THE IMPACT OF ANALOG AND BANG-BANG
STEERING GEAR CONTROL ON SHIP'S FUEL ECONOMY

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The latest years have shown considerable efforts towards improving steering generated propulsion losses of ships by the introduction of various sophisticated control algorithms in the autopilots. However, little previous attention has been given to the steering gear control loop, although it is found to be at least equally important regarding steering performance and fuel economy. The paper presents a comprehensive survey of steering gear principles commonly used, including relevant details of three analog steering gear servo principles, which have outperformed conventional designs. Control system performance is evaluated from direct measurements of speed and fuel consumption, and results from several ships are given.
The results presented should enhance the ability of ship owners and steering gear manufacturers to choose and design systems, which will minimize steering generated propulsion losses .

1. INTRODUCTION.

International organisations, national administrations, classification societies and ship owners have in the past 5 years together with yards and steering system manufacturers devoted considerable effort to the specification and design of safe and economic rudder control systems.

Apart from requirements of being economically feasible, to day's steering system is governed most strongly by the following two constraints:

1. The design must comply with the rules.

2. Steering performance must be optimal.

This paper will mainly be adressed to the performance requirements, but since the safety requirements of the "rules" of course have the highest priority of the two, and thereby give the ultimate decisions on the design, it would be wrong not to touch the basic implications of the rules.

2. RULES

A complicated set of requirements have been established as national and international standards for steering gears through the conferences of IMCO. (Now: International Maritime Organisation, IMO.) (Ref.: The Rules of the classification societies and of the national coast guards.)

The later amendmendts to the SOLAS 74, partly initiated by the stranding of the Amoco Cadiz with a full cargo of crude oil in France 1978, have upgraded the requirements considerably. Starting with the greater tankers, some of the new regulations are already in application. In the five years to come the remaining parts of the new regulations will become valid - at least for tankers. It is, however, expected that the same set of rules gradually will be adopted for all ships above 500 tons. From the huge set of rules, only one new, namely the "Single failure criterion" should, in a short and free interpretation, be mentioned:

Steering gear's power actuating and remote control systems must be duplicated. No single failure in one of the two systems must be able to kill the steering ability. After a failure, it shall be possible to regain steering within 45 seconds.

And:

Loss of hydraulic fluid shall be detected, and the defective system automatically isolated, so that a good working system halfpart will remain fully operational.

3. PERFORMANCE

By far, most published work on steering performance has been related to improvements of autopilot controllers. From a range of seatrials in the mid-seventies, EMRI however concluded, that that the commonly applied Bang-Bang steering gear servo systems were responsible for a considerable part of the imperfections in the overall system, and thereby also responsible for a relevant fraction of propulsion losses due to steering activity.
Redesigns of the rudder servo principles led to the introduction of the Analog Steering Systems. [4].

After a long range of seatrials, where the two principles were compared, it was concluded that the use of Analog servo principles saved 1,5 to 2 % fuel, when compared to Bang-Bang servos at the same ship's speed. [18].

At the same time is was concluded, that the analog servo outperformed the Bang-Bang type in precision steering systems for special purpose vessels, where steering quality was essential for the operations. [20].

