A Direct Damage Stability Calculation Method for an Onboard Loading Computer

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Abstract: The stability analysis of a damaged ship is both important and challenging for an onboard loading computer. To help ship operators make reasonable decisions, a Simplified Newton Iteration Method is proposed to calculate damage stability in real time based on 3D geometric models of the ship. A 7500-dead-weight-tonnage (DWT) asphalt tanker, “TAI HUA WAN”, is used to illustrate the effectiveness of the proposed approach. The damage stability results of 18 typical loading conditions are calculated. The average error of righting lever GZ is 0.002 m, and the average number of iterations is nine. The calculation results show that the proposed method is simple, with real-time processes, robustness, accuracy, and certain practical value for engineering. Furthermore, based on the proposed method, a loading computer, “SMART LOAD”, has been developed and approved by LR, DNV, CCS, ABS, NK and the BV Classification Society and has been installed on more than 150 vessels worldwide.

Keywords: damage stability; loading computer; Newton Iteration Method

1. Introduction

The loading computer system is a computer-based system consisting of a loading computer (hardware) and a calculation program (software) with which any ballast or loading condition can be easily and quickly ascertained. The International Association of Classification Societies (IACS) defines four different types of stability software in the Unified Regulations Regarding Onboard Computers for Stability Calculations [1,2]. Both a Type 3 and Type 4 loading computer needs to calculate the damage stability, as shown in Table 1. A loading computer system with damage stability analysis is an important tool for ships. An approved loading computer is to be supplied for all Category I ships of 100 m in length and above. Category I ships include chemical tankers, gas carriers and ships with large deck openings [3].

Many researchers have proposed various methods for damaged ship stability calculation. Umair Abbas developed a tool using VBA (Visual Basic for Applications) to obtain damaged stability results [4]. The stability of the inverted ship was calculated and analyzed using GHS software [5]. Pan described a framework for a damage survivability assessment system [6]. J. Majumder described a real-time decision support system COMAND-DSS for the mitigation of flooding emergencies onboard ships, which provides decision makers with information about crises and available resources [7]. Andrzej Jasonnowski presented a prototype of an ergonomic decision support function for a flooding situation [8]. Paulo Triunfante Martins presented a decision support system, BOSS [9]. This paper described a real-time counter-flooding decision support system for survivability maintenance [10]. Lifen Hu used a genetic algorithm to solve the counter-flooding decision optimization model [11]. The paper described a simulation system to support emergency planning decisions when ship flooding occurs [12]. An FEA-like (finite elements analysis) method
was used to develop an onboard stability system [13]. Francesca Calabrese described an FEA-like method for evaluating the ship equilibrium point [14]. S. Schalck presented a new method for the calculation of the hydrostatic properties of intact and damaged ship hulls [15]. A commercial software, STAR-CCM+, was applied to simulate the flooding [16]. A practical method was used for the stability assessment of a damaged ship [17]. Eivind Ruth presented some of the key learnings from CFD simulations of flooding events following collision damage. The software STAR-CCM+ was used and allowed for full-scale simulations of the fully coupled behavior of the vessel [18]. A genetic algorithm was used to calculate the ship’s float position based on NURBS (Non-Uniform Rational B-Splines) [19]. A nonlinear optimization method was used to calculate the ship’s floating position based on Vector [20]. A RANS-based CFD solver with VOF modeling of free surfaces was employed to investigate the effects of sloshing and flooding on damaged ships’ hydrodynamics [21]. CFD calculations were applied to obtain the discharge coefficient of the whole cross-flooding duct [22]. Ruponen presented a numerical method for the assessment of damage stability [23].

| Type | Description |
|------|-------------|
| Type 1 | Software calculating intact stability only (for vessels not required to meet a damage stability criterion). |
| Type 2 | Software calculating intact stability and checking damage stability on the basis of a limit curve (e.g., for vessels applicable to SOLAS Part B-1 damage stability calculations, etc.) or checking all the stability requirements (intact and damage stability) on the basis of a limit curve. |
| Type 3 | Software calculating intact stability and damage stability by the direct application of preprogrammed damage cases based on the relevant conventions or codes for each loading condition (for some tankers, etc.). |
| Type 4 | Software calculating intact stability and damage stability by the direct application of preprogrammed damage cases based on the relevant conventions or codes for each loading condition (for some tankers etc.). |

Furthermore, many commercial companies have developed loading computer products [24], such as Onboard-NAPA [25], Deltaload [26], Loadplus [27], CargoMax [28], Loadmaster [29], K-LOAD [30], LR SEASAFE Onboard [31], SHIPMANAGER-88 [32], etc. These programs can calculate the damage stability of a ship in real time and already have the General Approval Certificate of Lloyd’s Register (IACS URL5 Type 3). These programs’ algorithms are stable and reliable with good real-time performance. However, the details of the calculation method used in the software are rarely published due to commercial confidentiality.

