Development of a theoretical framework for investigation of compensation possibilities of deviations in the ship’s piping system

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Abstract. The improving technology of ship piping systems at the design stage is an actual problem. The authors have analyzed technological features of manufacturing ship piping systems and have also considered the current state of design, manufacture and installation of ship pipeline issues. The review of research in the field of compensation of deviations of pipeline routes is presented. The problem of improving technology of ship piping systems at the design stage is considered providing the possibility of manufacturing pipes without measuring at the site. The authors have proposed the solution for the issue within studies of relationship of configuration and compensatory possibilities of pipeline routes. The authors are suggesting the idea of using straight pipes for moving the pipeline route to compensate for errors in the manufacture of pipes and the installation of tightly fixed connections of equipment, saturation products, etc., which ensures collecting the route without changing configuration of ready-made pipes. The proposed development allows to control and reduce at the design stage possible deviations that occur in the manufacture of pipes, to minimize the gaps assigned to the tracing of pipelines.

1. Introduction

A modern vessel is a sophisticated technological complex consisting of various types of equipment, mechanisms, structures, which operation provides with the piping systems (Figure 1). The labor intensity of pipeline production and ship system installation is up to 11-20% of the total manpower effort at the shipyard. The technology of pipeline production is characterized by a variety of operations and low level of mechanization. This production requires considerable and complex preparation [1-9].

Figure 1. Modeling of pipelines of ship systems with the help of computer program
In connection with the above, it is important to increase the efficiency of the pipeline production by introducing new technologies for the processing of pipes according to project documentation without measuring on the site [10, 11]. Availability of sufficient information for the production and installation of pipes in the project documentation allows to combine work on the vessel construction and shorten the time of shipbuilding orders execution [1,2,10,11].

2. Methods and Materials

To develop alternative methods of compensation, a hypothesis was put forward on the relationship between the configuration and compensation capabilities of the piping design trajectory. This hypothesis was substantiated in [10, 11]. Its main idea is to use straight and parallel sections with pipe connections to move the piping route. This compensates for the general deviations of rigidly fixed connections that limit this route, and also compensates for errors in the manufacture and installation of pipes, which will ensure the assembly of the route without changing the configuration of the finished pipes.

In the process of installation of the pipeline route, all deviations of the welded cups offset are compensated (Figure 2).

![Figure 2. Pipeline corridor after deviation offset ΔX, ΔY, ΔZ – installation is effectively completed](image)

In this study, we define the equations for determining the path compensation area in the direct problem (when designing the pipeline). In other words, we determine the possibility of compensating deviations of a given route. Consider the piping route, which consists of a sequence of points. Each of them can be either a point of connection of two tubes consisting of a sequence of points \(C (x_C, y_C, z_C)\), \(C (x_{C1}, y_{C1}, z_{C1})\), ..., \(C (x_{Cm}, y_{Cm}, z_{Cm})\), without changing the direction of the pipeline corridor, or the bending point \(F (x_F1, y_F1, z_F1)\), \(F (x_F2, y_F2, z_F2)\), ..., \(F (x_Fn, y_Fn, z_Fn)\) without changing the direction of the pipeline corridor (Figure 3). The last (terminate) point is \(A (x_A, y_A, z_A)\). The corridor must connect the start (\(C\)) and end point (\(A\)). The exact actual position of which relative to each other at the time of the corridor design is unknown.

![Figure 3. The route of pipe](image)

The terminal point of the corridor describes the spherical segment while installing the first connection with the pipe squint, winding the corridor in the junction, found on these straight-through tubes (Figure 4). Further, while installing the second connection, non-perpendicular to the pipe axis, but parallel to each other, the terminate point of the pipeline corridor shifts under a certain trajectory. Likewise, while the axes of the following connections are shifted, the compensation area builds a three-dimensional body. This arc, surface and a three-dimensional body define the compensation area.
The maximum deviation depends on the length of straight pipes or the distance between two connections. The research objective is to develop a mathematical description of the compensation area. For task, it is necessary to apply the calculation method based on the development of relevant theoretical concepts and mathematical formulas.

3. Results
We use the Cartesian coordinate system $C_{xyz}$. When installing connections at point $C$ with a skew and rotation of the $CC_1$, we obtain three coordinates $(r, \theta, \varphi)$, with $r$ – the shortest distance to the origin; $\theta$, $\varphi$ – zenith and azimuth angles, respectively. For task, it is more convenient to use spherical coordinate systems instead of the Cartesian ones. 

Three coordinates $(r, \theta, \varphi)$ are defined as follows:
- $r \geq 0$ – distance from the origin of coordinates $C$ to a given point;
- $0 \leq \theta \leq \alpha$ – the angle between the axis $Cz$ and the segment connecting the origin of the coordinates and the last point of the pipe $C_1$ (thus, $Cz$ – the pipe axis); $\alpha$ determined by OST 5. 95057-90 [12].
- $0 \leq \varphi \leq 2\pi$ – the angle between the X axis and the projection of the segment connecting the origin with the point $C_1$ on the Cxy plane (thus, Cxyz is the plane of the pipe).