Approx. 10 makes of analog controlled steering gears are on the market in 1982. Fig 1 shows one of them, the SVENDBORG steering gear from ATLAS DANMARK. The design is fully duplicated and with electronic analog, single loop control. Note with reference to the steering safety, the Failure Control System for automatic isolation of a hydraulic leakage.
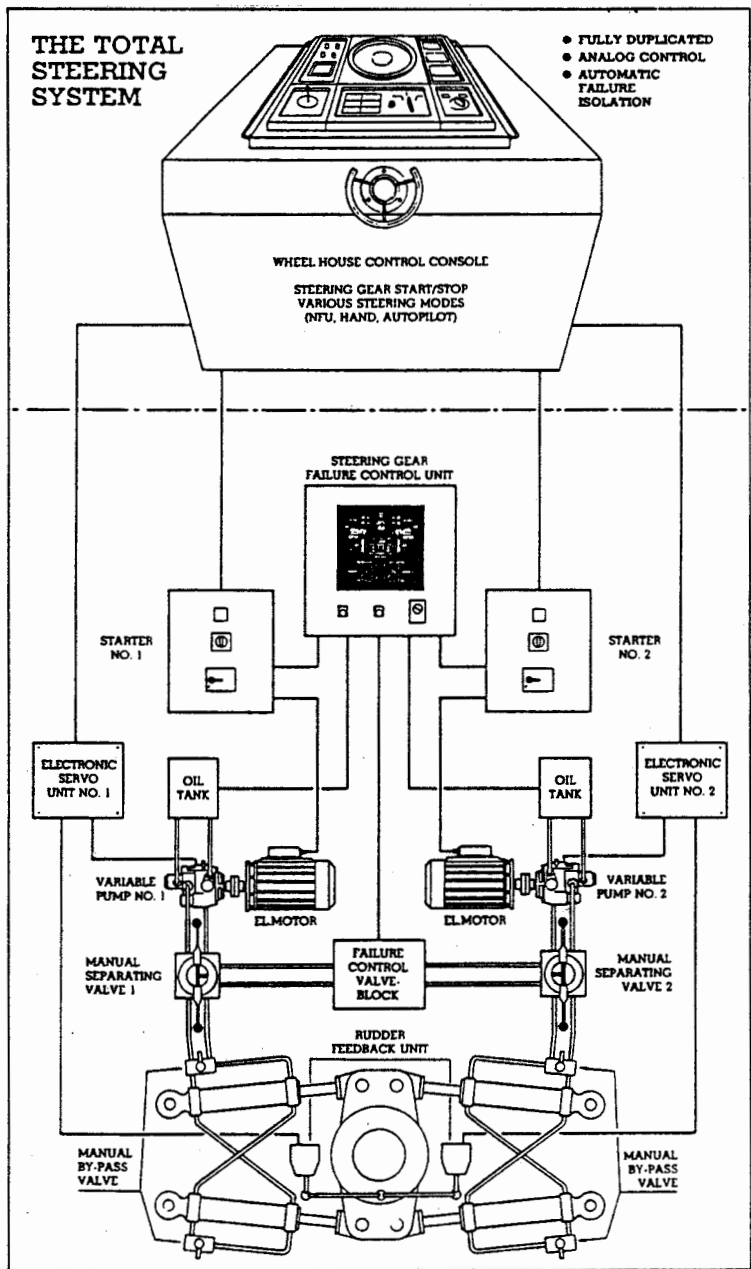
Fig. 1 Analog Controlled Steering Gear with Failure Control System. (SVENDBORG)

4. SURVEY OF STEERING GEAR TYPES

4.1 The Hydraulic Output Stage

In the analysis of steering systems it is a common and basic mistake to simulate the transfer from oil flow to rudder angle as a single integration. In other words, it is supposed, that the oil is uncompressible and that steering power is infinite.

A more correct, but still simplified model is given in fig. 2. Simplified because the rudder and the rudderstock are supposed stiff, but usable because important factors as the inertia of the rudder and water, the compression of the oil, and the limited slew rate and amplitude of the pressures have been taken into account.

The model, named $H(Q \rightarrow \delta)$, will give correct pressure responses to rudder forces. Hitting the hard stops, however requires an extended model with elasticity of the structure included. For the analysis of the behaviour of separated pump systems working on the same tiller and rudderstock, a model with two compression integrators will be required.

This model will illustrate the influence of static and dynamic counterpressures built up in the system due to unsymmetry. The validity of the models have been proved from the recordings of the pressures and rudder angle on seatrials.

In the following sections of type numbered descriptions of steering gears and servo principles, $H(Q \rightarrow \delta)$ is common to all types. Note that the term r_{eff}, the effective radius of of pressure action, takes all factors from cylinder or actuator configuration into consideration.

Q : TOTAL AVAILABLE FLOW

Q_c : FLOW FOR COMPRESSION (BOOST CAPAC.)

β : COMPRESSION RATIO (1% pr. 100 bar)

V_c : VOLUME OF OIL UNDER PRESSURE

Γ_{eff} : RADIUS OF PRESSURE ACTION

I_T : TOTAL INERTIA (RUDD. + WATER)