In summary, the methods for calculating damaged stability can be divided into four categories: (1) the Newton Iteration Method [14,17,33]; (2) the computational fluid dynamics (CFD) method [16,22,34]; (3) genetic algorithm, nonlinear programming and other optimization methods [10,11,19,20]; and (4) commercial software, including NAPA, Loadplus, etc. The advantages and disadvantages of these four methods are shown in Table 2. The CFD and optimization methods are not suitable for real-time calculation because of the huge amount of calculation needed. The Newton Iteration Method has fast convergence speed; generally, 3–5 iterations are required to obtain the final result. The disadvantage is that when calculating the Jacobian matrix coefficient, it is very difficult to calculate the inclined waterline parameters. The author has used the Newton Iteration Method to calculate damage stability and found that the iteration would fail in some cases (when the ship is in a large heel angle, for example) [17,33].
Table 2. Advantages and disadvantages of current research methods.

| Method               | Advantages                                                                 | Disadvantages                                                                 |
|----------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Newton Iteration     | Fast convergence speed (3–5 iterations).                                    | When calculating the Jacobian matrix coefficient, it is difficult to calculate the inclined waterline parameters. In some cases, the program will fail to converge. |
| Optimization method  | Compared with the Newton Iteration Method, there is no need to calculate the inclined waterline coefficient. Only the displacement and floating center of the ship need to be calculated. It has good robustness. | More iterations are required.                                                  |
| Commercial software  | Algorithms are stable and reliable with good real-time performance, and have been applied in practice. | The details of the calculation methods are not public.                        |

This paper presents a Simplified Newton Iteration Method to calculate a ship’s damage stability for a Type 3 loading computer. The 3D model database of the ship’s hull and all compartments is first established. Then, the real-time flow of liquid goods is considered. After that, a Simplified Newton Iteration Method is used to solve nonlinear equations.

2. Establishment of the 3D Model Database

The ship’s hull and all compartments are modeled as a 3D geometry mesh in the STL file format, which can be exported by the ship design software. Shown in Figure 1 is the STL model of the hull and compartments of the 59,000 DWT bulk carrier “BAOHANG 56”, which was designed by Shanghai Merchant Ship Design and Research Institute (SDARI) using the ship design software NAPA, which has become a global leader for supplying solutions for ship design and operation. For more details about the 3D model database, please refer to the author’s previous research papers [17, 33].

Figure 1. STL model of the hull and compartments of the 59,000 DWT bulk carrier “BAOHANG 56” designed by SDARI in 2022.
3. Simplified Newton Iteration Method for Damage Stability

There are two challenges in computing damage stability. The first challenge is the real-time flow of liquid cargo during the ship’s heeling, but the author previously solved this problem [17]. The second challenge is solving damage stability equations in real time. According to the above discussion, the Newton Iteration Method is more suitable for real-time calculation. However, the Newton Iteration Method has some shortcomings. A Simplified Newton Iteration Method, which can make up for the shortcomings of the traditional Newton Iteration Method, is proposed in this section.

3.1. Simplified Newton Iteration Method

To calculate the damage stability is to calculate the righting lever GZ [17, 23]. The free trim method is used in this section [23]. For a given fixed heel angle, the equilibrium state of the balanced trim and draft can be described as follows: the ship’s displacement equals the total weight, and the longitudinal center of gravity equals the longitudinal center of buoyancy:

\[
\begin{align*}
S \frac{\delta T_m}{\delta \tan \psi} + S \frac{\delta f_1(x)}{\delta \tan \psi} + S \frac{\delta f_2(x)}{\delta \tan \psi} &= 0 \\
S \frac{\delta T_m}{\delta \tan \psi} + S \frac{\delta f_1(x)}{\delta \tan \psi} + S \frac{\delta f_2(x)}{\delta \tan \psi} &= 0
\end{align*}
\]

