

Method for Compensating the Blockage of a Rudder Blade in an X-Shaped Rudder

The invention concerns a method for compensation of the blockage of a rudder blade in an X-shaped rudder system (in the following, X-shaped rudder) and thereby the maintenance of the maneuverability of the submarine with such an X-shaped rudder.

Instead of the conventional cross rudder, modern submarines, for example the German class 212a or the Israeli Dolphin class, have a so-called X-shaped rudder, with which the four rudder blades are each disposed diagonally to the horizontal or vertical in the normal position of the submarine.

In the case of an X-shaped rudder, the rudder blades are numbered as follows when viewed from the rear. Rudder blade 1 is disposed at the top right (starboard, top), rudder blade 2 is at the top left (port, top), rudder blade 3 is at the bottom right (starboard, bottom) and rudder blade 4 is at the bottom left (port, bottom). Thus, rudder blade 1 and rudder blade 4 as well as rudder blade 2 and rudder blade 3 respectively lie opposite each other.

By using an X-shaped rudder, two further positions are possible besides the use thereof corresponding to a virtual rudder or virtual stern plane. The virtual rudder or virtual stern plane corresponds to the rudder or the stern plane in a conventional arrangement of the rudder in a cross shape. With the virtual roll rudder, the rudder blades work together in such a way that the submarine is rotated about the longitudinal axis thereof without causing a further change of the direction of motion of the submarine, ostensibly performing a helical motion. With the virtual brake rudder, the rudder blades are disposed so that the direction of motion of the submarine is not changed, but the rudder blades exhibit a flow resistance and thus have a drag effect.

For practical reasons, the control is also carried out in the case of an X-shaped rudder by specifying an effect corresponding to a virtual rudder and a virtual stern plane, wherein in addition a roll rudder and a brake rudder are specified. The conversion between said specified values and the angles to be set on the rudder blades is given by:

$$\begin{pmatrix} \delta_r \\ \delta_s \\ \delta_p \\ \delta_u \end{pmatrix} = \frac{1}{4} \cdot \begin{pmatrix} -1 & 1 & 1 & -1 \\ 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{pmatrix} \quad \text{Equation 1}$$

with:

- δ_r deflection or control angle of the virtual rudder
- δ_s deflection or control angle of the virtual stern plane
- δ_p deflection or control angle of the virtual roll rudder
- δ_u deflection or control angle of the virtual brake rudder
- δ_1 deflection or control angle of the 1st rudder blade
- δ_2 deflection or control angle of the 2nd rudder blade
- δ_3 deflection or control angle of the 3rd rudder blade
- δ_4 deflection or control angle of the 4th rudder blade

Positive values for δ_1 , δ_2 , δ_3 and δ_4 as well as δ_s go down, positive values for δ_r go to port.

δ_1 , δ_2 , δ_3 and δ_4 are the control angles.

When specifying the rudders and the stern plane, the deflections of the rudder blades result according to the solution of equation 1:

$$\begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{pmatrix} = \begin{pmatrix} -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \delta_r \\ \delta_s \\ \delta_p \\ \delta_u \end{pmatrix} \quad \text{Equation 2}$$

The center position of the rudder is considered to be 0° deflection. If all rudders are in the center position, no force changing the direction of travel is acting on the rudder.

Because of the relatively complex design of the X-shaped rudder, a blocked rudder blade automatically has an effect on the virtual rudder and on the virtual stern plane.

A method for controlling a state of a vehicle, in particular of an underwater vehicle, is known from DE 10 2012 222 812 A1.

A controller for a rudder system for an X-shaped rudder is known from JP 2016-88 348 A.

It is the object of the invention to provide a method that enables maneuverability of the submarine even with a blocked rudder blade.

This object is achieved by the method with the features specified in claim 1. Advantageous developments result from the subordinate claims, the following description and the drawings.