U : SHIP'S SPEED

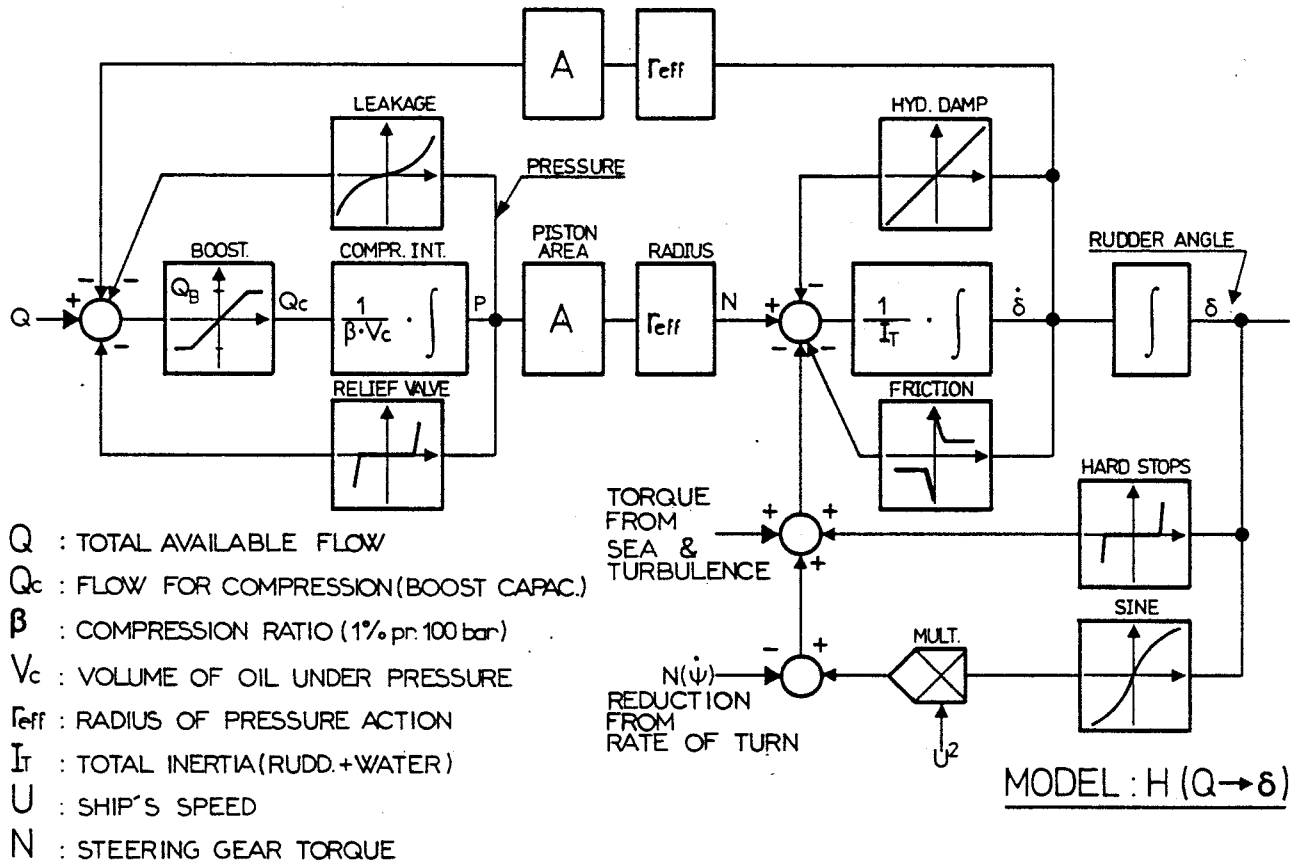N : STEERING GEAR TORQUE

MODEL : H (Q→δ)

Fig. 2 H(Q→δ), The Simplified Model of a Steering Gear from Oil Flow to Rudder Angle.

4.2 Control Principle

Analog Control in the steering gear remote control system is defined as the principle, where the rudder is moved with a speed that is proportional to the error in the servo system, unless this error has exceeded the proportional band, in which case full stroke of the pump(s) has been reached.

Bang-Bang Control in the steering gear remote control system is defined as the principle, where one or more servo loops have discrete levels:

1. Full speed order to PORT or STBD.

2. Zero speed order. (Within the deadband).

The deadband or insensitivity zone is measured in degrees of servo system error.

4.2 Loop Configuration

The number of loops with a state equivalent to rudder angle is counted, starting with the electronic feedback stage and ending with the rudder stock.

Single loop systems take electronic feedback directly from the rudder stock.

Twin loop systems include a telemotor stage, from which the electronic feedback is taken. The output stage employ mechanical feedback to a floating lever pump stroking mechanism.

Three or four loop systems are not considered relevant for further treatment, due to their complexity.