where the Jacobian matrix in Equation (3) can be described as [33]:

\[
S = \begin{pmatrix}
S_{xf} & S_{xg} & S_{yf} & S_{yg} & S_{xfyf} & S_{xgyg} & S_{xgyp}
\end{pmatrix}
\]

where \( S \) is the water plane projection area on the base plane; \( x_f, y_f \) and \( z_f \) are the centers of the water plane; \( I_{xf} \) and \( I_{yf} \) are the moments of inertia of the water plane area; and \( I_{xy} \) is the product of inertia. \( M_{xz} \) and \( M_{yz} \) are described as follows:

\[
\begin{align*}
M_{xz} &= V_{yf} - \frac{y_f}{\rho} y_G \\
M_{yz} &= V_{zf} - \frac{z_f}{\rho} z_G
\end{align*}
\]

The disadvantage of the Newton Iteration Method is that when calculating the Jacobian matrix coefficient, it is very difficult to calculate the inclined waterline parameters. As shown in Equation (6), six parameters are needed for calculation, which has a high computation cost. Another disadvantage is that when using the Newton Iteration Method to calculate the damage stability, the iteration would fail in some cases [17, 33].
This section presents a Simplified Newton Iteration Method to calculate the ship’s damage stability. As shown in Figure 2, the hull of the ship is replaced with a three-dimensional rectangular bounding box, which saves a lot of computing time.

Figure 2. Three-dimensional rectangular bounding box of ship hull.

The schematic diagram of the intersection between the ship and the inclined water plane is shown in Figure 3. As shown in Figures 4 and 5, the projection of the inclined waterline surface is a rectangle with length \( L \) and width \( B \), where \( L \) and \( B \) are the overall length and breadth of the ship.

Figure 3. Intersection of inclined water plane and ship.

Figure 4. Projection of inclined waterline surface (rectangle).
For a rectangle, it is easy to calculate the water plane parameters:

\[
\begin{align*}
&x_F = 0 \\
y_F = 0 \\
&I_{xyF} = 0 \\
&I_x = \frac{LB_3}{12} \\
&I_y = \frac{BL_3}{12}
\end{align*}
\]  

(7)

According to the parallel axes theorem:

\[
I_{yF} = I_y - Sx_F^2
\]

(8)

The Jacobian coefficient matrix in Equation (4) can be simplified as follows:

\[
\begin{bmatrix}
BL & 0 \\
0 & \frac{BL_3}{12} - \sin \theta \cos \theta M_{xz} + \cos^2 \theta (\frac{BL_3}{12} \tan^2 \varphi + M_{xy})
\end{bmatrix}
\]

(9)

As can be seen from Equation (9), because the parameters \( B \) and \( L \) are given in the ship’s loading manual, the Simplified Newton Iteration Method, which is the same as the optimization method, only needs to calculate the ship’s submerged volume and center of buoyancy. Compared with the traditional Newton Iteration Method, there is no need to calculate the inclined waterline. This algorithm is very easy to implement by computer programming.

3.2. Iteration Termination Condition

The Gauss elimination method is used to solve the linear equations in Equation (10).

\[
\begin{bmatrix}
BL & 0 \\
0 & \frac{BL_3}{12} - \sin \theta \cos \theta M_{xz} + \cos^2 \theta (\frac{BL_3}{12} \tan^2 \varphi + M_{xy})
\end{bmatrix}
\begin{bmatrix}
\delta T_m \\
\delta \tan \varphi
\end{bmatrix}
\]

(10)

To ensure the accuracy of the calculation results, the iteration termination condition must be set. In this paper, iterations are performed until the displacement equals the total weight, and the longitudinal distance of the centers of gravity and buoyancy is zero.

\[
\begin{align*}
&|f_1| = |\rho V - \Delta| \leq \varepsilon_1 \\
&|f_2| = |(x_B - x_G) - (y_B - y_G) \sin \theta \cos \theta \tan \psi + (z_B - z_G) \cos^2 \theta \tan \psi| \leq \varepsilon_2
\end{align*}
\]

(11)

where \( \varepsilon_1, \varepsilon_2 \) are tolerances:

\[
\begin{align*}
\varepsilon_1 &= 5 \text{ t} \\
\varepsilon_2 &= 0.001 \text{ m}
\end{align*}
\]

(12)
4. Results

A 7500-DWT asphalt tanker, “TAI HUA WAN”, was chosen to demonstrate the feasibility of the proposed approach. The hull and all holds of the ship are shown in Figure 6.