The method according to the invention for compensation of the blockage of a rudder blade in an X-shaped rudder comprises the following steps:

- a) check whether a rudder blade is blocked,
- b) determine which rudder blade is blocked,
- c) determine the angle at which the blocked rudder blade is blocked,
- d) compensate the control angle for the remaining three rudder blades,
- m) actuate the rudder blades.

The advantage of the method is that the submarine remains maneuverable even after being damaged. Uncontrolled positional changes and directional changes are avoided by the method. If a blocked rudder blade occurs during a combat deployment or during a reconnaissance mission, in particular surfacing of the submarine, which would reveal the position and presence of the submarine, can be avoided.

If a rudder blade is blocked, then the deflection is predetermined by the blocked position and can no longer be varied. With a specified virtual rudder and a specified virtual stern plane, equation 2 thus gives:

$$\begin{pmatrix} \delta_{1,jam} \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{pmatrix} = \begin{pmatrix} -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{r,com} \\ \delta_{s,com} \\ \delta_p \\ \delta_u \end{pmatrix}$$

Equation 3

with:

$\delta_{1,jam}$ deflection of the blocked 1st rudder blade

$\delta_{2,jam}$ deflection of the blocked 2nd rudder blade

$\delta_{3,jam}$ deflection of the blocked 3rd rudder blade

$\delta_{4,jam}$ deflection of the blocked 4th rudder blade

$\delta_{r,com}$ deflection of the rudder, predetermined

$\delta_{s,com}$ deflection of the stern plane, predetermined

Because rolling of a submarine is a highly adverse condition, the roll rudder is first held fixedly in the neutral position:

$$\delta_p = \delta_{p,neut} = 0^\circ$$

Equation 4

The compensation in step d) is thus given as:

For a blocked 1st rudder blade:

$$\begin{pmatrix} \delta_2 \\ \delta_3 \\ \delta_4 \\ \delta_u \end{pmatrix} = \begin{pmatrix} 1 & 2 & 0 & 2 \\ -1 & 0 & 2 & -2 \\ -1 & -2 & 2 & 0 \\ 1 & 1 & -1 & 1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{1,jam} \\ \delta_{r,com} \\ \delta_{s,com} \\ \delta_{p,neut} \end{pmatrix}$$

Equation 5

For a blocked 2nd rudder blade:

$$\begin{pmatrix} \delta_1 \\ \delta_4 \\ \delta_3 \\ \delta_u \end{pmatrix} = \begin{pmatrix} 1 & -2 & 0 & -2 \\ -1 & 0 & 2 & 2 \\ -1 & 2 & 2 & 0 \\ 1 & -1 & -1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{2,jam} \\ \delta_{r,com} \\ \delta_{s,com} \\ \delta_{p,neut} \end{pmatrix}$$

Equation 6

For a blocked 3rd rudder blade:

$$\begin{pmatrix} \delta_4 \\ \delta_1 \\ \delta_2 \\ \delta_u \end{pmatrix} = \begin{pmatrix} 1 & -2 & 0 & 2 \\ -1 & 0 & 2 & -2 \\ -1 & 2 & 2 & 0 \\ -1 & 1 & 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{3,jam} \\ \delta_{r,com} \\ \delta_{s,com} \\ \delta_{p,neut} \end{pmatrix} \quad \text{Equation 7}$$

For a blocked 4th rudder blade:

$$\begin{pmatrix} \delta_3 \\ \delta_2 \\ \delta_1 \\ \delta_u \end{pmatrix} = \begin{pmatrix} 1 & 2 & 0 & -2 \\ -1 & 0 & 2 & 2 \\ -1 & -2 & 2 & 0 \\ -1 & -1 & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{4,jam} \\ \delta_{r,com} \\ \delta_{s,com} \\ \delta_{p,neut} \end{pmatrix} \quad \text{Equation 8}$$

In all cases, the brake rudder is enabled as a variable, i.e. the drag effect by the rudder comes into effect to maintain the controllability of the boat. This means the smallest change in the control behavior of the submarine.

