation angle and Cardan angle

$$\begin{cases} W-\rho V=0 \\ y_g-y_b+(z_b-z_g)\tan\theta=0 \\ x_b-x_g+(z_b-z_g)\tan\psi=0 \end{cases} \quad (2)$$

Relation between parameter of vessel floatation angle and cardan angle: Two left-handed Cartesian coordinate system is shown in Fig. 2, fixed to the sea with the stationary coordinate system OX'Y'Z' and the coordinate system attached to the hull OXYZ, where the coordinate OX points the hull bow and OY points starboard. For convenience, it assumes that two coordinate origins coincide. Spatial position of vessel is determined by six parameters in general, that is, the three lines of coordinates and three angular coordinates. The coordinates of a line and two angular coordinates, a total of three floating modal parameters can determine vessel position when there exists the vertical force only.

In Fig. 2, OX'Y' is the horizontal plane and OZ'X and OZ'P are the vertical planes, OXY is the hull base plane, OZX is the central longitudinal plane, OZY is the midstation plane. Hull coordinate system relative to the fixed position of the coordinate system is composed of three Carlton Corner (Cardan angle), which is known as yaw angle, pitch angle and angle of heel. Coordinate system OX'Y'Z rotates the first axis OZ axes β_z to obtain OX'Y'Z' in the Cartesian coordinate system and then, Coordinate system OX'Y'Z' rotates the axis OY' axes β_y that has been rotated about an axis other than one of the coordinates axes to obtain OX"Y"Z", finally the coordinate system OXY"Z" rotates the remaining axis OX" as rotation axis β_x to get OX"'Y"'Z"' coordinate system. Such three rotation angles are called Cardan angles.

With Cardan angles, hull coordinate system OXYZ can be obtained by the three Carlton angle rotated three times in the fixed coordinate system OX'Y'Z'. As we know from Fig. 2, the yaw angle γ_a is measured in the horizontal plane, where starboard side of leeway is positive. Trim angle ψ_a is measured in the plumb surface, where the trim is positive. Heeling angle θ_a is measured in the midstation plane of the hull. Hull floating condition parameters include mean draft T_m, heeling angle θ and trim angle ι, where the mean draft T_m is the distance from the origin of coordinates O to the waterline plane in hull coordinate system OZ. T_m is positive in the above hull base plane. Heeling angle θ is measured in the hull midstation plane where heeling to starboard is positive and it is same to Cardan angle. Trim angle ι is measured in the hull central longitudinal plane, where the trim is positive. According to Fig. 2, yaw angle $\gamma_a = 0$ is frequent in the ship hydrostatics, so analytic methods can be used to obtain the relationship between Cardan angle and the vessel floating angle, as in (3):

$$\sin\psi_a=\frac{\cos\alpha}{\cos\psi}\sin\psi,\ \cos\psi_a=\frac{\cos\alpha}{\cos\theta},\ \theta_a=\theta \quad (3)$$

In (3), α is the tilts angle of the vessel namely the angle between waterline plane and the base plane.

Affine transformation method to decide water-plane equation: Before calculating ship static performance in the application of NURBS precisely, we need to decide water-plane equation based on three floating condition parameters of vessel, that is, mean draft, horizontal angle and vertical angle to determine the waterline surface equation in the hull coordinate system. The original affine transformation matrix is as in (4):

$$\begin{aligned} R_x &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_a & \sin(-\theta_a) & 0 \\ 0 & -\sin(-\theta_a) & \cos\theta_a & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ R_y &= \begin{bmatrix} \cos\psi_a & 0 & -\sin(-\psi_a) & 0 \\ 0 & 1 & 0 & 0 \\ \sin(-\psi_a) & 0 & \cos\psi_a & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ M &= R_x R_y \\ &= \begin{bmatrix} \cos\psi_a & 0 & \sin\psi_a & 0 \\ \sin\theta_a\sin\psi_a & \cos\theta_a & -\sin\theta_a\cos\psi_a & 0 \\ -\cos\theta_a\sin\psi_a & \sin\theta_a & \cos\theta_a\cos\psi_a & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \end{aligned} \quad (4)$$

Figure 2 is the left-handed coordinate system. If three Cardan angles are positive, the axis OZ' and OY' of the coordinate system rotates the direction of rotation is clockwise when facing the axis and the axis of rotation

OX’ is counterclockwise. If right-handed coordinate system of Fig. 2 is used and three Cardan angles are positive, applying the affine transformation, which keeps coordinate system fixed, water lines surfaces rotates the shaft OZ’ counterclockwise with rotation angle γ_a and rotates the axis OY’ counterclockwise with rotation angle $-\psi_a$ and rotate the axis OX’ counterclockwise with angle $-\theta_a$, then water lines surfaces in the fixed coordinate system can be transformed into the hull coordinate system.

