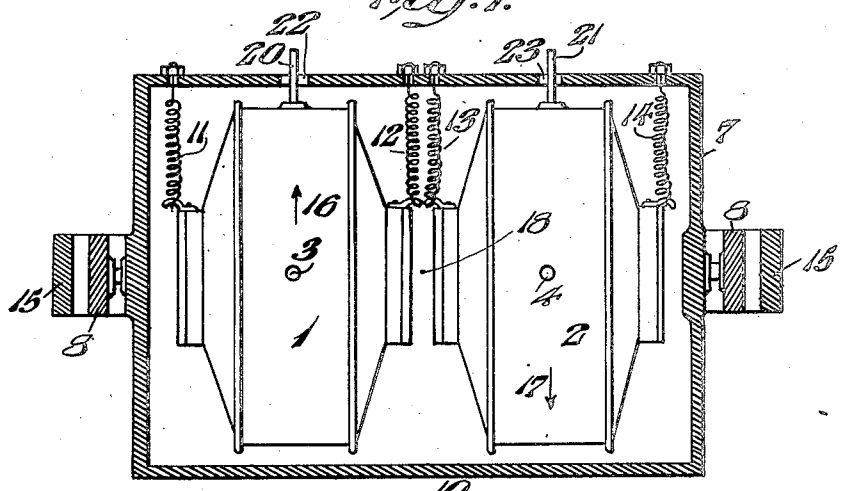
May 28, 1940. N. MINORSKY 2,202,162

ANTIROLLING STABILIZATION OF SHIPS

Original Filed Nov. 21, 1936 2 Sheets-Sheet 1

Fig. 1.



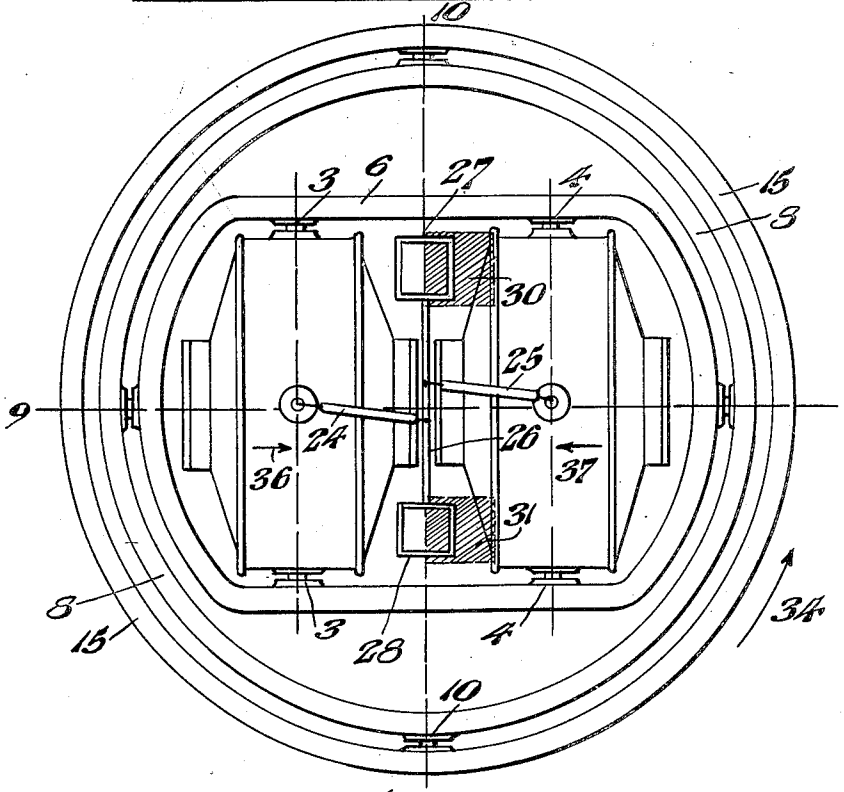


Fig. 2.

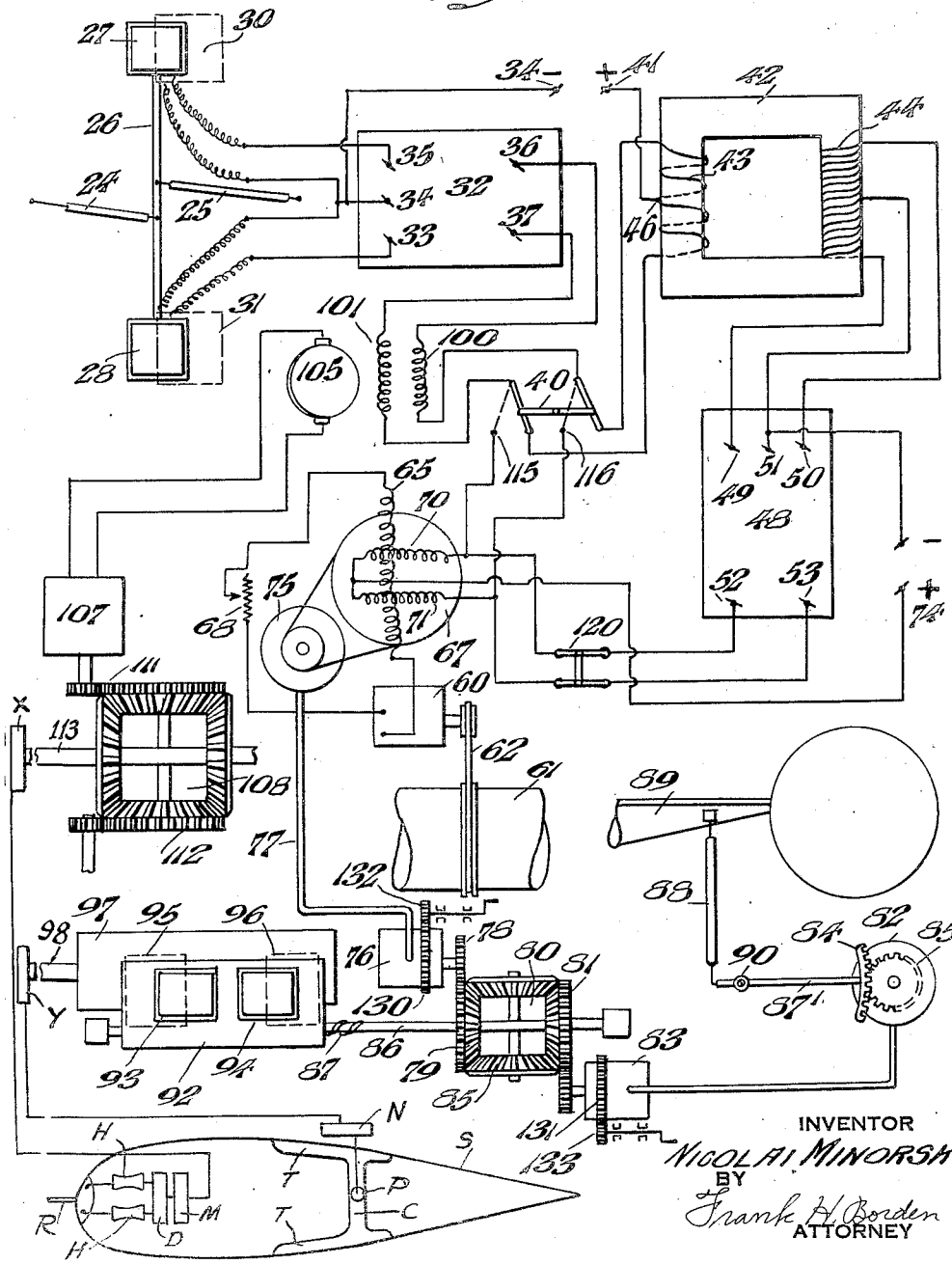
INVENTOR.
NICOLAI MINORSKY.
BY Frank H. Borden
ATTORNEY.