Figure 6. Hull and all holds of the tanker “TAI HUA WAN”.

The design parameters of the tanker “TAI HUA WAN” are listed in Table 3.

Table 3. Principal parameters of the tanker “TAI HUA WAN”.

| Item                                      | Value         | Unit |
|-------------------------------------------|---------------|------|
| Ship name                                 | TAI HUA WAN   |      |
| Type of ship                              | ASPHALT TANKER|      |
| IMO number                                | 9,814,387     |      |
| Overall length                            | 114.92        | m    |
| Length B.P                                | 108.5         | m    |
| Breadth                                   | 19.5          | m    |
| Depth                                     | 11            | m    |
| Scantling draft                           | 6.98          | m    |
| Displacement at full load summer draft (even keel) | 11,914.2 | t |
| Deadweight at full load summer draft (even keel) | 7414.2 | dwt |
| Service speed (at designed draft)         | 13.95         | kn   |
| Light ship weight                         | 4611.5        | t    |

4.1. Initial Conditions

A total of 18 typical loading conditions (Table 4) of the tanker “TAI HUA WAN” are calculated. The initial draft, trim, heel angle, displacement, longitudinal center of buoyancy (LCB), vertical center of buoyancy (VCB) and GM value are listed in Table 5.
Table 4. Description of the initial conditions.

| IDENT | CONDITION NAME                                                                 |
|-------|--------------------------------------------------------------------------------|
| INI01 | FULLY LOADED WITH HOMOGENEOUS CARGO (S.G. = 0.8872T/M³), DEPARTURE             |
| INI02 | FULLY LOADED WITH HOMOGENEOUS CARGO (S.G. = 0.8872T/M³), ARRIVAL               |
| INI03 | FULLY LOADED WITH 0.98T/M³ CARGO, DEPARTURE                                   |
| INI04 | FULLY LOADED WITH 0.98T/M³ CARGO, ARRIVAL                                     |
| INI05 | FULLY LOADED WITH 0.926T/M³ CARGO, DEPARTURE                                 |
| INI06 | FULLY LOADED WITH 0.926T/M³ CARGO, ARRIVAL                                   |
| INI07 | FULLY LOADED WITH 1.04T/M³ CARGO, DEPARTURE                                  |
| INI08 | FULLY LOADED WITH 1.04T/M³ CARGO, ARRIVAL                                    |
| INI09 | NO.14 C/H FULL NO.23 C/H EMPTY 1.04T/M³, DEPARTURE                           |
| INI10 | NO.14 C/H FULL NO.23 C/H EMPTY 1.04T/M³, ARRIVAL                             |
| INI11 | NO.23 C/H FULL NO.14 C/H EMPTY 1.04T/M³, DEPARTURE                           |
| INI12 | NO.23 C/H FULL NO.14 C/H EMPTY 1.04T/M³, ARRIVAL                             |
| INI13 | NO.13 C/H FULL NO.24 C/H EMPTY 1.04T/M³, DEPARTURE                           |
| INI14 | NO.13 C/H FULL NO.24 C/H EMPTY 1.04T/M³, ARRIVAL                             |
| INI15 | NO.24 C/H FULL NO.13 C/H EMPTY 1.04T/M³, DEPARTURE                           |
| INI16 | NO.24 C/H FULL NO.13 C/H EMPTY 1.04T/M³, ARRIVAL                             |
| INI17 | PARTIALLY LOADED WITH HOMOGENEOUS CARGO (S.G. = 1.04T/M³), DEPARTURE          |
| INI18 | PARTIALLY LOADED WITH HOMOGENEOUS CARGO (S.G. = 1.04T/M³), ARRIVAL            |

Table 5. Initial ship flotation and stability parameters.

