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Development of Modern Electrical Steering Gear System on Board Ships with Autopilot

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Abstract – *This article presents the steering system reliability due various existing modes, modified modes and methods of steering. Steering can be possible even in case of complete power failure. The working of autopilot with gyro compass and log sensors gives the choice to steer and maintain a fixed course without any human interference. Even in case of failure of gyro feed we can steer the ship in auto mode with feed from magnetic compass. This article is also aimed to define innovative inverter-fed full-electric actuation systems (PMLSA) in alternative to the hydraulics in the perspective of more "green ships". The new actuators had to guarantee the required dynamic performances i.e. very high torques/forces at very low speeds, besides high affordability, redundancy, and, mostly, high efficiency*.

Key Words: Modes of ship steering system, Electro-hydraulic, PMLSA, Rotary permanent magnetic motor, Autopilot.

1. INTRODUCTION

The steering control system with digital autopilot includes the monitoring and control elements, that are intended to provide the ship with a correct steering control. The steering gear arranged in the steering gear compartment serves for laying the rudder. The control of rudder angle is affected by means of the remote control from the bridge. Ship is normally steered from the bridge which is known as primary steering post by means of steering hand wheel or non follow up tiller. Steering is also possible by autopilot using heading and speed information from Gyro and Log sensors respectively. The rudder control can also be made from local steering post by non follow up tiller (NFU). In case of failure of electrical supply, the provision is also made for steering the ship by emergency steering hand wheel. The instantaneous position of the rudder is continuously displayed by rudder angle indicators. Feedback unit is mechanically coupled to the rudder to provide feedback to follow up amplifier, which generates error signal to actuate the electro-hydraulic solenoids and hence to steer the ship [1].

In this paper, the electro-hydraulic replacement of fully electrical steering gear system is presented. Oil-free direct-drive alternatives are being conceived by new concepts of low-speed permanent-magnet actuators fed by low-frequency inverters. The paper aims to realize a full-electric and oil-free drive for actuation of hydraulic loads in the perspective of more green ships. The electrical drives proposed are based on a fractional slot permanent magnet linear motor sized and optimized for high force and low speed operations, as required by hydraulics loads onboard ships.

In this paper, two mechanical arrangements were presented. The first is based on the fractional slot permanent magnet linear motor prototype featuring a very high thrusting force and very low electrical supply frequency. The second arrangement is which may be used to get the target, consisting on a rotary motor that is the rolled-up version of the linear motor. The said drive features are modularity, reduced weight, fault-tolerance, increased efficiency, twin rudder turning back and forth with successive angles: 0, 35, 0, - 35, 0 degrees with rate of speed 11cm/s (average) and performance and less maintenance. The main development factor is eco-friendly system, since no oil is used.

Further, additional magnetic compass feed unit that is magnetic compass sonde is fitted. This unit applies alternative magnetic course to input/output card in autopilot system which accepts the alternate course feed when main course feed not available during autopilot mode for failure less steering of ship.

1.1. Modes of steering gear system operation:

The steering can be operated in four modes. They are,

--- Autopilot mode
--- Follow – up mode
--- Tiller mode or non-follow up mode
--- Emergency hand wheel mode

In any ship actual course feed is given from the gyro compass for above operations. In case any failure in gyro feed, the operator has to steer manually to avoid the defect in the prescribed mechanism, the system modified by alternately fitted with magnetic compass feed [1,2].

2. LITERATURE SURVEY

In the paper[1], the steering gear (HS180X2S) consists of 02 numbers of steering motors (26 kW each), the steering engine with 04 cylinders, the rudder yoke fitted to the rudder head, the motor operated pump units and the steering equipment which transmits the control impulse initiated by the remote control to the pump units.

Each pump unit is connected with the cylinders of the rudder engine by means of separate piping of steel tubes. Valves arranged at the cylinder make it possible to disconnect parts of steering engine in case of necessary repair work. Each pump units is capable of putting the rudder through the working angle in the specified time. The other pump units can be connected at any moment just by switching on the motor. The instantaneous position of the rudder is continuously displayed by rudder angle indicators. Feedback unit is mechanically coupled to the rudder to provide feedback to follow up amplifier, which generates error signal to actuates the electro-hydraulic solenoids and hence to steer the ship [1].

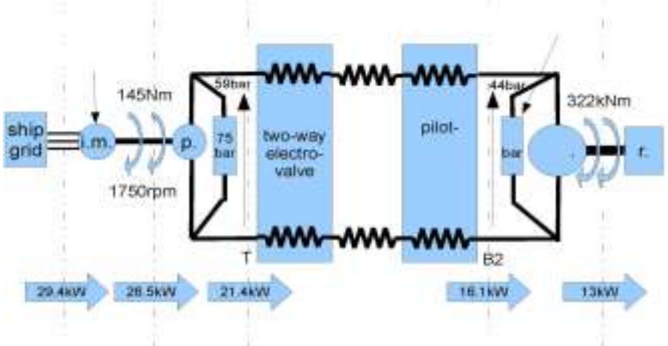

Fig. 1 shows power flow of electro-hydraulic steering gear.