4.4 Main Pump Comfiguration

Main pumps in hydraulic steering gears have either fixed or variable capacity. In high power systems, variable capacity pumps should be preferred from a power commutation point of view.

The relevant combinations from 4.2; 4.3 and 4.4 form the 6 segments of the hydraulic steering gear market. In fig 3 a type number is given to each segment. The type numbers have been selected so that the steering performance will increase with the numbers.

PRINCIPAL FEEDBACK LOOP ARRANGEMENT / MAIN PUMP CONFIGURATION / REMOTE CONTROL PRINCIPLE	SINGLE LOOP		TWIN LOOP
	FIXED CAPACITY	VARIABLE CAPACITY	VARIABLE CAPACITY
ANALOG	NB: HEAT! 6	5	4
BANG-BANG	1	3	2

STEERING PERFORMANCE INCREASES WITH THE NUMBERS

Fig. 3 Definition of the applied type numbers.

4.5 Type 1. Single Loop
Bang-Bang Controlled Full Capacity Valve

A 3-way valve directs the main flow of a pump. When the difference between the rudder order and the rudder angle is smaller than the value of the deadband, the oil is returned to the tank at low pressure. In the PORT or STBD full speed order zones, the tank return is blocked off, and the oil is directed to the relevant port of the actuator. The other port of the actuator returns oil to the tank, normally through some kind of restriction, in order to build up some braking action against negative loads.

The control loop (fig.4 and fig.5) looks simple, but it will require a considerable deadband for stability. To protect the equipment from pressure bursts (ref. fig. 2), valve action must be slow. In high power systems two stage hydraulic valves must be used, and the result is a delay between the stroke order and the actual flow. The delay is destabilizing in the servo-loop.In this kind of systems the pressure transients are always considerable due to the fast acceleration of heavy masses, and this adds up to give mechanical wear.

As a result a large deadband is required in the rudder angle control loop. Deadband magnitudes of 1 to 4 degrees are normal, and the deadband often must be increased as mechanical parts become worn. If optimized (i.e. set up with minimum deadband) with a single pump in action, these systems will normally be unstable with both pumps running. This situation must be avoided, as high power oscillations in the heavy mechanical gear eventually lead to breakdown.

The type 1 gear is unusable in small, fast vessels, and should, due to the fuel economy, be
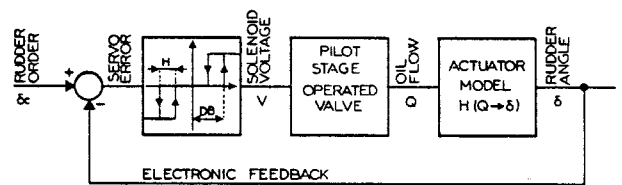
DB : DEADBAND IN BANG-BANG SERVO AMPLIFIER   (1-4deg)

H : HYSTERESIS IN BANG-BANG SERVO AMPLIFIER   (0,5-2 deg)

RUDDER SPEED: 65 deg IN NOT MORE THAN 28 sec.

Fig. 4 Type 1 Control Loop.

avoided, when the shaft horsepower exceeds 5.000 to 8.000 hp, and autopilot control is the normal operation.

There is, however, a great number of trawlers, coasters and tugs, where the principle is adequate, provided single stage valves are used.

Always be carefull, when high performance rudders (Becker etc.) are specified:

The destabilizing effect in the autopilot loop of the deadband is multiplied by the efficiency factor of the rudder. Even worse, of course, if the deadband has to be increased due to the application of a fast steering gear.