| NAME  | Draft (m) | Trim (m) | Heel Angle (deg) | Displacement (t) | LCB (m) | VCB (m) | GM (m) |
|-------|-----------|----------|------------------|------------------|---------|---------|--------|
| INI01 | 6.92      | −1.62    | 0.612            | 11,912.4         | 52.797  | 3.743   | 1.705  |
| INI02 | 6.559     | −1.131   | 0.375            | 11,135.7         | 53.725  | 3.52    | 1.84   |
| INI03 | 6.92      | −1.624   | 0.577            | 11,912.4         | 52.792  | 3.743   | 1.804  |
| INI04 | 6.559     | −1.134   | 0.354            | 11,135.7         | 53.72   | 3.52    | 1.946  |
| INI05 | 6.92      | −1.623   | 0.608            | 11,913.2         | 52.794  | 3.743   | 1.714  |
| INI06 | 6.559     | −1.133   | 0.373            | 11,136.5         | 53.722  | 3.521   | 1.849  |
| INI07 | 6.92      | −1.624   | 0.55             | 11,913.4         | 52.791  | 3.743   | 1.891  |
| INI08 | 6.559     | −1.135   | 0.338            | 11,136.7         | 53.719  | 3.521   | 2.039  |
| INI09 | 6.359     | −1.659   | 0.689            | 10,769.7         | 53.019  | 3.429   | 1.806  |
| INI10 | 5.991     | −1.121   | 0.463            | 9993             | 54.069  | 3.201   | 1.95   |
| INI11 | 6.303     | −1.072   | 0.675            | 10,613.8         | 53.97   | 3.375   | 1.72   |
| INI12 | 5.926     | −0.461   | 0.414            | 9837.1           | 55.116  | 3.149   | 1.861  |
| INI13 | 5.95      | −1.428   | 0.692            | 9928.9           | 53.602  | 3.189   | 1.713  |
| INI14 | 5.567     | −0.776   | 0.428            | 9152.2           | 54.805  | 2.957   | 1.884  |
| INI15 | 6.517     | −1.07    | 0.696            | 11,046.9         | 53.842  | 3.495   | 1.707  |
| INI16 | 6.146     | −0.505   | 0.447            | 10,270.2         | 54.927  | 3.272   | 1.83   |
| INI17 | 5.833     | −1.401   | 0.566            | 9693.9           | 53.703  | 3.122   | 2.193  |
| INI18 | 5.445     | −0.717   | 0.338            | 8917.2           | 54.949  | 2.889   | 2.421  |

4.2. Damage Cases

A total of 24 damage cases were calculated in the loading manual, but only 4 cases listed the GZ value of each heel angle in detail. For the other 20 cases, only the summary results are listed. To compare the results with the loading manual, four damage cases (DAM04, DAM08, DAM09 and DAM10) with detailed calculation results are selected. Damaged compartments of DAM04 are shown in Table 6 with cargo permeability (PERM), hold capacity (VOL), longitudinal coordinates of the center of gravity (LCG), the horizontal
coordinate of the center of gravity (TCG) and the vertical coordinates of the center of gravity (VCG). An illustration of damage case DAM04 is shown in Figure 7. Damaged compartments of DAM08, DAM09 and DAM10 are shown in Tables 7–9, respectively. Furthermore, the illustrations of damage cases DAM8, DAM09 and DAM10 are shown in Figures 8–10, respectively.

Figure 7. Illustration of damage case DAM04.

Figure 8. Illustration of damage case DAM08.
Figure 9. Illustration of damage case DAM09.

Table 6. Damaged compartments of DAM04.

| IDENT | NAME                     | PERM | VOL (m³) | LCG (m) | TCG (m) | VCG (m) |
|-------|--------------------------|------|----------|---------|---------|---------|
| R8.05 | PAINT STORE              | 0.95 | 45.6     | 101.19  | 5.79    | 12.88   |
| R8.00 | BOSUN STORE              | 0.95 | 286.9    | 105.28  | -0.92   | 12.97   |
| R8.04 | WINDLASS CTR. ROOM       | 0.95 | 52.5     | 101.25  | 0       | 12.9    |
| R8.07 | E.F.PR.M                 | 0.95 | 78.2     | 100.99  | -0.2    | 3.77    |
| R8.09 | LOGSOUND                 | 0.95 | 14.7     | 101.15  | 0       | 0.7     |
| R2.00P| FORE W.B.TK.P            | 0.95 | 126      | 101.18  | 2.89    | 8.07    |
| R2.00S| FORE W.B.TK.S            | 0.95 | 109.1    | 101.31  | -3.2    | 8.12    |
| R2.01P| NO.1 W.B.TK.P            | 0.95 | 370.8    | 91.58   | 7       | 5.89    |
| R9.01 | COFFERDAM FOR FORE.      | 0.95 | 1983     | 80.18   | 0       | 5.73    |
| R1.01P| NO.1 C.O.TANK P          | 0.95 | 773.8    | 89.66   | 2.97    | 6.32    |