Table -1: Rudder Plant HS180X2S Rated Data

Rated mechanical power (two pumps)	26kW
Rated electric power (two pumps)	59kW (440V, 60Hz)
Rated efficiency	44.3%
Rated speed (two pumps)	0.77rpm
Rated operating torque	322kNm
Maximum operating torque	462kNm
Mechanical design torque	604kNm
Overall weight	4300kg
Volume (excluding pipes)	$3m^3$
Plant footprint (excluding auxiliaries)	$9m^2$

In the paper [5], a typical hydraulic plant used onboard for rudder steering drive belongs to a very large ship (the 147m-long is given). The vane motor [5] is fed by two oil pumps. Two-way electro-valves control the pump oil flow, so the vane motor motion can be reversed. A check valve is embedded in the vane motor, for automatic oil flow stop. Other valves (pressure-relief type, in the pumps and in the vane motor) make safe of the oil circuit. The overall efficiency is low, usually below 44%. The followings drawbacks usually affect rudder and fin drives based on hydrostatic transmissions:

- Oil is used as force-fluid, whose periodic refill or replacement is fatiguing, time-consuming and costly.
- Oil leaks are frequent and must be timely detected.
- Seals and filters must be routinely checked and replaced (vane motor seal replacement requires motor dismounting).
- Air intrusion in the oil circuit is dangerous for both actuator and pumps.
- The plant efficiency is low, due to multiple energy conversions from the electric supply to the mechanical output.
- Plant weight and size are very large; plant encumbrance is heavily increased by pipes, valves, bulky oil tanks, etc.
- The overall plant complexity is considerable due to many components and connections. Plant cost is also high, due to mechanical components with very tight machining tolerances.
- The maintenance is heavy and troublesome. The hydraulics requires usually 60% of the total maintenance, whereas the electric motors only 20% (vibration and insulation check); the remaining 20% is for polishing and varnishing.
- Hydraulic plant control is sluggish. Synchros are used for rudder angle feedback between the steering gear room and the command deck. As the signal from the deck does not allow enough time for the pump to switch on and off, a continuously running pump is required, with large no-load losses and energy waste during long trips.
- Redundancy is only provided for the oil pumps. The actuator (vane motor) is actually non-redundant.

The classical oil-powered onboard actuators used for steering gears (rudders, roll-stabilizing fins) are usually cumbersome, weighty, low-efficiency and costly plants, also requiring a heavy maintenance burden. Here it is aimed to define innovative inverter-fed full-electric actuation systems i.e permanent-magnet linear synchronous actuator (PMLSA) in alternative to the hydraulics. The new actuators had to guarantee the required dynamic performances, i.e. very high torques/forces at very low speeds, besides high affordability, redundancy, and, mostly, high efficiency and proposes a new high-thrust permanent-magnet linear actuator for direct-drive of steering gears, through an appositely designed rotary-prismatic coupling. Mechanical and electrical drive sizing are shown, and force, speed, and efficiency performances are analyzed and compared with those of the original hydraulic plant [5].

Table -2: Rated Performances of Hydraulic plant and PMLSA

	HS180X2S					PMLSA					
	T	ω_m	ω_m	P_m	η_{HS180}	F	v	f	J	P_ρ	η_{PMLSA}
	kNm	rpm	rad/s	kW	%	kN	cm/s	Hz	A/mm^2	kW	%
no-load	0	0.933	0.098	0	0	0	13.1	0.526	0	0	90*
rated	322	0.774	0.081	26	44.3	239.4	10.9	0.437	2.83	15.2	63.2
max	462	0.704	0.074	34	46.2	343.5	9.94	0.398	5	47.6	41.7

*maximum value theoretically estimated.

The paper [6] aims to realize a full-electric and oil-free drive for actuation of hydraulic loads in the perspective of "more green ships". The electrical drive proposed is based on a fractional slot permanent magnet linear motor sized and optimized for high force and low speed operation, as required by hydraulic loads on board ships. In this paper [6] the electrical, mechanical and thermal design and the feasibility of the installation are shown.

In this paper [6], a novel drive is presented for on board linear loads, based on a fractional-slot permanent magnet linear motor featuring very high thrusting force and very low electrical supply frequency, which allows the use of solid-iron teeth in place of laminated poles. This adds much to the solidity and cheapness of the overall construction. The experimental installation will be placed on board a "Comandanti Class" ship in order to pursue the objective of more clean ships. The mechanical arrangement of the new motor in servo-assistance of the original plant is described, and the structural mechanical for proper component sizing is shown. The proposed drive features fault tolerance, modularity, reduced weight, encumbrance, and maintenance, increased efficiency and performances. Finally it is environmental-friendly, since no polluting oil is used.