As $\gamma_a = 0$ in the vessel hydrostatics, substituting the (3) into (4), affine transformation matrix we can obtain affine coordinate transformation matrix as in (5) with floating condition parameters from fixed coordinate system to vessel hull coordinate system:

$$M = \begin{bmatrix} \frac{1}{\cos\theta\sqrt{1+\tan^2\psi+\tan^2\theta}} & 0 & \frac{\tan\psi}{\sqrt{1+\tan^2\psi+\tan^2\theta}} & 0 \\ \frac{\tan\psi\sin\theta}{\sqrt{1+\tan^2\psi+\tan^2\theta}} & \cos\theta & -\frac{\tan\theta}{\sqrt{1+\tan^2\psi+\tan^2\theta}} & 0 \\ -\frac{\tan\psi\cos\theta}{\sqrt{1+\tan^2\psi+\tan^2\theta}} & \sin\theta & \frac{1}{\sqrt{1+\tan^2\psi+\tan^2\theta}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Suppose normal vector of horizontal plane is n = (0, 0, 1) in the fixed coordinate system, applying the Eq. 5, we can get the normal vector of waterline area, n' (A, B, C) in the vessel hull coordinate system, where [A B C 1] = [0 0 1 1] M, so:

$$\boldsymbol{n}' = (A, B, C) = \left(-\frac{\tan\psi\cos\theta}{\sqrt{1+\tan^2\psi+\tan^2\theta}}, \sin\theta, \frac{1}{\sqrt{1+\tan^2\psi+\tan^2\theta}}\right) \quad (6)$$

According to (6), water-plane equation of vessel hull coordinate system Ax+By+Cz+D = 0 can be obtained. Because the plane gets through the point (0, 0, T_m), so the point can be substituted into plane equation, the water-plane equation of the vessel hull coordinate system can be obtained as in (7):

$$x\tan\psi\cos\theta - y\sin\theta\sqrt{1+\tan^2\psi+\tan^2\theta} - z + T_m = 0 \quad (7)$$

When the heeling angle and trim angle is 0, water-plane equation of the vessel hull coordinate system becomes a = T_m, the ship is upright floating condition. When the trim angle is 0, water-plane equation of the vessel hull coordinate system becomes $z = -y\tan\theta + T_m$, which means that ship is in heeling state. When heeling angle is 0, water-plane equation of the vessel hull coordinate system becomes $z = x\tan\iota + T_m$, which means that ship is in trim condition.

Figure 3 shows the floatation state of one ro-ro passenger ship with the scale L_{∞} = 137.3 m, B = 23.4 m, D_1 = 14 m and D_2 = 8.6 m, where D_1 is the distance to the upper deck, D_2 is distance to the main deck. Floatation condition parameters of the vessel is T_m = 6 m, θ = 15° and ψ = 5°. Experiments show that affine transformation determines water-plane equation based on ship floating parameters is correct.

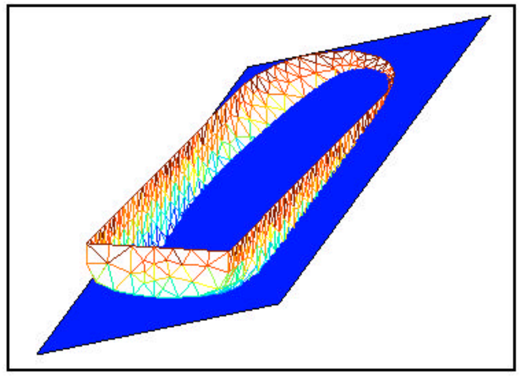

Fig. 3: Water plane decided by floatation parameters

DEFINITION AND COMPUTATION OF HYDROSTATIC PERFORMANCES

Vessel buoyancy and stability will change with loading conditions or draft changing. So, in order to make application easy, parameters that influence vessel buoyancy and stability should be computed in vessel design phase. Combining computation results with upright draft to draw a curve, we call these curve collections hydrostatic curves. Hydrostatic curves can be divided into three categories, that is, buoyancy parameters, stability parameters and coefficients of vessel type parameters. Referring to upright state, vessel hydrostatic performances can be categorized to buoyancy parameters, stability parameters and coefficients of vessel type parameters in arbitrary floating condition:

Buoyancy parameters:

- Volume of moulded displacement V (m^3), which refers to hull volume under water line
- Moulded displacement Δ (t), $\Delta = \rho V$
- Overall displacement Δ_k (t), $\Delta_k = K\Delta$ where K is vessel hull coefficient and assigned 1.006 in general.
- Water plane area A_w (m^2), which refers to area of the intersection plane for water plane and hull surface
- Longitudinal position of floatation center LCF (m), which refers to longitudinal position of geometric center of the water plane
- Transverse position of floatation center TCF (m), which refers to transverse position of geometric center of the water plane

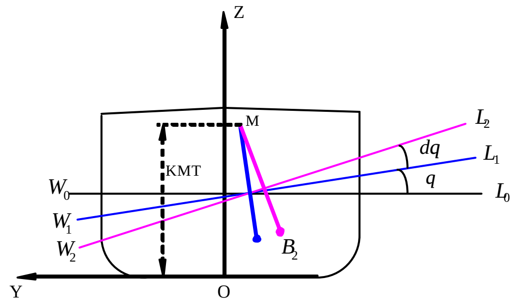

Fig. 4: Transverse meta-center, radius of transverse meta-center and KMT

- Vertical position of floatation center VCF (m),which refers to vertical position of geometric center of the water plane
- Longitudinal position of buoyancy center LCB (m), which refers to longitudinal position of geometric center of the draft volume
- Transverse position of buoyancy center TCB (m), which refers to transverse position of geometric center of the draft volume
- Vertical position of buoyancy center VCB (m), which refers to vertical position of geometric center of the draft volume
- Tons per centimeter TPC (t/cm), which refers to draft variation influencing by increasing or decreasing 1 centimeter of average draft maintaining the same buoyancy angle in some draft position, while keeps the water plane before parallel to the water plane when average draft changes

Stability parameters: Vertical position of transverse meta-center KMT (m), which refers to vertical position of the intersection point for projection of two buoyant force lines before heeling and after heeling in the cross section plane with small angle transverse heeling in arbitrary balancing conditions, shown in Fig. 4.

In Fig. 4, W_0L_0 is the even keel water line, W_1L_1 is the initial balancing water line with transverse heeling angle θ, W_2L_2 is the water line when vessel heels to a small angle $d\theta$ from the initial balancing state. Projection of water line W_1L_1 on the cross section plane influenced by buoyancy force is B_1M and projection of water line W_2L_2 on the cross section plane influenced by buoyancy force is B_2M. Their intersection point M is called transverse meta-center and it satisfies $R_t = |B_1M| = |B_2M|$, where R_t is called radius of transverse meta-center of the initial balancing condition. Based on geometric relationships and definitions, vertical position of transverse meta-center is:

$$\text{KMT} = R_t \cos\theta + \text{VCB} = \frac{I_t}{V}\cos\theta + \text{VCB} \tag{8}$$

where I_t is inertance moment of area of water plane to the longitudinal axis of the floatation center in the initial balancing condition.

- Vertical position of longitudinal meta-center KML (m), which refers to vertical position of the intersection point for projection of two buoyant force lines before heeling and after heeling in the longitudinal section plane with small angle transverse heeling in arbitrary balancing conditions. With similar definition for vertical position of transverse meta-center:

$$\text{KML} = R_L \cos\psi + \text{VCB} = \frac{I_L}{V}\cos\psi + \text{VCB}$$

where R_L is radius of longitudinal meta-center of the initial balancing condition, I_L is inertance moment of area of water plane to the longitudinal axis of the floatation center in the initial balancing condition and ι is the longitudinal heeling angle of even keel condition relative to the initial balancing condition

- Moment to change trim 1 cm MCT (tm/cm). Trim moment required for longitudinal heeling one centimeter in arbitrary balancing conditions:

$$\text{MCT} = \frac{\Delta(R_L \cos\psi + \text{VCB})\cos\psi}{100L}$$

where L is vessel length. When longitudinal heeling angle is zero or very small:

$$\text{MCT} \approx \frac{\Delta R_L}{100L}$$

From definitions of stability parameters, we can see stability parameters change with heeling angle changing and we can get different stability parameters with the same displacement and different heeling angles.