However, during the compensation it can occur that the maximum possible deflection of a rudder blade is exceeded. In order to solve this problem, in a further embodiment of the invention, steps following step d) can be carried out:

- e) check whether one of the compensating control angles is greater than the maximum permissible control angle,
- f) If e) is positive, then determine which compensating control angle has the greatest deflection,
- g) scale the compensating control angle,
- m) if e) is negative or following g), actuate the rudder blades.

In this case, the maximum permissible control angle is not only dependent on the design. For example, a rudder blade can be movable in the range from -45° to 45°. In addition, the maximum permissible control angle is also a function of the speed of the submarine. Whereas a deflection in the aforementioned case of -45° to 45° is possible at a standstill (0 kn), because of the water pressure caused by the flow onto the rudder blade, during rapid travel, for example at 20 kn, the deflection can be limited to -30° to 30°, for example, because the torque on the rudder machinery and hence the maximum available force is limited.

The scaling does quantitatively change the control behavior, but qualitatively the properties are maintained. Particularly preferably, the ratio of the stern plane to the rudder remains constant. For example, the submarine can also traverse a defined curve after the scaling, for example to starboard, without a significant change in the submersion depth occurring; only the radius of the turn is increased during extreme maneuvers. The control behavior thus remains predictable for the crew even under said conditions. A reduction in the accuracy of maintaining depth must be accepted if it occurs.

The scaling is carried out in such a way that the control angle of the rudder blade with the greatest deflection is set to the maximum value and the remaining deflections of the remaining two rudder blades are scaled accordingly.

Where the index sc for the control angle $\delta_{n,sc}$ is selected as n from the group 1, 2, 3 or 4, this means that the control angle of the rudder n is scaled to the maximum value.

a is defined for

$$\delta_{r,com} = a \cdot \delta_{s,com} \quad \text{Equation 9}$$

If the 1st rudder blade is blocked, then for maximum deflection of the 2nd rudder blade we get from equation 5 and equation 9:

$$\delta_{r,com,sc} = \frac{1}{2}(\delta_{2,sc} - \delta_{1,jam}) \quad \text{Equation 10}$$

$$\delta_{s,com,sc} = \frac{1}{2a}(\delta_{2,sc} - \delta_{1,jam}) \quad \text{Equation 11}$$

If the 1st rudder blade is blocked, then for maximum deflection of the 3rd rudder blade we get from equation 5 and equation 9:

$$\delta_{s,com,sc} = \frac{1}{2}(\delta_{3,sc} + \delta_{1,jam}) \quad \text{Equation 12}$$

$$\delta_{r,com,sc} = \frac{1}{2a}(\delta_{3,sc} + \delta_{1,jam}) \quad \text{Equation 13}$$

If the 1st rudder blade is blocked, then for maximum deflection of the 4th rudder blade we get from equation 5 and equation 9:

$$\delta_{s,com,sc} = \frac{\delta_{4,sc} + \delta_{1,jam}}{2(1-a)} \quad \text{Equation 14}$$

$$\delta_{r,com,sc} = a \frac{\delta_{4,sc} + \delta_{1,jam}}{2(1-a)} \quad \text{Equation 15}$$

If the 2nd rudder blade is blocked, then for maximum deflection of the 1st rudder blade we get from equation 6 and equation 9:

$$\delta_{r,com,sc} = \frac{1}{2}(\delta_{2,jam} - \delta_{1,sc}) \quad \text{Equation 16}$$

$$\delta_{s,com,sc} = \frac{1}{2a}(\delta_{2,jam} - \delta_{1,sc}) \quad \text{Equation 17}$$

If the 2nd rudder blade is blocked, then for maximum deflection of the 3rd rudder blade we get from equation 6 and equation 9:

$$\delta_{s,com,sc} = \frac{\delta_{2,jam} + \delta_{3,sc}}{2(1+a)} \quad \text{Equation 18}$$

$$\delta_{r,com,sc} = a \frac{\delta_{2,jam} + \delta_{3,sc}}{2(1+a)} \quad \text{Equation 19}$$