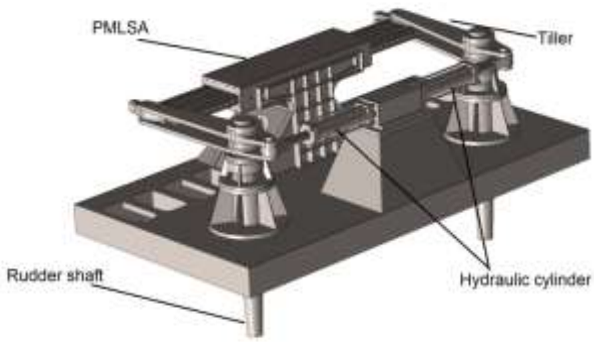

Fig.2: 3D Solid model of the electromagnetic drive coupled to the hydraulic double-rudder steering gear.

In this paper [7], "Electrical Direct Drive Actuator" (EDDA) is aimed to designed and tested, it is basically permanent magnet linear motor coupled to load via rotary-prismatic joints or special joints in order to transfer the linear motion to rotary motion. With respect to classical hydrostatic drives, the linear motor reduces both weight and encumbrance. Furthermore, oil-free drive allows to obtain a more eco-friendly ship in addition to the reduced maintenance. In terms both efficiency and overall capabilities the electrical gains better performance than the hydraulic drives as already discussed.

An alternative solution proposed in this paper [7] and it is rotary permanent magnet motor that is the round-up version of the linear motor presented. The rotary motor, or torque motor, has a stroke limited at +/- 90 degrees, while a special central crack mechanism turns the rudder of +/- 35 degrees via two tapped rods.

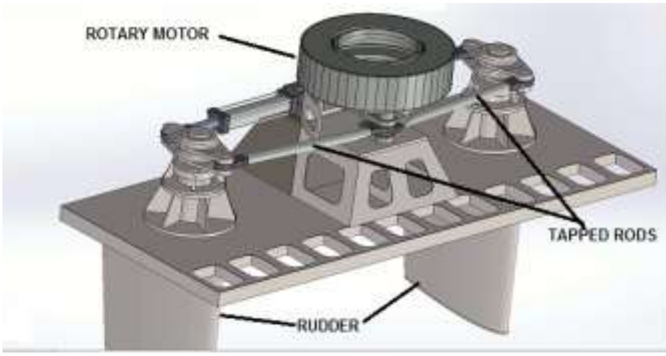

Fig.3: 3D Solid model of rotary electromagnetic drive in servo-assistance to the hydraulic steering gear.

The rod-crack system features a useful torque mechanical gain thus lowering the motor torque. In fact the rod-crank system allows to exploit the reaction force of the constraint offered by the bearings of the crank mechanism itself, for supporting the resistant (load) torque of the rudder, in the point of maximum effort (i.e. +/- 35 degrees), while the required engine torque lowers to zero. The torque motor develops the maximum torque when its rotation angle is equal to 45 degrees and simultaneously the driving force is about 45% of the maximum force requested by rudders. Contemporaneously the rotation speed is higher, due to the mechanical gain. The rotary motor size is finally about 65% lighter than the linear version [7].

Because of said proposal for the electromagnetic drive is fault-tolerance, modularity, reduced weight and encumbrances, reduced maintenance, increases efficiency and performance and finally they are environmental-friendly.

3. PROBLEM FORMULATION:

This section summaries the limitations of the method that are presently adopted and available in international literature. There is limitation in operation in autopilot mode i.e in any ship actual course feed is given from the gyro compass for above operations. In case any failure in gyro feed operator has to steer manually [1].

In the paper [5] also some deficiencies are observed, the mechanical stability of the system was not analyzed for generation of requisite torque for rudder movements. During continue operation, the PMLSA system behavior and cooling methods were not analyzed. The system was developed with laminated poles which generates electrical losses and less efficiency.

In the paper [6], also have few limitations and they are, additional cooling system required for this type of design which is increases the system cost. This system is occupying more space as well as maintenance also difficult. The torque gain is less, thus increase the motor torque requirement for required output.

The paper [7] also has few significant limitations, which are, the rotary version is very expensive and more complex design in mechanical construction. Further studies to be carry out in respect to thermal aspects and design of proper cooling system in futures.

4. METHODOLOGY

In any ship actual course feed is given from the gyro compass for above operations. In case any failure in gyro feed operator has to steer manually to avoid this defect, the system modified by alternately fitted with magnetic compass feed [1,2]. For magnetic compass feed additional unit fitted that is magnetic compass sonde. This unit requires the 3.5V to 4.5V, 400 HZ supply which is given from SFC (Static frequency converter) which also giving supply to ship's radar. This supply applied to internal coils which are mechanically attached to magnetic course indicating parts that compares with resistors and resultant feed applied to input/output card in autopilot system which accepts the alternate course feed when main course feed not available.