If the spherical coordinates of the point $C_1$ are given, then the transition to the Cartesian $C_{xyz}$ is carried out by the formulas:

$$
\begin{align*}
C_{xyz} & = r_i \cdot \sin \theta_i \cdot \cos \varphi_i, \\
C_{x_1} & = r_i \cdot \sin \theta_i \cdot \sin \varphi_i; \\
C_{z_1} & = r_i \cdot \cos \theta_i,
\end{align*}
$$

where $r_i = CC_1 = \sqrt{x_i^2 + y_i^2 + z_i^2} = \sqrt{(x_{c1} - x_c)^2 + (y_{c1} - y_c)^2 + (z_{c1} - z_c)^2}$; $\theta_i$ – skew angle $[0, \alpha]$; $\varphi_i$ – angle of rotation $[0, 2\pi]$.

Let’s move back from Cartesian coordinates to spherical coordinates:

$$
\begin{align*}
\theta_i &= \arccos \left( \frac{z_i}{\sqrt{x_i^2 + y_i^2 + z_i^2}} \right) = \arctg \left( \frac{\sqrt{x_i^2 + y_i^2}}{z_i} \right), \\
\varphi_i &= \arctg \left( \frac{y_i}{x_i} \right)
\end{align*}
$$

The system of equations of coordinates (1) determines the trajectory of moving point $C_1$. This trajectory is presented in Figure 5.
Figure 5. The trajectory of the point $C_1$ when turning the first pipe

With parallel transfer of the coordinate system $C_{x_1y_1z_1}$ to point $C_i$, we will get a new coordinate system $C_{ix_1y_1z_1}$ (Figure 4). The formulas for the transition from $C_{xyz}$ system to $C_{ix_1y_1z_1}$ system take the form:

$$\begin{align*}
x &= x_1 + x_{C_i}; \\
y &= y_1 + y_{C_i}; \\
z &= z_1 + z_{C_i}.
\end{align*}$$

In the new coordinate system $C_{ix_1y_1z_1}$, the coordinates of the connection point $C_2$ take the form:

$$\begin{align*}
x_{C_2} &= r_2 \sin \theta_2 \cos \phi_2; \\
y_{C_2} &= r_2 \sin \theta_2 \sin \phi_2; \\
z_{C_2} &= r_2 \cos \theta_2,
\end{align*}$$

with $r_2 = C_{i1}C_2 = \sqrt{x_{C_2}^2 + y_{C_2}^2 + z_{C_2}^2} = \sqrt{(x_{C_2} - x_{C_1})^2 + (y_{C_2} - y_{C_1})^2 + (z_{C_2} - z_{C_1})^2}$.

Replace the systems of equations (1), (3), in the system of equations (2), the coordinates of the connection point $C_2$ take the form:

$$\begin{align*}
x &= x_{C_2} + x_{C_1}; \\
y &= y_{C_2} + y_{C_1}; \\
z &= z_{C_2} + z_{C_1}.
\end{align*}$$

We get:

$$\begin{align*}
x &= r_1 \sin \theta_1 \cdot \cos \phi_1 + r_2 \sin \theta_2 \cdot \cos \phi_2; \\
y &= r_1 \sin \theta_1 \cdot \sin \phi_1 + r_2 \sin \theta_2 \cdot \sin \phi_2; \\
z &= r_1 \cos \theta_1 + r_2 \cos \theta_2.
\end{align*}$$

Similarly, if the coordinate system of the following connection points is transferred in parallel (except for the last point $A$), then the coordinates of point $A$ in the original coordinate system $C_{xyz}$ take the form:

$$\begin{align*}
x_A &= \sum_{i=1}^{m} r_i \sin \theta_i \cdot \cos \phi_i; \\
y_A &= \sum_{i=1}^{m} r_i \sin \theta_i \cdot \sin \phi_i; \\
z_A &= \sum_{i=1}^{m} r_i \cos \theta_i,
\end{align*}$$

with $r_i = C_{i1}C_i = \sqrt{x_i^2 + y_i^2 + z_i^2} = \sqrt{(x_{C_{i-1}} - x_{C_i})^2 + (y_{C_{i-1}} - y_{C_i})^2 + (z_{C_{i-1}} - z_{C_i})^2}$; $m$ – quantity of free connections in the pipe’s route ($C, C_1, C_2, \ldots, C_m$); $\theta_i$ – skew angle $[0, \alpha]$; $\phi_i$ – angle of rotation $[0, 2\pi]$. 
Thus, \(x_A, y_A, z_A\) are the coordinates of the vector \(\overrightarrow{CA}\). To determine the coordinates \(A\) after shifting the corridor on the junction in the original coordinate system \(Oxyz\), use the formula:

\[
\overrightarrow{OA} = \overrightarrow{OC} + \overrightarrow{CA}
\]

Figure 6 shows two coordinate systems \(OXYZ\) and \(Cxyz\):

![Figure 6: Communication between the Cxyz system and the original OXYZ system](image)

For them:
- \(\hat{i}, \hat{j}, \hat{k}\) – unit vectors directed along each axis \(X, Y, Z\) of system \(O\);
- \(\hat{i}', \hat{j}', \hat{k}'\) – unit vectors directed along each axis \(x, y, z\) of system \(C\).