Table 7. Damaged compartments of DAM08.

| IDENT | NAME                     | PERM | VOL (m³) | LCG (m) | TCG (m) | VCG (m) |
|-------|--------------------------|------|----------|---------|---------|---------|
| R2.02P| NO.2 W.B.TK.P            | 0.95 | 272.6    | 73.88   | 8.92    | 5.79    |
| R2.03P| NO.3 W.B.TK.P            | 0.95 | 451.9    | 55.08   | 8.15    | 4.84    |
| R9.01 | COFFERDAM FOR FORE.      | 0.95 | 1983     | 80.18   | 0       | 5.73    |
| R1.02P| NO.2 C.O.TANK            | 0.95 | 1021     | 74.44   | 3.72    | 5.95    |
| R3.01P| NO.1 H.F.O.TK.P          | 0.95 | 228.1    | 62.25   | 6.32    | 6.37    |

Table 8. Damaged compartments of DAM09.

| IDENT | NAME                     | PERM | VOL (m³) | LCG (m) | TCG (m) | VCG (m) |
|-------|--------------------------|------|----------|---------|---------|---------|
| R2.03P| NO.3 W.B.TK.P            | 0.95 | 451.9    | 55.08   | 8.15    | 4.84    |
| R9.02 | COFFERDAM FOR AFT        | 0.95 | 2157.7   | 43.77   | 0       | 5.32    |
| R1.03P| SLOP TANK                | 0.95 | 1026.6   | 50.02   | 3.74    | 5.93    |
| R3.01P| NO.1 H.F.O.TK.P          | 0.95 | 228.1    | 62.25   | 6.32    | 6.37    |
Table 9. Damaged compartments of DAM10.

| IDENT | NAME                  | PERM | VOL  | LCG  | TCG  | VCG  |
|-------|-----------------------|------|------|------|------|------|
| R2.03P | NO.3 W.B.TK.P         | 0.95 | 451.9| 55.08| 8.15 | 4.84 |
| R9.02 | COFFERDAM FOR AFT    | 0.95 | 2157.7| 43.77| 0    | 5.32 |
| R1.03P | SLOP TANK             | 0.95 | 1026.6| 50.02| 3.74 | 5.93 |

Figure 10. Illustration of damage case DAM10.

4.3. Damage Stability Results

A total of 18 typical loading conditions of tanker “TAI HUA WAN”, as listed in Table 4, are calculated. Figure 11 shows the GZ curve of INI01-DAM08. The calculation error and iteration number of each heel angle are shown in Table 10. The maximum error of each angle (0°, 1°, 3°, 5°, 7°, 10°, 12°, 15°, 20°, 30°, 40°, 50°, 60° and 70°) is −0.008 m, and the average error is −0.003 m. The maximum number of iterations is 37 when the ship’s heel angle is 70 degrees. The average number of iterations of all heel angles is 9.42.

Table 10. GZ calculation result of INI01-DAM08.

| HEEL (deg) | Loading Manual (m) | Proposed Method (m) | Iteration Number | Absolute Error (m) |
|------------|--------------------|---------------------|------------------|--------------------|
| 0          | −0.284             | −0.285              | 7                | −0.001             |
| 1          | −0.258             | −0.259              | 3                | −0.001             |
| 3          | −0.206             | −0.207              | 4                | −0.001             |
| 5          | −0.151             | −0.152              | 4                | −0.001             |
| 7          | −0.094             | −0.094              | 4                | 0                  |
| 10         | −0.002             | −0.002              | 4                | 0                  |
| 12         | 0.063              | 0.062               | 4                | −0.001             |
| 15         | 0.166              | 0.165               | 4                | −0.001             |
| 20         | 0.338              | 0.337               | 6                | −0.001             |
| 30         | 0.597              | 0.595               | 8                | −0.002             |
| 40         | 0.823              | 0.817               | 10               | −0.006             |
| 50         | 0.866              | 0.86                | 15               | −0.006             |
| 60         | 0.718              | 0.711               | 22               | −0.007             |
| 70         | 0.464              | 0.456               | 37               | −0.008             |
Figure 11. GZ curve of INI01-DAM08.

