Modelling of compensation process for the deviations of ship pipeline routes

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Abstract. In this paper, the solutions for problems related to increase in manufacturability of pipelines at a design stage were stated. The authors considered conditions and possibilities for compensating deviations of the pipeline route and adjacent structures during pipe installation. The task was set to produce a fitting pipe according to the design information without specifying dimensions and configuration in place on the ship. The fitting pipe was manufactured according to the design information with the assignment of technical allowances at the end sections in certain directions, if necessary. Moreover, the authors presented a method for compensating deviations in the routes of ship pipelines using rotations of pipe parallel section pairs, and developed the procedure for compensation and installation of pipelines from prefabricated pipes manufactured according to design information without specifying dimensions on the ship. Mathematical and graphic modeling of deviation compensation in pipelines during their installation was performed.

1. Introduction
A modern vessel is a complex multifunctional technological complex comprising various types of equipment, mechanisms and other structures for the operation of which piping systems serve. In global shipbuilding there are significant changes in the methods of design, technology of manufacturing and installation of ship pipelines. Nowadays it is typical to apply on a wide scale system approach to complex solution of design issues, technological preparation of production and manufacturing pipelines based on extensive use of computer technology [1-15].

At present, even with the development of automated pipeline design systems, the share of pipelines produced according to project information in advance in the shop is about 40%. The remaining part of pipes, called “fitting pipes”, can only be manufactured after dimensions have been taken on the ship. This affects adversely both construction time of the vessel and final cost of work [16].

In connection with the foregoing, the key contemporary approaches to the design, manufacture and installation of ship pipelines is to develop a concept for improving manufacturability of pipelines and eliminating the need for dimensioning at a place on the ship when performing shipbuilding orders.

2. Handling the issue of fitting pipes
“Fitting pipes” are those pipes, that are installed last and compensate for inaccuracies in the construction of the hull, inaccurate installation of mechanisms and fittings to which they join, and inaccuracies in the manufacture of pipes. Fitting pipes made on the basis of the design model, where all equipment is installed in regular places, will be unsuitable for installation on the ship, where the equipment is installed
with certain tolerances. Therefore, it is necessary to take into account actual dimensions and position of hull structures and system components based on measurements of the actual position of pipes on the vessel.

A characteristic feature of fitting pipes is that they can be manufactured only after main pipes of the pipeline route have been installed. To compensate for all possible deviations in the route in three coordinate directions, the adjusted pipe must always have at least two bends. Due to allowances at the ends of the pipe, it is possible to compensate for deviations in two coordinate directions. Deviation in the third direction is refined in place and compensated for by the received size for bending of the pipe. Therefore, fitting pipes cannot be manufactured in advance, since the size between bends is used as compensation for deviations and will be known only after the installation of main pipes for each route. In addition, manufacturing process of fitting pipes is much more labor-intensive than production of main pipes and additionally includes removal of the template in place and fitting locally.

In connection with the foregoing, to improve manufacturability of pipelines, the fitting pipe must be manufactured according to design information without specifying dimensions in place. Design documentation for fitting pipes will differ from documentation for the main pipes only by presence of technological allowances at the ends of the pipe. For the successful installation fitting pipe routes, during the installation it is necessary to be able to move the route, compensating for the deviations of both pipes and adjacent structures in directions that cannot be compensated for by allowances on the fitting pipe [16]. The pipeline route must be able to be moved at least in one coordinate direction.

In the work [16] it is established that movement of the route is possible if there are parallel section pairs and free connections located in these sections in the route. Based on the results of the study, a formula is defined for the area of compensation capacities of pipeline routes using rotations of pipe parallel sections pairs:

\[
\Delta S(t_1, t_2, ..., t_n) = \sum_{i=1}^{n} \left( R_i \sin(t_i) \bar{u}_i - R_i \left(1 - \cos(t_i)\right) \bar{e}_i \right)
\]

where:
- \(\Delta S\) – area of route compensation capacities;
- \(n\) – number of parallel pipe section pairs;
- \(t_1, t_2, ..., t_n\) – rotation angles of corresponding of parallel pipe section pairs;
- \(R_i\) – rotation radius of parallel pipe section pairs;
- \(\bar{u}_i, \bar{e}_i\) – basic vectors to the rotation circle of parallel section pairs.