The limitations observed in paper [5] are overcome in paper [6], that are, the electromagnetic, mechanical, and cooling solutions for an innovative direct-drive suited for steering gears on board ships. The aims to realize a full-electric and oil-free drive for actuation of hydraulic loads in the perspective of "more green ships". The electrical drive proposed is based on a fractional slot permanent magnet linear motor sized and optimized for high force and low speed operation, as required by hydraulic loads on board ships. In this paper [6] the electrical, mechanical and thermal design and the feasibility of the installation are shown. The mechanical arrangement of the new motor in servo-assistance of the original plant is described, and the structural mechanical FEAs for proper component sizing is shown. The paper [6] also shows the electromagnetic coupled circuit-FEM co-simulations for SOAs and inverter sizing, as well as the CFD simulations for air-cooling system sizing. The proposed drive features fault tolerance, modularity, reduced weight, encumbrance, and maintenance, increased efficiency and performances.

The remedies for limitation observed in paper [6] are discussed in paper [7], that are, the mechanical solutions for installation of innovative direct-drive suited for steering gears onboard ships. The electrical drives proposed are based on a fractional slot permanent magnet linear motor sized and optimized for high force and low speed operation, as required by hydraulic loads onboard ships. Here, two mechanical arrangements were presented [7]. The first is based on a fractional slot permanent magnet linear motor prototype featuring a very high thrusting force and very low electrical supply frequency, which allows the use of solid-iron in place of laminated poles. The second preliminary arrangement which may be used to get the target, consisting on a rotary motor, that is the rolled-up version of the linear motor. Because of said proposal for the electromagnetic drive is fault-tolerance, modularity, reduced weight and encumbrances, reduced maintenance, increases efficiency and performance and finally they are environmental-friendly.

5. RESULTS

It is given an idea about high-thrust inverter-fed novel PMLSA for ship rudder steering gears through direct force-torque conversion. The mechanical, magnetic, and electrical drive sizing are detailed. It is shown that high-force and low-speed performances can be attained, comparable with those of the oil drive; moreover, the PMLSA-based drive turns out to be more light, small, and efficient. Structural simplicity, modularity, and component redundancy provide increased affordability, fault tolerance, reduced weight and encumbrances, with reduced maintenance. The magnetic optimization by FEM analysis proves that very high forces/torques can be obtained, competitive with those of oil-drives. Losses and efficiency have been analyzed and mapped on the drive force-speed operating range, to obtain a clear view of drive performances and feasibility. Theoretical trends of powers and efficiency have been explained. The study proves that the proposed drive features superior efficiencies with respect classical oil drives, so permitting significant energy saving on board ship.

Further, the autopilot checked satisfactorily in following existing modes:

-- Course controlled by gyro compass
-- Course change with maneuvers at a given rate of turn.
-- Emergency mode.

The autopilot checked in modified modes

-- Course control with magnetic compass.

This is checked by interrupting the gyro feed manually.

6. CONCLUSIONS

It shows that steering system has great reliability due various existing modes, modified modes and methods of steering. Steering can be possible even in case of complete power failure on board ship.

The working of autopilot with gyro compass and log sensors gave the choice to steer and maintain a fixed course without any human interference. Even in case failure of gyro feed we can steer ship in auto mode with feed from magnetic compass.

This paper deals with the mechanical solutions for installation of innovative direct-drives suited for steering gears on board ship, further, Affordability, redundancy, as well as space, weight, and energy savings are main issues on board ship. Classical oil-powered onboard actuators used for steering gears are usually cumbersome, weighty, low-efficiency and costly plants, also requiring a heavy maintenance burden. This paper is, aimed to define innovative inverter-fed full-electric actuation systems in alternative to the hydraulics in the perspective of more "green ships". The new actuators had to guarantee the required dynamic performances, i.e. very high torques/forces at very low speeds, besides high affordability, redundancy, and, mostly, high efficiency. It is also designed a new high-thrust permanent-magnet linear actuator for direct-drive of steering gears, through an appositely designed rotary-prismatic coupling. Mechanical and electrical drive sizing are shown, and force, speed, and efficiency performances are analyzed and compared with those of the original hydraulic plant.

This paper also helps in modifying the system in view of future requirements/ expansions and to cope with changing environment in the field of control engineering.

Further research can be pursuing for alternative solution in rudder actuation and cooling system. It consists on a rotary permanent magnet motor that is round-up version of the linear motor with central crank mechanism. The rod-crank system features a useful torque mechanical gain, thus allow lowering the motor torque. It is 65% lighter than the liner version.

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