May 28, 1940. N. MINORSKY 2,202,162

ANTIROLLING STABILIZATION OF SHIPS

Original Filed Nov. 21, 1936 2 Sheets-Sheet 2

Fig. 3.



INVENTOR
NICOLAI MINORSKY.
BY
Frank H. Borden
ATTORNEY

Patented May 28, 1940

2,202,162

UNITED STATES PATENT OFFICE

2,202,162

ANTIROLLING STABILIZATION OF SHIPS

Nicolai Minorsky, Brooklyn, N. Y.

Application November 21, 1936, Serial No. 112,003
Renewed November 9, 1939

21 Claims. (Cl. 114—122)

This invention relates to improvements in devices for antirolling stabilization of ships, submarines, airships and other moving bodies.

More specifically it deals with the compensation or quenching of the component of angular motion of ships in the rolling degree of freedom, that is about the longitudinal axis, which is not rolling proper but rather heeling or listing arising from forced yawing among waves frequently observed in ships acted upon by a following sea.

This new component of angular motion has been studied only recently and, as a result of this study it has been ascertained that the ship's position relatively to the following sea is that of unstable equilibrium due to the forced yawing motion. The latter, in combination with the forward motion of the ship, accounts for the appearance of centrifugal force in a substantially horizontal direction applied to the center of gravity, which causes the heeling. To this is added the action of the rudder trying to check the yawing and thereby developing yawing in the opposite direction with a corresponding change in the direction of the centrifugal force and, therefore, of heeling. Contrary to the pure rolling which is a purely cumulative or resonance effect, this yaw-heeling is of a different nature and is a non-resonance dynamical effect insofar as it develops completely during one period of yawing. It is not a strictly periodic phenomenon either insofar as it depends on the conditions of seaway, action of the rudder and similar factors. It manifests itself, however, in the rolling degree of freedom and frequently is erroneously considered as rolling, although the underlying dynamical causes of this yaw-heeling are entirely different from pure rolling which, as is well known, is governed by Froude's theory established more than sixty years ago. Such yawing or turning, whether unintentional and from the action of the sea, or intentional from the action of a rudder, or as a resultant of both, is a function of centrifugal force acting on the ship about the longitudinal axis thereof. Obviously "turning" and "yawing" are interchangeable terms and yawing as used herein contemplates any turning of the ship whether deliberate or accidental, just as the heeling referred to as yaw-heeling includes any heeling or rolling as an incident of the application of centrifugal force about the longitudinal axis of the ship.

As a result of this situation controlling stabilizing means adequate for quenching the rolling proper fail to control the yaw-heeling, and observations borne out from actual experiments with antirolling stabilization of ships confirm this in a very definite manner.

This invention has for its object to provide a new anti-yaw-heel control and to interlock it properly with the antirolling control so as to obtain under all possible conditions of rolling, yaw-heeling, or any combination of these component motions an adequate control of stabilization in the rolling degree of freedom of the ship.

The yaw-heel component of stabilization as its very name implies splits itself into two subcomponents—yawing and heeling.

Any stabilizing action dealing with yawing proper relates to the realm of automatic steering devices and as such is outside the direct purpose and scope of this present invention. As a side issue, however, this invention provides a means for improving the steering, whether manual or automatic and from this standpoint helps materially to reduce the yawing. As far as the heeling component is concerned, it is obvious that any method dealing with reduction of angular motion in the rolling degree of freedom, such as tanks, moving weights, fins, etc., must be employed although the underlying dynamical phenomena and therefore the controlling means intended to deal with them are entirely different from those adapted to deal with rolling, properly speaking.

In reality in a confused seaway which is of a frequent occurrence, particularly in the North Atlantic routes, both motions, that is rolling as well as heeling arising from a forced yawing, appear simultaneously and the two controlling systems, antirolling and anti-yaw-heeling must cooperate, each taking care of its component disturbing motion.

For that reason a suitable interlocking of both controls is of a great importance. The whole problem is thus reduced to the solution of two partial problems, viz; (*a*) to produce an adequate anti-yaw-heeling control and (*b*) to interlock it properly with the antirolling control.

In order to be able to produce an adequate anti-yaw-heeling control it is necessary to closely analyze the dynamics of this disturbing cause. The heeling is due to the centrifugal force

$$F=\frac{mv^2}{r} \qquad (1)$$

where

m is the mass of the ship
v is its speed
r is the radius of curvature of the yawing path.

Since $v=\omega r$, where ω is the angular velocity of

yawing the preceding Equation 1 can be written as $F=mv\omega$ (2). Thus the centrifugal force tending to heel the ship is proportional to the product of v and ω. Any compensating action to be set up in the rolling degree of freedom of the ship must, therefore, be of the same form, that is proportional to the product $v.\omega$. If this compensating or quenching action is produced by the transfer of liquid ballast between the tanks the instantaneous excess of ballast in the tank situated on the inward side of the yawing path must be varied in proportion to the product $v.\omega$. if this compensating action is produced by fins the angle of fins taking care of this heeling must stand in a relation to the same product $v.\omega$.