If the 2nd rudder blade is blocked, then for maximum deflection of the 4th rudder blade we get from equation 6 and equation 9:

$$\delta_{s,com,sc} = \frac{1}{2}(\delta_{2,jam} + \delta_{4,sc}) \quad \text{Equation 20}$$

$$\delta_{r,com,sc} = \frac{1}{2}a(\delta_{2,jam} + \delta_{4,sc}) \quad \text{Equation 21}$$

If the 3rd rudder blade is blocked, then we get for maximum deflection of the 1st rudder blade from equation 7 and equation 9:

$$\delta_{s,com,sc} = \frac{1}{2}(\delta_{3,jam} + \delta_{1,sc}) \quad \text{Equation 22}$$

$$\delta_{r,com,sc} = \frac{1}{2}a(\delta_{3,jam} + \delta_{1,sc}) \quad \text{Equation 23}$$

If the 3rd rudder blade is blocked, then we get for maximum deflection of the 2nd rudder blade from equation 7 and equation 9:

$$\delta_{s,com,sc} = \frac{\delta_{2,sc} + \delta_{3,jam}}{2(1+a)} \quad \text{Equation 24}$$

$$\delta_{r,com,sc} = a \frac{\delta_{2,sc} + \delta_{3,jam}}{2(1+a)} \quad \text{Equation 25}$$

If the 3rd rudder blade is blocked, then we get for maximum deflection of the 4th rudder blade from equation 7 and equation 9:

$$\delta_{r,com,sc} = \frac{1}{2}(\delta_{3,jam} - \delta_{4,sc}) \quad \text{Equation 26}$$

$$\delta_{s,com,sc} = \frac{1}{2a}(\delta_{3,jam} - \delta_{4,sc}) \quad \text{Equation 27}$$

If the 4th rudder blade is blocked, then we get for maximum deflection of the 1st rudder blade from equation 8 and equation 9:

$$\delta_{s,com,sc} = \frac{\delta_{1,sc} + \delta_{4,jam}}{2(1-a)} \quad \text{Equation 28}$$

$$\delta_{r,com,sc} = a \frac{\delta_{1,sc} + \delta_{4,jam}}{2(1-a)} \quad \text{Equation 29}$$

If the 4th rudder blade is blocked, then we get for maximum deflection of the 2nd rudder blade from equation 8 and equation 9:

$$\delta_{s,com,sc} = \frac{1}{2}(\delta_{2,sc} + \delta_{4,jam}) \quad \text{Equation 30}$$

$$\delta_{r,com,sc} = \frac{1}{2}a(\delta_{2,sc} + \delta_{4,jam}) \quad \text{Equation 31}$$

If the 4th rudder blade is blocked, then we get for maximum deflection of the 3rd rudder blade from equation 8 and equation 9:

$$\delta_{r,com,sc} = \frac{1}{2}(\delta_{3,sc} - \delta_{4,jam}) \quad \text{Equation 32}$$

$$\delta_{s,com,sc} = \frac{1}{2a}(\delta_{3,sc} - \delta_{4,jam}) \quad \text{Equation 33}$$

With the scaled virtual deflections $\delta_{r,com,sc}$ and $\delta_{s,com,sc}$ from equations 10 through 37 and equations 5 through 8 the control angles become:

For the blocked 1st rudder blade:

$$\begin{pmatrix} \delta_2 \\ \delta_3 \\ \delta_4 \\ \delta_u \end{pmatrix} = \begin{pmatrix} 1 & 2 & 0 & 2 \\ -1 & 0 & 2 & -2 \\ -1 & -2 & 2 & 0 \\ 1 & 1 & -1 & 1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{1,jam} \\ \delta_{r,com,sc} \\ \delta_{s,com,sc} \\ \delta_{p,neut} \end{pmatrix}$$