Concluding: Be carefull with the specification of a type 1 steering gear, and avoid the use of pilot stage operated valves.
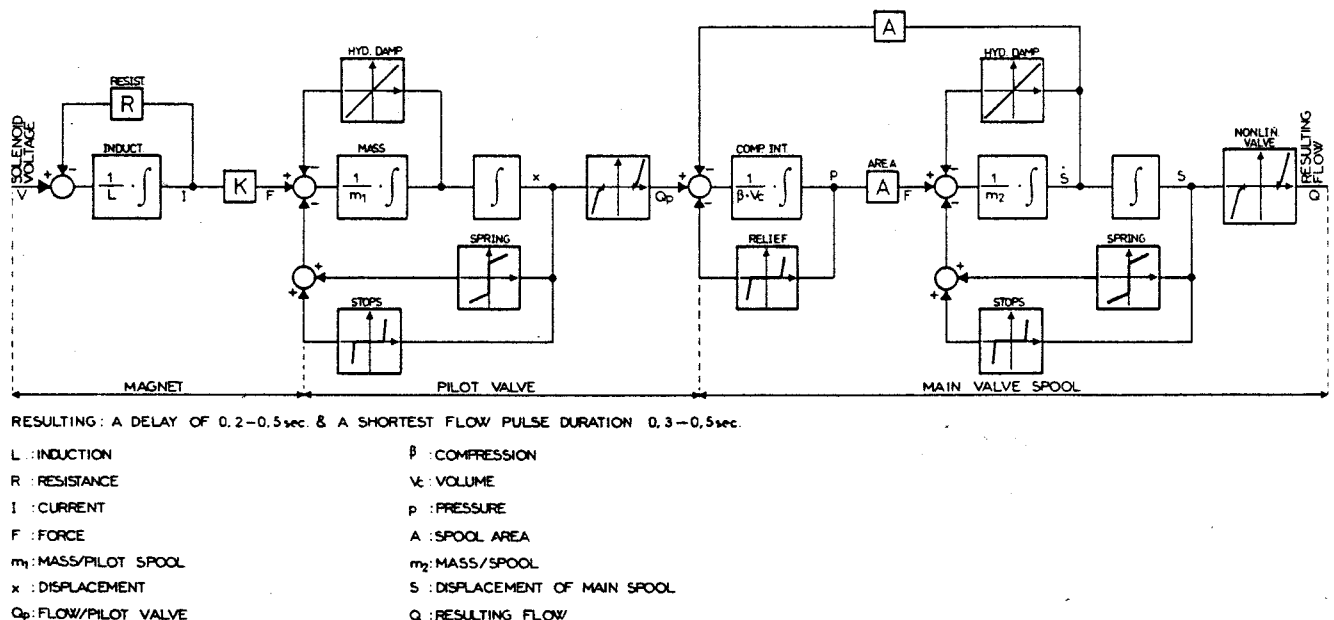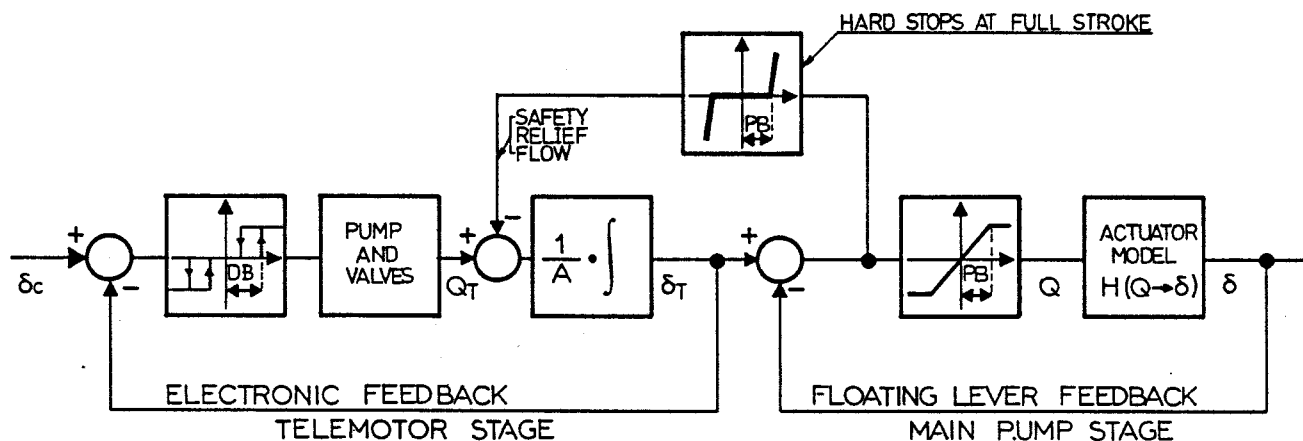

RESULTING: A DELAY OF 0.2-0.5sec. & A SHORTEST FLOW PULSE DURATION 0,3-0,5sec.

L : INDUCTION   β : COMPRESSION
R : RESISTANCE   Vc : VOLUME
I : CURRENT   p : PRESSURE
F : FORCE   A : SPOOL AREA
m₁ : MASS/PILOT SPOOL   m₂ : MASS/SPOOL
x : DISPLACEMENT   S : DISPLACEMENT OF MAIN SPOOL
Qp : FLOW/PILOT VALVE   Q : RESULTING FLOW

Fig. 5 Simplified Model of the Pilot Stage operated Hydraulic Valve. (Fig. 4, Center Block.)