3. Modelling the compensation process for deviations of pipeline routes

The pipeline route is given by a sequence of points \(T_1, T_2, ..., T_m\). Each of them can be either a bend point (change of the route direction), or a point of 2-pipe connection (without changing route direction). Numbers of connection points are specified by an array \(s_1, s_2, ..., s_i\). If necessary \(s_i\) can be calculated using \(T_i\). The route must connect start and end points, whose exact position (relative to each other) at the time of route design remains unknown. The error is determined by the area of possible deviations at the end point of the route. This area is given in the form of a rectangular parallelepiped (determined by maximum deviations from the end point of the route for each of the coordinates).

The part of the route where the initial and final straight sections are parallel can be used to move the end point of the route by turning the route in the connections located on these straight sections to angles up to the restriction of adjacent structures. The area that will be described by the end point \(A = T_m\), is area of possible deviation compensation. When the route is rotated around the axis of its first segment, the route end point forms an arc of the circle. If there is a section parallel to the first in the route, then after part of the route that is located behind the second parallel section, has rotated to the same angle but in the opposite direction, all parts of this part of the route remain parallel to its original position. The
end point position of the route will correspond to the result of its moving along an arc formed by
transferring the second parallel section relative to the first. Such displacements can be made using
parallel sections located anywhere in the route, i.e. transferring the arcs formed by them to the final
point of the route and using them to move the route during its installation in order to compensate for the
deviations that have arisen.

When two different pairs of parallel sections rotate, the end point of the route moves along a certain
surface.

When three or more pairs of segments rotate, compensation area is a three-dimensional body. These
arcs, surface and the three-dimensional body determine compensation areas.

Let us fix mathematically basic concepts.

**Parallelism of sections.** There is part of the route given by points \( T_1, T_{i+1}, \ldots, T_{j-1}, T_j \); \( j \geq i + 2 \). In
addition to the initial and final, there must be at least two bending points so that the sections can be
parallel. Parallelism of route sections can be determined from the angle between the directions at the
beginning (the first section) and at the end (the second section).

Direction at the beginning: \( \mathbf{v}_i = \mathbf{V}_i \), after rationing: \( \mathbf{v}_i = \frac{\mathbf{V}_i}{|\mathbf{V}_i|} \). Direction at the end:

\[
\mathbf{v}_2 = \mathbf{V}_2 - \mathbf{V}_1, \quad \mathbf{v}_2 = \frac{\mathbf{V}_2}{|\mathbf{V}_2|}.
\]

The angle is determined by scalar or vector product:

\[
\cos \gamma = \left( \mathbf{v}_1, \mathbf{v}_2 \right); \sin \gamma = \left[ \mathbf{v}_1, \mathbf{v}_2 \right].
\]

For parallel lines: \( \cos \gamma = 1; \sin \gamma = 0 \) (1)

If two sections meet this requirement, then parameters of the circle arc are determined. It will be
described by the second section when it is rotated relative to the axis formed by the direction of the first
one.

**Normal.** The normal is the direction at the beginning: \( \mathbf{n} = \mathbf{v}_1 \).

**Radius.** To determine the radius, a vector is defined that connects the beginning of the first and the
end of the second section \( \Delta \mathbf{T} = \mathbf{V}_2 - \mathbf{V}_1 \). Then the radius is given by:

\[
R = \sqrt{(\Delta \mathbf{T}, \Delta \mathbf{T}) - (\Delta \mathbf{T}, \mathbf{n})^2}
\]

If the radius is close to zero, then both sections lie on one line and their rotation is not considered.

**Basis vectors.** To specify the plane of a circle, three basis vectors are necessary. One of them (the
normal) has already been found, the other two are determined by the relations:

\[
\mathbf{e} = \frac{\mathbf{O}T_i - \mathbf{O}C}{R}, \quad \mathbf{u} = [\mathbf{n}, \mathbf{e}]
\]

Equation of circle \( S_1 \).

\[
\overrightarrow{OP_1} = R \sin(t \alpha_1) \mathbf{u} - R \left( 1 - \cos(t \alpha_1) \right) \mathbf{e}; \quad -\alpha_1 \leq t \leq \beta_1,
\]

where \( P_1 \) – arbitrary point of the first circle.