As mentioned in my Patent No. 2,017,072 it is generally difficult to control the amount of the ballast, if the time for such transfer is relatively short, but it is easier to control the rate of transfer

$$\frac{dw}{dt}$$

if w designates the amount of transferred ballast. Differentiating the preceding equation one has:

$$\frac{dw}{dt}=k\left(v\frac{d\omega}{dt}+\omega\frac{dv}{dt}\right)$$

where k is a suitable coefficient of proportionality. If one neglects small variations in the ship's speed, the preceding equation is simplified and becomes:

$$\frac{dw}{dt}=kv\frac{d\omega}{dt} \quad \text{----------(2)}$$

I adopt Equation 2 as the starting point for my anti-yaw-heel control described in this invention.

In my Patent No. 2,017,072 I have shown that in order to obtain a correct stabilizing action in the case of pure rolling the rate of transfer of ballast must be proportional to the linear acceleration

$$\frac{d^2\theta}{dt^2}$$

that is it should be of the form:

$$\frac{dw}{dt}=a\frac{d^2\theta}{dt^2}$$

where a is a suitable coefficient of proportionality.

In view of the fact that with this control the stabilizing decrement or damping is proportional to the first derivative

$$\frac{d\theta}{dt}$$

of rolling motion, the linear feature of the differential equation of rolling is emphasized over the non-linear, so that, to the first approximation it is legitimate to assume the principle of superposition.

It is thus possible to interlock both components

$$kv\frac{d\omega}{dt} \text{ and } a\frac{d^2\theta}{dt^2}$$

in the control while maintaining their superposition in the stabilizing action. The resultant transfer of ballast in this most general form when both rolling and yaw-heeling are being quenched at the same time should therefore be of the form:

$$\frac{dw}{dt}=a\frac{d^2\theta}{dt^2}+kv\frac{d\omega}{dt} \quad \text{----------(3)}$$

With this form of transfer the secondary or follow-up part of the stabilizing equipment remains the same as shown in my Patent No. 2,017,072, that is, it remains responsive to the rate of transfer of the ballast, and only on the primary side the controlling action of the accelerometer

$$a\frac{d_2\theta}{dt^2}$$

must be supplemented by a corrective term

$$kv\frac{d\omega}{dt}$$

taking into account the yaw-heeling compensation.

In order to introduce this corrective action I provide two means of which one is responsive to the angular acceleration

$$\frac{d\omega}{dt}$$

of the ship's yawing motion and the other means is responsive to the ship's speed v, and then their indications are combined so as to obtain a quantity proportional to the product,

$$kv\frac{d\omega}{dt}$$

k being a suitable coefficient of proportionality to be adjusted during the trials so as to obtain the optimum performance. In the preferred embodiment, I transform the quantities

$$\frac{d\omega}{dt} \text{ and } v$$

into proportional electrical currents and pass one of these currents into one coil of the electrodynamometer and the other into the other coil of the same instrument. The movable system of the electrodynamometer under these circumstances will give the indication proportional to the quantity

$$v\frac{d\omega}{dt}=v\frac{d^2\alpha}{dt^2}$$

and being combined with the corresponding quantity proportional to

$$\frac{d^2\theta}{dt^2}$$

derived from the accelerometer 51 shown on Fig. 2 of the above referred to patent gives the required control.

In cases in which the yaw-heeling has a rather long period, I prefer to modify the anti-heeling control by making it of the form

$$\frac{dw}{dt}=kv\omega$$

instead of

$$kv\frac{d\omega}{dt}$$

as previously mentioned. In this case instead of dynamical relationship governing the transfer of the ballast a rather static actuation, more consistent with the considerable duration of disturbing motion, is provided. The pump or any other ballast actuating means in this case will transfer the ballast so as to produce the compensating moment at a rate proportional to the angular velocity, instead of the angular acceleration of yawing.

With this new anti-yaw-heel control the applicability of the stabilizing system disclosed in my Patent No. 2,017,072 is considerably extended for quenching not only the rolling proper but also

this newly recognized or discovered yaw-heeling motion as well. Furthermore any combination of rolling and yaw-heeling will be automatically dealt with, each component control taking care of its corresponding component disturbing motion to the desired extent and with the proper phase relation.

Other features of this invention will be more clearly seen from the following description accompanied by the following drawings, in which

Fig. 1 represents an angular velocity responsive instrument actuating the yaw-heel control, shown in side elevation,

Fig. 2 shows the same instrument in plan, and

Fig. 3 shows the general diagram of yaw-heel controlling instruments and circuits, as well as their interconnection with the pure anti-rolling control disclosed in my Patent No. 2,017,072.

Referring to Figs. 1 and 2, 1 and 2 represent two identical gyroscopes, shown as enclosed within the casings shown on these figures. The internal structure of these gyroscopes, such as stator, rotor, bearings, etc., is not shown because it does not form any subject of this invention. The gyroscopes are pivotally mounted about trunnion axes 3 and 4 within a ring 6 belonging also to the external casing 7 surrounding the gyroscopes substantially as shown. The casing 7 containing the gyroscopes is mounted within gimbal rings 8 and 15 by means of axes 9 and 10 in the usual manner.

The center of gravity of the system formed by gyroscopes 1 and 2, casing 7 with additional parts described below, is arranged to be below the fixed point 18 determined at the intersection point of the axes 9 and 10 of gimbal mounting so that the system in question has a certain amount of static stability or pendulousness about this fixed point 18 and forms thus the so called spherical pendulum the period of which can be properly adjusted.

The gyroscopes 1 and 2 are yieldingly constrained about their respective axes 3 and 4 by means of springs 11, 12, 13 and 14 fastened to gyroscopic casings on their lower ends and to the top plate of the outer casing 7 on their upper ends substantially as shown. This arrangement of springs while constraining the gyroscopes in a yielding manner at the same time relieves the trunnions 3 and 4 from the major part of the weight, whereby a substantially frictionless performance of the instrument is obtained. The gyroscopes are made to spin in opposite directions, for instance, as shown by arrows 16 and 17, so that when the whole system undergoes a rotation about an axis perpendicular to the plane containing both pivotal axes 3 and 4 of angular rate ω, the gyroscopes tilt in opposite directions over a small ankle β given by equation $S\beta=K\omega$ where K is the angular momentum of the gyroscope and S is the yielding moment or torque of springs about the trunnion axes 3 and 4 per unit angle.