Equation 34

For the blocked 2nd rudder blade:

$$\begin{pmatrix} \delta_1 \\ \delta_4 \\ \delta_3 \\ \delta_u \end{pmatrix} = \begin{pmatrix} 1 & -2 & 0 & -2 \\ -1 & 0 & 2 & 2 \\ -1 & 2 & 2 & 0 \\ 1 & -1 & -1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{2,jam} \\ \delta_{r,com,sc} \\ \delta_{s,com,sc} \\ \delta_{p,neut} \end{pmatrix}$$

Equation 35

For the blocked 3rd rudder blade:

$$\begin{pmatrix} \delta_4 \\ \delta_1 \\ \delta_2 \\ \delta_u \end{pmatrix} = \begin{pmatrix} 1 & -2 & 0 & 2 \\ -1 & 0 & 2 & -2 \\ -1 & 2 & 2 & 0 \\ -1 & 1 & 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{3,jam} \\ \delta_{r,com,sc} \\ \delta_{s,com,sc} \\ \delta_{p,neut} \end{pmatrix}$$

Equation 36

For the blocked 4th rudder blade:

$$\begin{pmatrix} \delta_3 \\ \delta_2 \\ \delta_1 \\ \delta_u \end{pmatrix} = \begin{pmatrix} 1 & 2 & 0 & -2 \\ -1 & 0 & 2 & 2 \\ -1 & -2 & 2 & 0 \\ -1 & -1 & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} \delta_{4,jam} \\ \delta_{r,com,sc} \\ \delta_{s,com,sc} \\ \delta_{p,neut} \end{pmatrix}$$

Equation 37

Unfortunately, it is also not possible with this to actuate in all directions if a rudder is blocked in the maximum position, for example $\pm 45^\circ$. In order to still improve the maneuverability in such cases, it can be necessary to release the roll rudder and permit a rotation about the longitudinal axis. Therefore, in a further embodiment of the invention the following steps are carried out:

- h) check whether the magnitude of the specified stern plane is greater than or equal to 1° and the magnitude of the scaled stern plane is less than 1° ,
- i) if h) is negative, then perform an adjustment with the scaled rudder and scaled stern plane according to step g) and continue with step m),
- j) if h) is positive, then re-scale taking into account the roll rudder,
- k) determine the re-scaled rudder, the re-scaled stern plane and the re-scaled roll rudder,
- l) then perform an adjustment with the re-scaled rudder, re-scaled stern plane and re-scaled roll rudder,
- m) if e) is negative or following i) or following l), actuate the rudder blades.

Because depth and course can no longer be maintained in this case, the priority is placed on the submersion depth and thereby on the stern plane. This is preferred because both being less than the maximum submersion depth and surfacing can represent a high risk for the submarine.

In the following, $\delta_{r,ord}$ denotes the re-scaled rudder and $\delta_{p,ord}$ denotes the re-scaled roll rudder, wherein in this case these are not completely correctly scaled values. The values are determined in such a way that $\delta_{s,com}$ can be achieved. $\delta_{r,com}$ can by contrast no longer be achieved, because δ_p is enabled as a further degree of freedom. In this case, the variation is selected so that $\delta_{r,ord}$ is minimal.

For the blocked 1st rudder blade we get:

$$\delta_{r,ord} = \frac{1}{2}(-\delta_{1,jam} - \delta_4 + 2\delta_{s,com}) \quad \text{Equation 38}$$

$$\delta_{p,ord} = \frac{1}{2}(\delta_2 - \delta_{1,jam} - 2\delta_{r,ord}), \text{ wenn } |\delta_{1,jam} - 2\delta_{r,ord}| > 45^\circ \quad \text{Equation 39}$$

$$\delta_{p,ord} = \frac{1}{2}(-\delta_3 - \delta_{1,jam} + 2\delta_{s,com}), \text{ wenn } |\delta_{1,jam} + 2\delta_{s,com}| > 45^\circ \quad \text{Equation 40}$$