Figure 12 shows the GZ curve of INI11-DAM04. The calculation error and iteration number of each heel angle are shown in Table 11. The maximum error and average error of the GZ value are 0.003 m and 0.001 m. The maximum and average number of iterations are 53 and 12.78, respectively.

Figure 12. GZ curve of INI11-DAM04.

Figure 13 shows the GZ curve of INI16-DAM09. The calculation error and iteration number of each heel angle are shown in Table 12. The maximum error and average error of the GZ value are −0.012 m and −0.005 m. The maximum and average number of iterations are 26 and 6.85, respectively.
Table 11. GZ calculation result of INI11-DAM04.

| HEEL (deg) | Loading Manual (m) | Proposed Method (m) | Iterations | Absolute Error (m) |
|-----------|--------------------|---------------------|------------|--------------------|
| 0         | −0.08              | −0.08               | 9          | 0                  |
| 1         | −0.052             | −0.051              | 3          | 0.001              |
| 3         | 0.007              | 0.008               | 4          | 0.001              |
| 5         | 0.066              | 0.067               | 4          | 0.001              |
| 7         | 0.127              | 0.128               | 4          | 0.001              |
| 10        | 0.223              | 0.224               | 5          | 0.001              |
| 12        | 0.29               | 0.291               | 5          | 0.001              |
| 15        | 0.395              | 0.396               | 5          | 0.001              |
| 20        | 0.564              | 0.565               | 7          | 0.001              |
| 30        | 0.766              | 0.769               | 11         | 0.003              |
| 40        | 0.824              | 0.826               | 15         | 0.002              |
| 50        | 0.731              | 0.734               | 22         | 0.003              |
| 60        | 0.488              | 0.49                | 32         | 0.002              |
| 70        | 0.149              | 0.15                | 53         | 0.001              |

Figure 13. GZ curve of INI16-DAM09.

Figure 14 shows the GZ curve of INI15-DAM10. The calculation error and iteration number of each heel angle are shown in Table 13. The maximum error and average error of the GZ value are −0.013 m and −0.005 m. The maximum and average number of iterations are 28 and 6.92, respectively.

Limited by the word limit of the article, the other calculation results of the 18 loading conditions are listed in summary Table 14. The maximum error of absolute value, the average error of absolute value, the maximum iteration number and the average iteration number are shown in Table 14. According to the calculation results, the following conclusions can be drawn:

- The feasibility and accuracy of the algorithm are verified. The calculation error is small. The maximum and average error of the 18 loading conditions are 0.013 m and 0.002 m, respectively.
- The real-time performance of the algorithm is verified. The convergence rate of the algorithm is fast. The maximum and average number of iterations of the 18 loading conditions are 53 and 9, respectively.
Table 12. GZ calculation result of INI16-DAM09.

| HEEL (deg) | Loading Manual (m) | Proposed Method (m) | Iterations | Absolute Error (m) |
|-----------|--------------------|---------------------|-----------|-------------------|
| 0         | 0.577              | 0.578               | 6         | 0.001             |
| 1         | 0.539              | 0.54                | 3         | 0.001             |
| 3         | 0.462              | 0.464               | 3         | 0.002             |
| 5         | 0.383              | 0.385               | 3         | 0.002             |
| 7         | 0.301              | 0.303               | 3         | 0.002             |
| 10        | 0.172              | 0.174               | 3         | 0.002             |
| 12        | 0.082              | 0.084               | 3         | 0.002             |
| 15        | 0.059              | 0.057               | 3         | 0.002             |
| 20        | 0.316              | 0.314               | 3         | 0.002             |
| 30        | 0.777              | 0.772               | 5         | 0.005             |
| 40        | 1.132              | 1.121               | 8         | 0.011             |
| 50        | 1.174              | 1.165               | 11        | 0.009             |
| 60        | 1.011              | 1                   | 16        | 0.011             |
| 70        | 0.731              | 0.719               | 26        | 0.012             |

Table 13. GZ calculation result of INI15-DAM10.