In view of equal and opposite precessional moments applied from gyroscopes to the casing 7 the latter is not influenced by these moments and maintains a substantial verticality within its gimbal suspension. In view of this the instrument thus formed reacts only on the component of angular velocity vector perpendicular to the plane containing the trunnion axes 3 and 4, and because of the verticality of the instrument, is responsive solely to the angular velocity of yawing motion about the vertical.

In order to obtain a controlling action I provide an arrangement shown partially on Fig. 1, but more fully on Fig. 2. On the upper part of the gyroscopes, are mounted two studs 20 and 21 protruding through the holes 22 and 23 in the top plate of casing 7. These studs are connected through the so called rigid elastic junction rods or links 24 and 25, to a light rod 26 carrying at its ends two plane coils 27 and 28 capable of changing their relative position within airgaps of electro-magnets 30 and 31 excited by alternating current. For the sake of clarity electro-magnets are indicated only by the projected area of their pole faces indicated by cross hatching. When an angular velocity of yawing of the rate 2 in the direction of arrow 34 appears, the gyroscopes tilt in the direction of arrows 36 and 37 and through the links 24, 25 the rod 26 is moved counter-clockwise, whereby the coil 28 enters more into the region of the flux of electro-magnet 31 and the coil 27 recedes from the flux area of the electro-magnet 30. For an opposite rotation the performance is reversed. Furthermore by virtue of the yielding constraint there exists a proportionality between the angular velocity of yawing and the angle of rotation of rod 26, which also follows from the preceding equation of precession.

The arrangement of coils 27 and 28 with respect to electro-magnets 30 and 31 is exactly the same as that which is described in connection with Fig. 6 of my Patent No. 2,017,072. It follows, therefore, that the amplitude variation of electromotive forces induced in coils 27 and 28 by alternating magnetic fluxes of electro-magnets 30 and 31 is proportional to the corresponding variation of angular velocity of yawing within the limits for which the instrument is designed.

Having described the yaw responsive instrument with the associated parts of its electrical control, the anti-yaw-heel controlling system will now be described.

Referring to Fig. 3, control coils 27 and 28, shown in conjunction with gyroscopes in Fig. 2, are connected to a thermionic amplifier 32. This amplifier may be of any suitable type, for example of the so called, push-pull type, with the first stages working as amplifiers and the latter power stage working as a rectifier, with a suitable filter system. In view of the fact that this amplifier system was extensively explained in connection with Fig. 7 of my Patent #2,017,072 and also because amplifiers of this kind are well known in the art, it is indicated by a rectangle with five terminals 33, 34, 35 on the input side and 36 and 37 on the output side. The terminal 34 is a common negative terminal of the plate supply to which the common point 38 of the control coils 27 and 28 is connected and 33 and 35 are the grid terminals of the first stage.

It may be noted at this point that in case of a sufficiently great number of turns on the coils 27 and 28 and with sufficient area, the whole amplifier 32 may be reduced to one single stage. Under this condition, with amplifier 32, as explained in detail in connection with a similar scheme shown on Fig. 7 of my Patent No. 2,017,072, to a displacement of the coils 27 and 28 relatively to the electro-magnets 30 and 31 will correspond a substantially proportional variation of the rectified output currents flowing from the output terminals 36 and 37. These output currents pass through the switch 40 into the primary winding 43 of a transformer 42 made preferably of a high permeability ferronickle alloy such as "hypernick," "permalloy," etc. The middle point

46 of the primary is taken out to a terminal connected to the positive terminal 41 of the source furnishing the plate voltage to the amplifier, while its negative terminal is connected to the point 34. The secondary winding 44 of the transformer is made of a great number of turns of a fine wire so as to obtain a preferably high ratio of transformation. The secondary winding 44 of transformer 42 is connected to a direct current amplifier 48 also of a push-pull type, with 51 being a common negative terminal of the plate supply voltage 49, 50 being connected to the grids of the tubes of the first stage and 52, 53 being the terminals of the output circuit connected to the plates of the last power tubes. I wish it to be understood that certain details such as filament supply batteries or transformers, grid bias batteries, filter system and similar well known parts are omitted for the sake of clarity. Furthermore, if the ratio of transformation of transformer 42 is great enough the amplifier 48 can be reduced to one single stage. 60 is a tachometer generator; its voltage is made to be substantially proportional to the ship's speed v; on Fig. 3 it is shown to be driven from the propeller's shaft 61 by means of any suitable coupling shown as a belt 62. It may be connected equally to any other speed measuring device such as any form of ship's log, for example. The voltage of the tachometer generator 60 is closed on the coil 65 of an electro-dynamometer instrument 67, an adjustable resistor 68 is provided in series with the circuit of generator 60 and coil 65.

The other coil, which may be, for example, a movable coil mounted on the movable element 67, is constituted by two coils 70, 71 wound in opposite directions and connected to the output terminals 52, 53 of the amplifier 48, and at the other end the coils 70, 71 are connected together and brought to the terminal 74. The plus terminal of the plate voltage of the amplifier 48, which may be connected to the terminal 41 if the same plate voltage supply is used for both amplifiers. To the movable element of the electrodynamometer 67 an armature of an angle transmitting device 75 is rotatably associated, which may be of any well known type. Its stator is connected to the stator of a corresponding angle repeating device 76 by a cable 77; the rotor of the angle repeating device 76 is connected through a pinion 78 to the component gear 79 of the differential gear 80. The other component gear 81 of the differential 80 is connected to a similar repeater 83 actuated from a transmitter 82 in a similar manner. The armature of the angle transmitting device 82 is actuated from a toothed sector 84 in mesh with the pinion 85. The toothed sector 84 is fixed to a lever 87' pivoted at the point 90 and actuated by a rigid elastic link 88 connected to the accelerometer's arm 89. The link 88, pivotal point 90 and accelerometer's arm 89 correspond to numbers 70, 72 and 51 of Fig. 3 of my Patent No. 2,017,072.