For the blocked 2nd rudder blade we get:

$$\delta_{r,ord} = \frac{1}{2}(\delta_{2,jam} + \delta_3 - 2\delta_{s,com}) \quad \text{Equation 41}$$

$$\delta_{p,ord} = \frac{1}{2}(-\delta_1 + \delta_{2,jam} - 2\delta_{r,ord}), \text{ wenn } |\delta_{2,jam} - 2\delta_{r,ord}| > 45^\circ \quad \text{Equation 42}$$

$$\delta_{p,ord} = \frac{1}{2}(\delta_4 + \delta_{2,jam} - 2\delta_{s,com}), \text{ wenn } |\delta_{2,jam} - 2\delta_{s,com}| > 45^\circ \quad \text{Equation 43}$$

For the blocked 3rd rudder blade we get:

$$\delta_{r,ord} = \frac{1}{2}(\delta_{3,jam} + \delta_2 - 2\delta_{s,com}) \quad \text{Equation 44}$$

$$\delta_{p,ord} = \frac{1}{2}(\delta_4 - \delta_{3,jam} + 2\delta_{r,ord}), \text{ wenn } |\delta_{3,jam} + 2\delta_{r,ord}| > 45^\circ \quad \text{Equation 45}$$

$$\delta_{p,ord} = \frac{1}{2}(-\delta_1 - \delta_{3,jam} + 2\delta_{s,com}), \text{ wenn } |\delta_{3,jam} + 2\delta_{s,com}| > 45^\circ \quad \text{Equation 46}$$

For the blocked 4th rudder blade we get:

$$\delta_{r,ord} = \frac{1}{2}(-\delta_{4,jam} - \delta_1 + 2\delta_{s,com}) \quad \text{Equation 47}$$

$$\delta_{p,ord} = \frac{1}{2}(-\delta_3 + \delta_{4,jam} + 2\delta_{r,ord}), \text{ wenn } |\delta_{4,jam} + 2\delta_{r,ord}| > 45^\circ \quad \text{Equation 48}$$

$$\delta_{p,ord} = \frac{1}{2}(\delta_2 + \delta_{4,jam} - 2\delta_{s,com}), \text{ wenn } |\delta_{4,jam} - 2\delta_{s,com}| > 45^\circ \quad \text{Equation 49}$$

In an alternative method, the priority is placed on the course and the submersion depth is varied. In said alternative embodiment of the invention, the following steps are carried out:

- h') Check whether the magnitude of the specified rudders is greater than or equal to 1° and the magnitude of the scaled rudder is less than 1° ,
- i') if h') is negative, then perform an adjustment with a scaled rudder and a scaled stern plane,
- j') if h') is positive, then re-scale taking into account the roll rudder,
- k') determine the re-scaled stern plane, the re-scaled rudder and the re-scaled roll rudder,
- l') then perform an adjustment with a re-scaled stern plane, re-scaled rudder and re-scaled roll rudder,
- m) if e) is negative or following i') or following l'), actuate the rudder blades.

In this case, the calculation is carried out in a similar manner to the previous methods, as the priority was placed on the submersion depth and thereby on the stern plane.

The method according to the invention is described in detail below using an exemplary embodiment represented in the drawing.

Fig. 1 flow chart

Fig. 2 rudder arrangement

In Fig. 1, a flow chart for the actuation of rudder blades of an X-shaped rudder is shown.

In step A, the value for the rudder $\delta_{r,com}$ and the value for the stern plane $\delta_{s,com}$ are specified.

In step B, the values are converted into the control angles δ_i of the four rudder blades according to equation 2.

In step C, a check is carried out as to whether a rudder blade is blocked. If no rudder blade is blocked, the method is continued with step N; if a rudder blade is blocked, then the method is continued with step D.

In step N, a check is carried out as to whether one of the control angles δ_i of the four rudder blades is greater than the maximum control angle. If this is the case, then the method is continued with step O; if this is not the case, then the method is continued with step K.