| HEEL (deg) | Loading Manual (m) | Proposed Method (m) | Iteration Number | Absolute Error (m) |
|-----------|--------------------|---------------------|------------------|-------------------|
| 0         | 0.492              | 0.493               | 5                | 0.001             |
| 1         | 0.456              | 0.457               | 2                | 0.001             |
| 3         | 0.383              | 0.384               | 3                | 0.001             |
| 5         | 0.308              | 0.309               | 3                | 0.001             |
| 7         | 0.229              | 0.231               | 3                | 0.002             |
| 10        | 0.107              | 0.109               | 3                | 0.002             |
| 12        | 0.021              | 0.023               | 3                | 0.002             |
| 15        | 0.113              | 0.111               | 3                | 0.002             |
| 20        | 0.348              | 0.345               | 3                | 0.003             |
| 30        | 0.756              | 0.75                | 5                | 0.006             |
| 40        | 1.031              | 1.021               | 8                | 0.01              |
| 50        | 1.057              | 1.046               | 11               | 0.011             |
| 60        | 0.882              | 0.869               | 17               | 0.013             |
| 70        | 0.598              | 0.586               | 28               | 0.012             |

Figure 14. GZ curve of INI15-DAM10.
Table 14. GZ calculation results of 18 loading conditions.

| Case   | Max Error (m) | Average Error (m) | Max Iter. Number | Average Iter. Number |
|--------|---------------|-------------------|------------------|----------------------|
| INI01  | 0.008         | 0.003             | 37               | 9.4                  |
| INI02  | 0.007         | 0.002             | 37               | 9.4                  |
| INI03  | 0.008         | 0.003             | 38               | 9.5                  |
| INI04  | 0.007         | 0.002             | 37               | 9.5                  |
| INI05  | 0.009         | 0.003             | 37               | 9.4                  |
| INI06  | 0.007         | 0.002             | 37               | 9.4                  |
| INI07  | 0.008         | 0.003             | 38               | 9.6                  |
| INI08  | 0.008         | 0.002             | 37               | 9.5                  |
| INI09  | 0.007         | 0.002             | 16               | 5.9                  |
| INI10  | 0.005         | 0.001             | 35               | 9.1                  |
| INI11  | 0.003         | 0.001             | 53               | 12.7                 |
| INI12  | 0.005         | 0.002             | 32               | 8.7                  |
| INI13  | 0.006         | 0.002             | 35               | 9.1                  |
| INI14  | 0.005         | 0.001             | 35               | 9.1                  |
| INI15  | 0.012         | 0.005             | 28               | 6.9                  |
| INI16  | 0.013         | 0.005             | 26               | 6.9                  |
| INI17  | 0.007         | 0.002             | 32               | 8.6                  |
| INI18  | 0.007         | 0.002             | 31               | 8.6                  |

5. Conclusions

This paper presents a Simplified Newton Iteration Method to calculate damage stability for a Type 3 loading computer. Based on the proposed method, a loading computer named “SMART LOAD” for bulk carriers and tankers was developed, which was approved (IACS UR L5 Type 1, 2 and 3) by the LR Classification Society in 2020 and the DNV Classification Society in 2021. The proposed approach provides the following satisfactory conclusions:

(1) A simplified method for engineering applications is discussed for a loading computer. The solution of the Jacobian matrix coefficient is simplified, and there is no need to calculate six water plane parameters ($S$, $x_F$, $y_F$, $z_F$, $I_{yF}$ and $I_{xyF}$). Compared with the Newton Iteration Method, the calculation requirement is decreased because only displacement volume and center of buoyancy need to be computed.

(2) Compared with the CFD method and the optimization method, the proposed algorithm has a faster convergence rate. Approximately 9–10 iterations are required to obtain accurate results for each heel angle. This method is very suitable for real-time calculation.

(3) Unlike the commercial software, the approach presented in this paper is completely open.

(4) The longitudinal equilibrium equation of the ship is taken as the termination condition to ensure the accuracy of the result.

Since 2017, the loading computer “SMART LOAD” has been installed on more than 150 ships worldwide and has been approved by major classification societies, including LR, DNV-GL, BV, ABS, CCS and NK. “SMART LOAD” for the tanker “TAI HUA WAN” is illustrated in Figure 15. Based on the proposed method, the web version of “SMART LOAD” is being developed in 2022, as shown in Figure 16. In summary, the method is extremely simple, with real-time processes, robustness, accuracy and certain engineering application value.
Figure 15. “SMART LOAD” loading computer for the tanker “TAI HUA WAN”.

Figure 16. Web version of “SMART LOAD”.

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**Data Availability Statement:** Readers can access our data by sending an email to the corresponding author, Chunlei Liu.

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