It is therefore obvious that the accelerometer control affects the angle of rotation of the gear 81 and according to this invention the new yaw-heel control is introduced through the gear 79 as will now be explained. The differential gear 80 is therefore means combining anti-rolling and anti-yaw-heeling controls.

It is well known that the couple of any electro-dynamometer instrument for small deviations is proportional to the product of the two currents or rather amperturns of both coils, in this case to the product of amperturns in the coil 65 and resultant amperturns in the differentially wound coils 70, 71.

When there is no yawing, the gyroscopes 1, 2 are in a parallel position, the coils 27, 28 occupy the symmetrical position relatively to the magnets 30, 31 as shown, the pushpull amplifier 32 is balanced and steady, rectified currents flow from the terminals 36, 37. Under those conditions the magnetic flux in the transformer 44 is substantially zero. No electromotive force is induced in the secondary 44 and the amplifier 48 is equally balanced so that the amperturns of the two coils 70, 71 on the movable element of the electro-dynamometer 67 cancel each other and the electro-dynamometer is at its zero point although the current in the coil 65 may exist in proportion to the ship's speed v. When there exists a yawing of variable magnitude, the gyroscopic reactions and hence the tilt of gyroscopes vary, and this causes a variation of position of control coils 27, 28 relatively to the magnets 30, 31, and hence proportional variations in the amplified outputs flowing from the plates 36, 37; thus, for example, the current flowing from the terminal 36 may increase and that from the terminal 37 may decrease in time so that the flux in the transformer 42 varies substantially in proportion to the angular velocity of yawing. In fact throughout the whole chain of transformations such as gyroscopic reactions, angles of tilt, variation of the amplitudes of electromotive forces induced in coils 27, 28 and finally amplified currents from the terminals 36, 37 this proportionality can be substantially obtained by a suitable design.

By virtue of the law of induction the electromotive force induced in the secondary 44 of the transformer is proportional to the rate of change of the flux. The latter is in phase with the primary current and hence with the angular velocity of yawing. It follows therefore that this induced voltage in the coil 44 is substantially proportional to the rate of change of angular velocity of yawing, that is to

$$\frac{d\omega}{dt}$$

otherwise to the angular acceleration of yawing in the preceding notations. I prefer to adjust the amplifier to function on a linear part of its characteristic so that to the input voltage proportional to

$$\frac{d\omega}{dt}$$

there will correspond the difference of the output currents flowing from terminals 52, 53 also proportional to the same quantity

$$\frac{d\omega}{dt}$$

and in view of the connection of terminals 52, 53 with the differential coils 70, 71 of the electrodynamometer, the resultant amperturns of coils 70, 71 at any moment will be thus proportional to

$$\frac{d\omega}{dt}$$

The angle transmitting armature of the device 75 connected by its rotor to the movable element of the electrodynamometer will thus undergo a deviation proportional to the product

$$v\frac{d\omega}{dt}$$

75

as necessary for the purpose of producing an action compensating for the centrifugal force

$$\frac{mv^2}{r}=mv\omega$$

of yawing, as previously explained. It is obviously apparent that since the repeating motor 83 introduces an angle α_1 proportional to the angular acceleration of rolling,

$$\alpha_1=a\frac{d^2\theta}{dt^2}$$

and since the repeating motor 76 introduces an angle α_2 proportional to the product

$$v\frac{d\omega}{dt}$$

say

$$\alpha_2=kv\frac{d\omega}{dt}$$

the planetary gear 85 of the differential gear 80 will turn over an angle $\alpha=\frac{1}{2}(\alpha_1+\alpha_2)$ that is this angle of rotation will be of the form

$$\alpha=a\frac{d^2\theta}{dt^2}+kv\frac{d\omega}{dt}$$

as previously set forth. Thus the right component gear 81 of the differential will continuously introduce anti-rolling control of exactly the same type as shown in my Patent No. 2,017,072, and the left component gear 79 will also continuously introduce the anti-yaw-heel control, as just explained. The remainder of the control is exactly the same as disclosed in my Patent No. 2,017,072; that is, the planetary shaft 86 through a worm 87 will displace a platform 92 supporting the control coils 93 and 94. The system of electromagnets 95 and 96 operatively associated with coils 93 and 94 is supported by a platform 97 and is capable of being moved parallel to the platform 92 by a rod 98 of the hydraulic, velocity of ballast responsive, follow up.

In Fig. 3, the parts 93, 94, 95, 96, 98 correspond exactly to the parts 77, 78, 79, 80 and 90 of Figs. 6 and 4 of my Patent No. 2,017,072.

It will therefore be evident that the resultant actuation of the ballast will be of the form

$$\frac{dw}{dt}=a\frac{d^2\theta}{dt^2}+kv\frac{d\omega}{dt}$$

as required by the theoretical analysis of the problem.

The success of the anti-yaw-heel control previously described hinges not only on the elimination of heel but also on the reduction of the yaw which is the cause of heeling. The last mentioned problem rather relates to improvements in antomatic steering devices which are outside the immediate scope of this invention. Since, however, the reduction of yaw is vital to this problem and because the elements of higher time derivatives control necessary for accurate anticipatory steering are already available in the above described invention, I provide the following additional elements; in series with the output currents flowing from the plate terminals 36, 37 of the amplifier 32, there are two coils 100, 101 of a differentially wound field of a small direct current generator 105 driven by a source of power not shown. The generator is connected to the armature of a separately excited direct current motor 107 actuating one side 111 of a differential gear 108 substantially as shown. A series brake, not shown, may be provided on the motor 107. The other half 112 of the differential gear may be operated either by the helmsman in the usual manner or by any form of existing automatic steering devices.

The lower part of Fig. 3 includes a diaphragm of a ship, having a rudder R actuated by hydraulic rams H, or the like, controlled by a variable delivery hydraulic pump D, the variable delivery of which is controlled by a Selsyn motor M operatively associated with the pump D, and the speed and direction of which is controlled by the coupled Selsyn motor X, mounted on the shaft 113 of the differential 108. The tanks T are operatively associated through a channel C, and the flow therethrough is controlled by a pump P controlled by a Selsyn motor N coupled in operative association with a Selsyn motor Y mounted operatively on the end of shaft 98.