As shown above, \(x_A, y_A, z_A\) – coordinates of point \(A\) in the system \(Cxyz\); \(X_A, Y_A, Z_A\) – coordinates of point \(A\) in the system \(OXYZ\).

So in the original system \(OXYZ\): \(\overrightarrow{OA} = \hat{i}.X_A + \hat{j}.Y_A + \hat{k}.Z_A\); \(\overrightarrow{OC} = \hat{i}.x_c + \hat{j}.y_c + \hat{k}.z_c\)

In the system \(Cxyz\): \(\overrightarrow{CA} = \hat{i}'.x_A + \hat{j}'.y_A + \hat{k}'.z_A\)

By the rule of addition of vectors, we have:

\[
\overrightarrow{OA} = \overrightarrow{OC} + \overrightarrow{CA},
\]

It means:

\[
i.X_A + j.Y_A + k.Z_A = i.x_c + j.y_c + k.z_c + i'.x_A + j'.y_A + k'.z_A
\]

Multiplying (4) by \(\hat{i}\), we get:

\[
(i\hat{i}).X_A + (i\hat{j}).Y_A + (i\hat{k}).Z_A = (i\hat{i}).x_c + (i\hat{j}).y_c + (i\hat{k}).z_c +
\]

\[
+ (i\hat{i}'.x_A + (i\hat{j}'.y_A + (i\hat{k}'.z_A)
\]

According to the scalar product of vectors: \(\langle \hat{i}\hat{i} \rangle = 1.1.\cos0^\circ = 1\), \(\langle \hat{i}\hat{j} \rangle = 1.1.\cos90^\circ = 0\), \(\langle \hat{i}\hat{k} \rangle = 1.1.\cos90^\circ = 0\).

Formula (4) can be written as: \(X_A = x_c + (i\hat{i}).x_A + (i\hat{j}).y_A + (i\hat{k}).z_A\)

Similarly, multiplying (4) by \(\hat{j}\) and \(\hat{k}\) we get:

\(Y_A = y_c + (j\hat{i}).x_A + (j\hat{j}).y_A + (j\hat{k}).z_A\)
\n\(Z_A = z_c + (k\hat{i}).x_A + (k\hat{j}).y_A + (k\hat{k}).z_A\)

Determine the angles between \(\hat{i}, \hat{j}, \hat{k}\) and \(\hat{i}', \hat{j}', \hat{k}'\). Assign the axis of the first pipe \(CC_1 - Cy\).

So:

\[
\hat{j} = \frac{CC_1'}{CC_1}
\]

This implies:

\[
\cos(\hat{j}\hat{j}') = \frac{y_c - y_c}{CC_1}.
\]
Because the vectors $\vec{i}$, $\vec{j}$, $\vec{k}$ and $\vec{i}'$, $\vec{j}'$, $\vec{k}'$ are mutually parallel or perpendicular, therefore, knowing the angle $(\vec{j}, \vec{j}')$, we can determine the remaining angles.

We obtain the coordinates of point A in the original OXYZ system:

$$
\begin{align*}
X_A &= x_C + x_A; \\
Y_A &= y_C + y_A; \\
Z_A &= z_C + z_A;
\end{align*}
$$

or:

$$
\begin{align*}
x_A &= x_C + \sum_{i=1}^{m} r_i \sin \theta_i \cos \varphi_i; \\
y_A &= y_C + \sum_{i=1}^{m} r_i \cos \theta_i; \\
z_A &= z_C + \sum_{i=1}^{m} r_i \sin \theta_i \sin \varphi_i;
\end{align*}
$$

Equation (7) determines the trajectory of the displacement of the last point of trace A. This trajectory is shown in Figure 3.

![Figure 7](image_url) - The trajectory of the displacement of point A when the route is rotated

4. Conclusions

To sum up the conducted studies, the following results were obtained: a mathematical description of the compensatory capabilities of pipeline routes was made using straight pipes; 3D models of the compensation area are constructed; the theoretical basis for the creation of an automated program is developed, which will allow determining the areas of compensatory opportunities for pipeline routes; it is possible to replace the measured pipes with the ready ones, which will help to reduce the time for building ships.

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