**Compensation area.** After determining all straight sections of the route and successive connections
of pipes, options with parallel sections are selected, checking condition (1). The resulting sequence of
circles is the material for constructing compensation area.

Compensation area, acquired by use of \( k \) arcs:
\[
\overrightarrow{OP}_n(t_1, t_2, \ldots, t_n) = \overrightarrow{OK} + \sum_{i=1}^{n} \left( R_i \sin(t_i) \overrightarrow{u_i} - R_i \left( 1 - \cos(t_i) \right) \overrightarrow{e_i} \right)
\]

where \( P_i \) – arbitrary point of surface \( S_i \).

Since the area is modeled in three-dimensional space, only three parameters \( t_i \) can be independent variables. If the rest \( k - 3 \) parameters are fixed in extreme meanings, then we obtain some areas that intersect and contain point \( A \). Combining them, we obtain area \( S_k \).

**Deviation area.** There is deviation area, given in the form of a parallelepiped, i.e. maximum deviations from the end point of the route are given for each of the coordinates \( \Delta = [\Delta x, \Delta y, \Delta z] \). At partial absorption of deviation parallelepiped by route compensation capacities area there is a possibility of partial compensation for deviations (see figure 1). When the deviation parallelepiped is completely absorbed by route compensation capacities area, it is viable to completely compensate for the deviations (see figure 2).

Modeling the process of deviation compensation is presented on the example of a 4-pipe route connecting the weld on the bulkhead to the pump (figures 3–5). In each of the five connections of the route there are free flanges, which allow turning the pipes in the joints around the pipeline axis at angles up to 360°.

In accordance with the current technology for project information, only three pipes are manufactured (in reserve); mounted on the ship; dimensions of the fourth pipe are determined by location and only after that, manufacturing process begins. This drags out construction of the ship significantly.

A new conceptual approach to the design, manufacture and installation of pipeline routes, based on the relationship of configuration and compensation capacities of the project route, provides for simultaneous manufacture and subsequent installation of all four pipes (figure 3a).

Let us consider in more detail the process of deviation compensation: discrepancy between the flange of the last pipe and the flange of the pump branch has occurred in all three coordinate directions of 30 mm (see figure 3b).

When the last pipe is rotated, before the point of the route coincides with X axis, deviation along Z axis is compensated (see figure 4a).

Rotation of the third pipe removes deviation along X-axis (see figure 4b).

It remains to compensate for deviation along Y-axis (see figure 4c). By turning the first pipe, the route is connected to the pump (see figure 4d). Compensation for deviations and installation of the route have been successfully completed.
Depending on the actual position of the pump and the bulk pick-up, the direction and magnitude of rotation angles of pipes during installation will change.

![Figure 3. Pipeline route: a – route before compensation; b – deviations in three coordinate directions dx, dy, dz.](image)

**Figure 3.** Pipeline route: a – route before compensation; b – deviations in three coordinate directions dx, dy, dz.

![Figure 4. Compensation for route deviations: a - compensation of deviation dz by rotating the last (green) pipe, b - compensation of deviation dx by rotating the third (violet) pipe, c - deviation in the remaining coordinate direction dy, d - rotations of the first (red) pipe to compensate for deviation dy.](image)

**Figure 4.** Compensation for route deviations: a - compensation of deviation dz by rotating the last (green) pipe, b - compensation of deviation dx by rotating the third (violet) pipe, c - deviation in the remaining coordinate direction dy, d - rotations of the first (red) pipe to compensate for deviation dy.

4. **Conclusion**

In course of research, modeling compensation process for deviations in the ship pipeline routes is performed using rotations of parallel pipe section pairs during their installation. The procedure for compensation and installation of pipelines from prefabricated pipes manufactured according to design information without specifying the dimensions in place has been developed.

With regard to more pipelines, it is feasible to use fitting pipes to compensate for deviations. Bending of such pipes will be carried out according to project sizes, without clarification in place. This
contributes to reducing construction period of facilities, composite technological complexes equipped with pipelines.

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