As soon as the incipient yaw occurs the push-pull circuit of the amplifier 32, as well as the field coils 100, 101, become unbalanced in proportion to the angular velocity of yawing and the generator's armature acquires a voltage proportional to angular velocity of yaw which in turn starts the motor 107 and hence the steering gear in proportion to the same yaw velocity, thus materially reducing the yaw and helping to improve the steering. Under such conditions the yaw in the following sea being materially reduced the heeling will also be reduced and will acquire a more or less periodic character of small amplitude which the control of the type described will be efficient to quench, on the same basis as that on which the quenching of pure rolling is accomplished. The long period heeling due to excessive yawing when the ship seems to hang over a rather considerable angle of list will thus be eliminated, since the cause for such heeling of long duration will be steadily eliminated by, reducing the yawing on the one hand, and by providing an adequate moment. to compensate the centrifugal force of yawing accounting for the heeling on the other hand.

The two parts of the control will cooperate continuously with a proper phase of the controlling action as now will be shown.

Recent studies of rolling among following waves show that at the initial moment of instability of ship's course both effects due to rolling and yaw-heeling act in the same direction. The yaw-heel thus exaggerates appreciably the angle of rolling as compared to what it would be normally in accordance with Froude's theory of pure rolling. In such a case both the accelerometer control through the component gear 81 of the differential 80, and the yaw-heel control through the gear 79 of the same differential will co-act in the same direction and will start the controlling action in the manner extensively described in my Patent No. 2,017,072, with great intensity, so as to counteract both rolling and yaw-heeling components at the same time; simultaneously with this an early anticipatory action to check the yawing will be launched by the motor 107. The disturbance will thus be met simultaneously on all three fronts, rolling, heeling, and yawing, against the first two by the tank system and against the last by the rudder. At later instants of exceedingly complicated resultant motions each of these component controls will maintain its individuality; at times the anti-rolling control may be in opposition to the yaw-heeling control. This may happen, for example, when the instantaneous yaw is to starboard, thereby developing a centrifugal yaw-heel couple to port, and the position of the wave slope on which the

ship is riding at this instant has a tendency to roll her to starboard. In this case, following a similar line or argument, the accelerometer and the yaw-heel control will be in opposition in the differential, so that the resultant control will be of the form

$$\frac{dw}{dt}=a\frac{d^2\theta}{dt^2}-kv\frac{d\omega}{dt}$$

Equation 3 can, however, be used in all cases if it is understood algebraically.

On some rather rare occasions when the apparent periodicity of the forced yawing is very low, that is when the ship's speed and the apparent speed of the following waves are almost the same, it may be of advantage, instead of the rate of transfer control of the ballast, to control the amount of ballast directly, which means that instead of the yaw-heel control of the type

$$\frac{dw}{dt}=kv\frac{d\omega}{dt}$$

as is assumed in the preceding description, it may be found preferable to have a control in which the pump, airblast or other power actuating means is released by the control to create the compensating action at a rate proportional to the angular velocity ω of yawing, rather than to the angular acceleration

$$\frac{d\omega}{dt}$$

of yawing. When this rather unusual condition arises, the switch **40**, normally closed as shown, will be closed on the contacts **115**, **116**, as shown by dotted lines. In this case the electro-dynamometer coils **70**, **71** will be connected directly to the output of the amplifier **32**, as it becomes balanced to the output of the amplifier **48** and it is immaterial as to whether it continues to remain connected to the coils **70**, **71** on the output side, or is in the meantime disconnected by a switch **120** when the switch **40**, **41** is closed on the contacts **115**, **116**.

In this case the electrodynamometer control will be of the type $kv\omega$ and in view of the old follow-up connection the control will be of the form

$$kv\omega=\frac{dw}{dt}$$

instead of

$$kv\frac{d\omega}{dt}=\frac{dw}{dt}$$

as before.

With this modified form of control the rate at which the impeller pump, or air pressure or other agency, will tend to create the flow of ballast, will be proportional to angular velocity of yawing. This form of control is less rapid or anticipatory than that previously described in conection with the control of the form

$$\frac{dw}{dt}=kv\frac{d\omega}{dt}$$

but in the case of exceedingly slow yawing among waves it may be found preferable, since the full power of the power supply can be released better during these comparatively long time intervals.

In some cases there may be a dissymmetry in the behavior of the ship in the seaway owing to complicated conditions of wind, trim and the like; the ship may fall off with greater accelerations, for example, to port than to starboard. This dissymmetary in view of time lags may also cause a dissymmetry in the performance of the stabilizing plant. To be able to compensate for this dissymmetry, I provide a manual adjustment for zero point both on antirolling and anti-yaw-heeling components of the control, by providing means to rotate the stators of angle repeating devices **76** and **83**, about rotor axes by means of an arrangement shown as gears **130**, **131** and pinions **132**, **133** adjusted manually.

As a second adjustment the rheostat **68** can be employed. Owing to this second adjustment the relative importance of the yaw-heel control can be properly fixed by observations during the ship's trials.

I wish it to be understood that the disclosed invention should be contemplated broadly in the spirit and scope of its claims and not in the sense of limiting it to the disclosure shown. In fact a great variety of changes and modifications are possible. For example, instead of a yaw detecting instrument of the type shown, one could use an angular accelerometer in the yawing degree of freedom similar to that employed in the rolling degree of freedom for the purpose of obtaining the quantity

$$\frac{d\omega}{dt}$$

the angular acceleration of yawing.

Instead of having an electrodynamometer with a direct drive of the angle transmitting instrument **75**, a follow-up arrangement can be provided. Likewise instead of suspending the yaw detecting instrument in gimbal suspension one could rigidly secure it to the deck, in which case the rolling and pitching disturbance would be eliminated in the differential functioning of gyroscopes as shown in my Patent No. 1,372,184, and the yawing component would not be affected from any practical standpoint. In this last mentioned case the accelerometer described in connection with Fig. 3 of my Patent No. 2,017,072 and the rod **26** of the yaw detecting instrument described on Fig. 2 of this patent application can be differentially coupled by suitable mechanical means eliminating a series of intermediate instruments and devices, such as amplifiers, electrodynamometer and the like, although the adjustability of such a scheme would not be so great as that of the arrangement previously described, and the element proportional to the ship's speed in this case should be introduced as a definite setting to be changed each time this speed is changed. In a similar manner instead of thermionic devices one could use ordinary controlling means such as rheostats actuated by follow-up motors.