Coefficients of vessel type parameters:

- Water plane coefficient C_w. A cuboid is constructed with vessel length, breadth and moulded depth as length, width and height of B_{cub} and cutting the cuboid B_{cub} with the water line plane to get the sectional area S_{cub} and get:

$$C_w = \frac{A_w}{S_{cub}}$$

- Block coefficient C_b. Supposing volume of cuboid B_{cub} under the water line plane is V_{cub}, then:

$$C_b = \frac{V}{V_{cub}}$$

- Midship coefficient C_m. Set sectional area under water as A_{cub}, which can be obtained from cutting cuboid B_{cub} by midship section and supposing area of midship section under water is A_m, then:

$$C_m = \frac{A_m}{A_{cub}}$$

- Longitudinal prismatic coefficient C_p. A cylinder B_{cylind} is constructed with midship section as top and bottom surface and vessel length as height. Cutting this cylinder with water-plane to get the volume under water V_{cylind}, then:

$$C_p = \frac{V}{V_{cylind}}$$

- Vertical prismatic coefficient C_{vp}. A cylinder B_{cylind} is constructed with water-plane and projection plane of water-plane on vessel base plane as top and bottom surface. Suppose the volume of this cylinder under water is V_{cylind}, then:

$$C_{vp} = \frac{V}{V_{cylind}}$$

- Wet surface area S_w (m^2), which refers to waterline hull below the surface area of the surface

EXPERIMENAL RESULTS

Applying surface discretization, intersection algorithm of plane and surface and geometric properties computation method for arbitrary sealed polyhedron, computation results of hydrostatic performances for a general arrangement and cargo hold loading conditions of a bulk carrier is shown in Fig. 5.

Based on lines plan and given loading state of the bulk carrier, we get the stability curve according to our methods shown in Fig. 6.

Computation results show engineering practicability of our hydrostatic performance computation methods.

CONCLUSION

The key of precise calculation of hydrostatics performances is to determine water-plane equation based on ship floating parameters. This study applies the theory

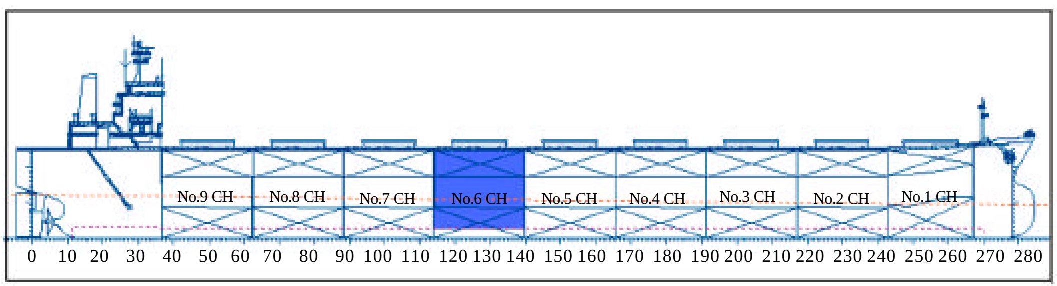

Fig. 5: Arrangement of a bulk carrier

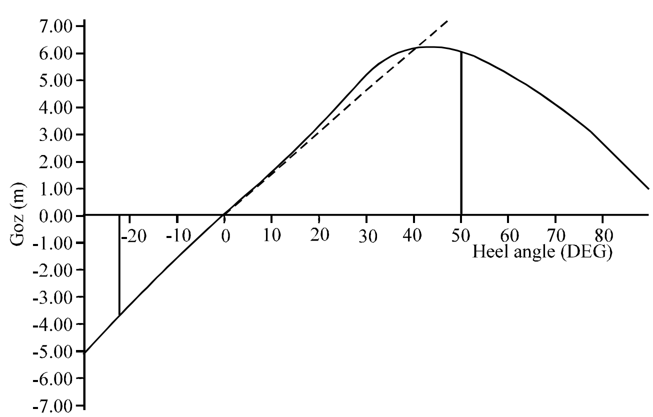

Fig. 6: Stability curve of a bulk carrier under given loading condition

of affine transformation into confirm the water-plane equation according to floating parameters. It applies flat and curved intersection algorithm and arbitrary closed polygons, arbitrary closed polyhedral geometry of the general algorithm accurately into calculate the vessel hydrostatics performances in the arbitrary floating condition in the space. Experimental results show that the algorithm is effective. Our future work will mainly focus on precise computation of vessel hydrostatics performances based on NURBS curves.

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