HARD STOPS AT FULL STROKE

ELECTRONIC FEEDBACK TELEMOTOR STAGE

FLOATING LEVER FEEDBACK MAIN PUMP STAGE

MAX TELEMOTOR SPEED : δ_T = 6 deg/sec. TYPICAL PROPORTIONAL BAND PB=6 deg

TYPICAL DEADBAND : DB = 1 deg   RUDDER SPEED:65deg IN NOT MORE THAN 28sec.

Fig. 6   Type 2 Control Loop.   Twin Loop.   Bang-Bang Controlled Telemotor.

4.6   Type 2.   Twin Loop
Bang-Bang Controlled Telemotor

The telemotor is typically a hydraulic actuator, driven by a small 3-way valve which in turn is supplied from a fixed capacity pump. The electronic servoloop with Bang-Bang control is closed around the telemotor. Deadband typically is 0,5 to 1 deg. The power stage following the telemotor has variable pumps, analog control and mechanical feedback to a floating lever.

Performance of this system is considerably better than of the type 1 system, but due to added complexity, the overall price will be higher too. The principle has been widely applied through the years.

Note, that due to tradition, it is the autopilot supplier, that decides the control law (Analog or Bang-Bang), through the supply of the small hydraulic power pack, driving the telemotor.

It will be seen from fig. 6, that although the telemotor is faster than the main gear,the max difference between the two states is equal to the proportional band of the power stage. The telemotor must be faster than the power stage, in order to be able to stroke the main pump completely. When two pumps are applied simultaneously, the telemotor speed must be further increased.

4.7   Type 3.   Single Loop.   Bang-Bang Control
### Variable Capacity Pump

A small 3-way valve controls the stroke of a variable capacity pump to either full PORT, full STBD or zero flow.
Although it is a Bang-Bang system, it is far better than the Type 1 system: Stroke builds up gradually, full pressure negative loads can be taken and smaller deadbands are possible, which all add up to improve control.

It is possible to use very small deadbands,f.ex. 0,25 deg, but the pumps will suffer from the many resulting operations and be worn early. Further the larger rudder order responses will give overshoot (damped oscillations) when the deadband is smaller than the stopping distance of the pump stroke servo.

In a way, Bang-Bang control of variable capacity pumps is a mismatch, but it might be the compromise, until all autopilot suppliers are able to deliver analog output from their controllers. It should be noted, however, that it is the steering gear supplier, that decides the control principle, as he, by tradition, supplies the control valves, and thereby the stroke mechanism of the main pump in the type 3 case.

Fig. 7 shows the control diagram, which is much like fig. 4. The difference in the block diagrams of the type 1 and the type 3 systems appears from fig. 8, where the stroke servo S is explained schematically. The delay action of the type 3 pumps is 5 - 10 times smaller than that of the type 1 gear. (Fig. 5.)
Note that short relay commands only will stroke the type 3 pump partially. A closed hydraulic circuit is used. This requires approximately symmetric hydraulic actuators, and the application of a booster pump to supply oil for the compression.

ELECTRONIC FEEDBACK
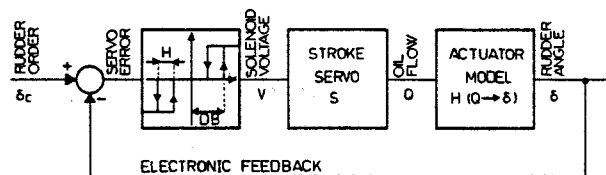
DB : DEADBAND IN BANG-BANG SERVOAMPLIFIER   (0.5 - 1.5 deg)

H : HYSTERESIS IN BANG-BANG SERVOAMPLIFIER   (0.25 - 0.75 deg)

RUDDER SPEED : 65 deg IN NOT MORE THAN 28 sec.