Finally, I wish it to be understood that the general form of the anti-yaw-heel control as described insofar as it relates to the dynamics of the ship in a following sea, is much broader than a particular method of stabilization which produces a stabilizing moment in the rolling degree of freedom of the ship. For example this control can be equally effective when the ship, instead of being stabilized by tanks is stabilized by movable fins fitted in the ship's hull. It is well known that in this case for a given speed of the ship the magnitude of stabilizing moment stands in a certain functional relation with the angle of fins. Since the stabilizing moment must be in phase with the angular velocity of rolling the angle of fins should be also in a suitable functional relation to said angular velocity. This scheme, however, does not eliminate the yaw-

heeling, just as the control described in my Patent No. 2,017,072 does not eliminate it either. In view of the fact that the yaw-heeling moment is of the form $kv\omega$, the compensating moment of fins must also stand in a suitable relation to this quantity. Such a control can be obtained according to this invention by establishing this relation between the electrodynamometer 67 through a suitable follow-up mechanism and the angle of fins. Since in this case the control is by the angle of fins and not by the rate of its variation the switch 40 must be in its left position closing the contacts 115 and 116. Under such conditions when the yawing occurs, for example, to starboard and the ship heels to port the leading edge of the port fin will be lowered by an angle related to the quantity $kv\omega$ which produces an upward pressure applied to this port side while the leading edge of the starboard fin will be raised by an equal amount, producing a downward pressure on that side, so that anti-heeling moment created will be directed against the heeling moment and will compensate it in view of the fact that it is of the same form $kv\omega$ as the latter.

In some other systems, fins have a fixed angle but their effective area is changed by displacing fins in their own plan. In such a case the preceding description relative to the angle of fins is applicable to their displacement in this particular case.

Many other modifications will occur to those skilled in the art, and I wish all such to be included in the scope of the invention and the appended claims.

I claim:

1. In an antirolling stabilizing system for stabilizing a ship, means for producing a stabilizing moment about a longitudinal axis of said ship, means responsve to centrifugal acceleration of said ship on yawing, controlling means operatively associated with said acceleration responsive means and controlling said moment producing means as a function of said acceleration whereby a stabilizing action about said axis is produced and the heeling caused by said yawing is substantially reduced.

2. In an antirolling stabilizing system for stabilizing a ship, means for producing a stabilizing moment about the longitudinal axis of said ship, means responsive to centrifugal acceleration of said ship on its yawing path, controlling means operatively associated with said acceleration responsive means and causing variations in the moment produced by said moment producing means in proportion to said acceleration whereby a stabilizing action about said axis is produced and the heeling caused by said yawing is substantially reduced.

3. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, means responsive to centrifugal acceleration of said ship on its yawing path, controlling means operatively associated with said acceleration responsive means and controlling said moment producing means in response to said acceleration so as to continuously compensate for the heeling moment caused by yawing motion of the ship, and means for varying the proportionality factor between said acceleration and said anti-heeling compensating moment, means whereby said compensation can be accurately adjusted.

4. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, a rudder to control the yawing, means responsive to a function of ship's speed and of angular velocity of yawing, comprising said speed responsive and said velocity responsive means, and controlling said moment producing means in response to centrifugal force of yawing motion, whereby the heeling component of yaw-heel is reduced directly, means operatively associated with said angular velocity responsive means and controlling said rudder whereby the yawing component of yaw-heel is reduced, which indirectly reduces the heeling component.

5. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, means responsive to the ship's speed, means responsive to angular velocity of the ship's yawing, means combining responses of said speed and said velocity means into a resultant action proportional to the centrifugal acceleration of the ship on its yawing path and controlling said moment producing means in proportion to, and in phase with said centrifugal acceleration whereby the heeling component of the yaw-heeling moment is continuously compensated.

6. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, means responsive to ship's speed, means responsive to angular velocity of ship's yawing, means producing a response proportional to the product of response of said speed and said velocity means whereby a response proportional to the centrifugal acceleration of the yawing motion is produced, and means operatively associated with said last mentioned means and controlling said moment producing means so as to compensate continuously for the heeling component of the yaw-heeling moment.

7. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, a rudder to control the yawing motion of said ship, means responsive to ship's speed, means responsive to ship's yawing, means responsive to a function of said speed and said yawing so as to produce a response proportional to, and in phase with, the centrifugal acceleration of the ship on its yawing path and controlling said moment producing means so as to directly compensate for the yaw-heel moment produced by the yawing, and means establishing an operative cooperation between said yawing responsive means and said rudder and controlling the latter so as to continuously reduce the yawing whereby the yaw-heel moment is reduced indirectly.

8. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, a rudder to control the yawing motion of said ship, means responsive to centrifugal acceleration of said ship on its yawing path, comprising means responsive to ship's speed and means responsive to ship's yawing, means operatively associated with said centrifugal acceleration means and controlling said moment producing means so as to continuously compensate for the yaw-heel moment by the direct action, and means operatively associated with said yawing responsive means and controlling said rudder so as to continuously reduce the yaw, whereby the yaw-heel moment is reduced indirectly, insofar as the yawing is reduced.

9. In an antirolling stabilizing system for

stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, a rudder to control the yawing motion of said ship, means responsive to the centrifugal acceleration of said ship on its yawing path, means operatively associated with said acceleration responsive means and adapted to control said moment producing means so as to compensate for the yaw-heel in the rolling degree of freedom of said ship and a component of said centrifugal acceleration responsive means adapted to compensate for the yaw-heel in the yawing degree of freedom of said ship, by an action exerted through said rudder.

10. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, a rudder to control the yawing motion of said ship, means responsive to ship's rolling of a synchronous, cumulative type, means responsive to ship's yaw-heeling of a non-synchronous, centrifugal force of yaw type, means combining the responses of said rolling and said yaw-heeling responsive means and operatively associated with said moment producing means so as to control the latter in response to the resultant action of rolling and yaw-heeling, whereby stabilization of said ship about said longitudinal axis against the combined action caused by rolling and yaw-heeling is produced.

11. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, a rudder to control the yawing motion of said ship, means responsive to ship's rolling of a synchronous cumulative type, means responsive to ship's yaw-heeling of a non-synchronous, centrifugal force of yaw type, means combining the responses of said rolling and said yaw-heeling responsive means, and operatively associated with said moment producing means so as to control the latter in response to resultant action of rolling and yaw-heeling and a means operatively associated with said yaw-heel responsive means and adapted to control the yaw through said rudder whereby the synchronous rolling and the heeling component of the yaw-heeling are compensated for by the action exerted by said moment producing means and the yaw is reduced through the rudder which reduces the magnitude of the yaw-heel disturbing moment.

12. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stablilizing said ship about its longitudinal axis, a rudder to control the yawing motion of said ship, means responsive to ship's rolling motion of a synchronous cumulative type, means responsive to ship's yaw-heeling of a non-synchronous, non-cumulative, centrifugal force of yaw type, means for combining responses of said rolling and said yaw-heeling responsive means means for varying the relative value of said rolling and said yaw-heeling responsive means with which their participation in said combining means is effected, said combining means being operatively associated with said moment producing means so as to control the latter in response to resultant action of yawing and yaw-heeling and means operatively associated with said yaw-heel responsive means and adapted to control the yaw through said rudder whereby both synchronous rolling and yaw-heeling are substantially reduced by the action of said moment producing means and the yaw is reduced through the rudder.

13. In an antirolling stabilizing system for stabilizing a ship, means for producing a moment stabilizing said ship about its longitudinal axis, controlling means responsive to the centrifugal force due to ship's yawing and means combining the responses of both last mentioned means and actuating said moment producing means so as to compensate for the action of disturbing moment applied to the ship about said axis whether due

14. In an antirolling stabilizing system for ships and the like, a yaw-heel controlling system comprising an angular velocity responsive instrument, a ship's speed responsive instrument, a device for combining responses of both said instruments so as to produce a resultant response to the centrifugal acceleration of ship's yawing motion, a moment producing device capable of counter-acting ship's angular motion about its longitudinal axis of symmetry passing through its center of gravity, and a controlling system responsive to said centrifugal acceleration device controlling said moment producing device so as to exert an action compensating for the yaw-heel moment.

15. In an antirolling stabilizing system for stabilizing a ship, a device for producing a moment about the longitudinal axis of said ship, a primary higher time derivatives of rolling motion responsive system, a secondary follow-up system having its responses in a predetermined functional relation with the value of the moment produced by said moment producing device, a yaw-heel control system responsive to the centrifugal acceleration of the ship on its yawing path, a device for combining the responses of said higher time derivatives' and said centrifugal acceleration systems and controlling said moment producing device so as to develop a moment compensating for the resultant disturbing moment due to the action of the waves as well as of the yaw-heel.

16. In an antirolling stabilizing system for stabilizing a ship, a device for producing a moment about the longitudinal axis of said ship, a follow-up element responsive to the rate of variation of said moment, an attachment for the yaw-heel control comprising an angular acceleration responsive device, means responsive to the ship's speed, an instrument for combining responses of said acceleration device and said speed responsive means, so as to produce a response to the rate of variation of centrifugal acceleration of the yaw and controlling the rate at which said moment is varied whereby the correct value of said moment is continuously maintained as to compensate for the disturbing yaw-heel moment.

17. In an antirolling stabilizing system for stabilizing a ship, a device for producing a moment about the longitudinal axis of said ship, a follow-up element responsive to the rate of variation of said moment, a yaw-heel control system comprising an angular-acceleration-of-yaw responsive element, an element responsive to ship's speed, a device for combining responses of said acceleration responsive and said speed responsive elements so as to produce a response substantially proportional to the centrifugal acceleration acting on said ship on its yawing path and controlling the rate at which said moment is varied so as to oppose continuously to the yaw-heel moment an equal and opposite moment produced by said moment producing means.

18. In an antirolling stabilizing system for stabilizing a ship, a device for producing a

moment about the longitudinal axis of the ship, a follow-up element responsive to the rate of variation of said moment, a yaw-heel control system comprising an angular-velocity-of-yaw-responsive element, an element differentiating the response of said angular velocity element to produce a response to the angular acceleration of yaw, an element responsive to ship's speed, an element for combining responses of said differentiating element with said speed responsive element so as to produce a response to the centrifugal acceleration of the ship on its yawing path, a selective device permitting elimination of said differentiating element whereby said combining element is made to respond to the product of ship's speed times the angular-velocity-of-yaw and means for establishing an operative cooperation between said combining means and said moment producing means so as to produce selectively either static or dynamic actuation of said moment producing means depending upon the operation of said selective device.

19. In an antirolling stabilizing system for stabilizing a ship, a device for producing a moment about the longitudinal axis of said ship, a controlling system having a predeterminedly variable zero point and responsive to the centrifugal acceleration of the ship on its yawing path controlling means operatively associated with said acceleration responsive means, and controlling said moment producing device so as to produce a moment arising from the symmetrical or a symmetrical behavior of the ship to counteract the yaw-heel moment.

20. In an antirolling system for stabilizing a ship, a control system responsive to rolling of said ship caused by the waves, a control system responsive to centrifugal acceleration caused by the yaw, a device for producing a moment about the longitudinal axis of said ship and means for controlling said device in response to both said control systems.

21. In an antirolling stabilizing system for stabilizing ships, a device for producing a moment about the longitudinal axis of said ship, a controlling system responsive to centrifugal acceleration of the ship on its yawing path, means establishing a predetermined functional relation between the moment produced by said device and said controlling system whereby the magnitude of said moment is controlled so as to compensate for the action of the moment of centrifugal force producing heeling.

NICOLAI MINORSKY.

Certificate of Correction

Patent No. 2,202,162. May 28, 1940.

NICOLAI MINORSKY

It is hereby certified that errors appear in the printed specification of the above numbered patent requiring correction as follows: Page 2, second column, lines 7 and 8, for "$a\frac{d_2\theta}{dt^2}$" read $a\frac{d^2\theta}{dt^2}$; page 3, first column, line 59, for "ankle" read *angle;* page 6, first column, line 3, for "or" read *of;* page 8, first column, line 61, claim 12, after "means" insert a comma; and second column, line 9, claim 13, after "due" insert the words and period *to waves or to the centrifugal force of yawing.*; page 9, second column, line 6, claim 19, for "a symmetrical" read *asymmetrical;* and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 17th day of September, A. D. 1940.

[SEAL]

HENRY VAN ARSDALE,
Acting Commissioner of Patents.