In step O, the control angles δ_i of the four rudder blades are scaled so that the highest value of the control angle δ_i of the four rudder blades adopts the value of the maximum control angle. Then the method is continued with step K.

In step D, a check is carried out as to which rudder blade is blocked and as to the angle δ_i at which the blocked rudder blade is blocked.

In step E, the control angles for the remaining three rudder blades are calculated to compensate the blocked rudder blade. The calculation is carried out according to the equations 5 through 8.

In step F, a check is carried out as to whether one of the control angles δ_i of the four rudder blades is greater than the maximum control angle. If this is the case, then the method is continued with step G; if this is not the case, then the method is continued with step K.

In step G, the rudder blade having the largest compensating control angle is determined.

In step H, the control angles are scaled in order to reduce the largest compensating control angle to the maximum control angle. The scaling is carried out by means of equations 10 through 33.

In step I, a check is carried out as to whether the magnitude of the specified stern plane is greater than or equal to 1 and whether the magnitude of the scaled stern plane is less than 1. If this is the case, then the method is continued with step L; if this is not the case, then the method is continued with step J.

In step J, the individual rudder positions for the control angle scaled in step H are calculated. The calculation is carried out according to the equations 34 through 37.

In step L, the control angles with variable roll rudder are calculated by means of the equations 38 through 49.

In step M, the individual rudder positions for the scaled control variables are calculated according to equations 5 through 8 or according to equations 34 through 37.

In step K, the rudder blades are actuated.

In Fig. 2, the four rudder blades and the virtual rudder 50 and the virtual stern plane 60 are shown, wherein the submarine is viewed from the rear in the direction of travel here.

Rudder blade 1 10, rudder blade 2 20, rudder blade 3 30 and rudder blade 4 40 and the virtual rudder 50 and the virtual stern plane 60 can be seen.

Claims

1. A method for compensation of the blockage of a rudder blade in an X-shaped rudder, wherein the method comprises the following steps:
 - a) check whether a rudder blade is blocked,
 - b) determine which rudder blade is blocked,
 - c) determine the angle at which the blocked rudder blade is blocked,
 - d) compensate the control angle for the remaining three rudder blades,
 - m) actuate the rudder blades.

2. The method as claimed in claim 1, **characterized in that** following step d) the following steps are carried out:
 - e) check whether one of the compensating control angles is greater than the maximum permissible control angle,
 - f) if e) is positive, then determine which compensating control angle has the largest deflection,
 - g) scale the compensating control angle,
 - m) if e) is negative or following g), actuate the rudder blades.

3. The method as claimed in claim 2, **characterized in that** following step g), the following steps are carried out:
 - h) check whether the magnitude of the specified stern plane is greater than or equal to 1° and the magnitude of the scaled stern plane is less than 1° ,
 - i) if h) is negative, then perform an adjustment with a scaled rudder and a scaled stern plane according to step g) and continue with step m),
 - j) if h) is positive then re-scale, taking into account the roll rudder,
 - k) determine the re-scaled rudder, the re-scaled stern plane and the re-scaled roll rudder,
 - l) then perform an adjustment with the re-scaled rudder, re-scaled stern plane and re-scaled roll rudder,
 - m) if e) is negative or following i) or following l), actuate the rudder blades.

4. The method as claimed in claim 2, **characterized in that** following step g), the following steps are carried out:
- h') check whether the magnitude of the specified rudder is greater than or equal to 1° and the magnitude of the scaled rudder is less than 1° ,
 - i') if h') is negative, then perform an adjustment with the scaled rudder and the scaled stern plane,
 - j') if h') is positive, then re-scale taking into account the roll rudder,
 - k') determine the re-scaled stern plane, the re-scaled rudders and the re-scaled roll rudder,
 - l') then perform an adjustment with the re-scaled stern plane, re-scaled rudder and re-scaled roll rudder,
 - m) if e) is negative or following i') or following l'), actuate the rudder blades.