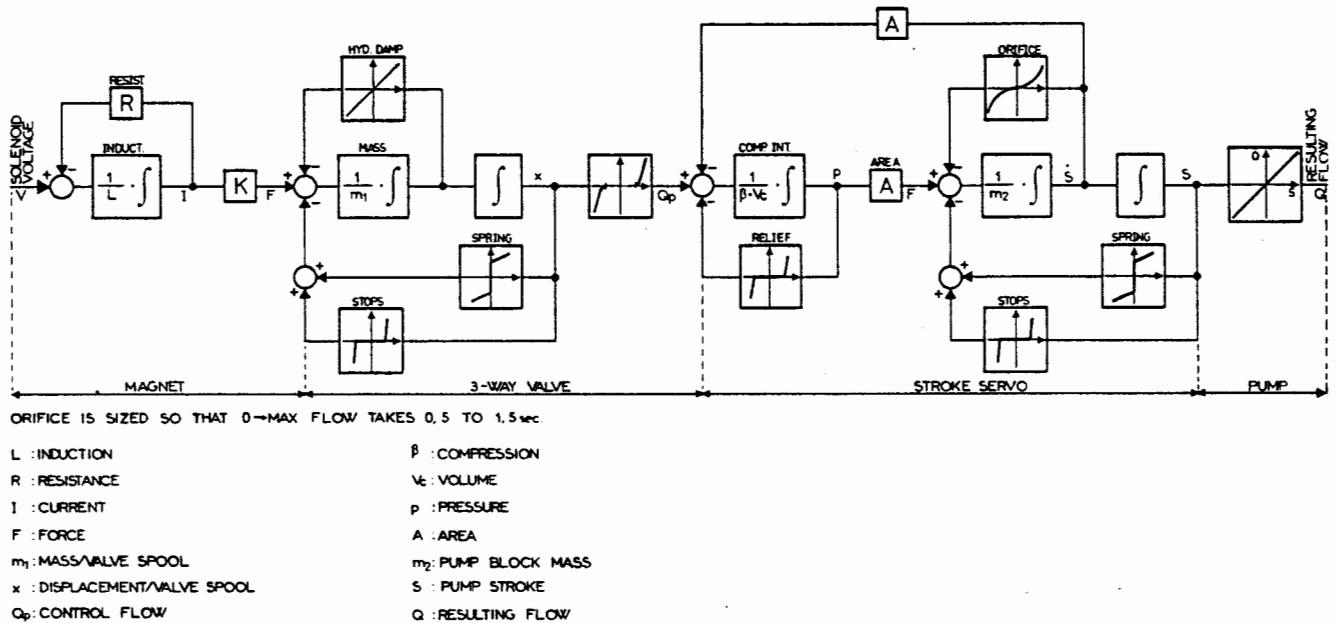Fig. 7 Type 3 Control Loop. (Variable Pump).

ORIFICE IS SIZED SO THAT 0→MAX FLOW TAKES 0.5 TO 1.5 sec.

L : INDUCTION	β : COMPRESSION
R : RESISTANCE	V_c : VOLUME
I : CURRENT	p : PRESSURE
F : FORCE	A : AREA
m_1 : MASS/VALVE SPOOL	m_2 : PUMP BLOCK MASS
x : DISPLACEMENT/VALVE SPOOL	S : PUMP STROKE
Q_p : CONTROL FLOW	Q : RESULTING FLOW

Fig. 8 Simplified Model of the Type 3, Bang-Bang operated Stroke Servo.

4.8 Type 4.   Twin Loop
Analog Controlled Telemotor

Analog control is obtained, if the telemotor is supplied from either a servovalve or a small servopump. (Variable capacity.) Proportional band in the telemotor servo should be selected within: 1 deg $\leq$ PB $\leq$ 3 deg. The selection should be matched to the max telemotor speed:

$\cdot$ 3 deg/sec $\leq \dot{\delta}_{tm} \leq$ 6 deg/sec, so that the

ratio, which is the servo time constant, is approximately constant. (0,4 sec.)

Like type 2, the power stage, that follows the telemotor, has variable pumps, analog control and floating lever feedback. A type 2 gear can be modified to a type 4 gear. All installations on twin loop gears made by EMRI have so far employed both a type 2 and a type 4 control.

The 3-way valves of the type 2 control are recommended for emergency NFU control. (Non Follow Up).

Also in the type 4 system, the max difference between the rudder order of the telemotor and the actual rudder angle is limited to the size of the proportional band of the power stage.

Performance of the analog controlled type 4 gear is considerably better than of the Bang-Bang controlled type 2 gear. Analog control was enabled by the rapid development of microelectronics and of servohydraulics that took place in the seventies. Due to this continuing development, and to the better price/performance ratio, it is expected that analog control will dominate the market within a few years.

Fig. 9 shows the block diagram.
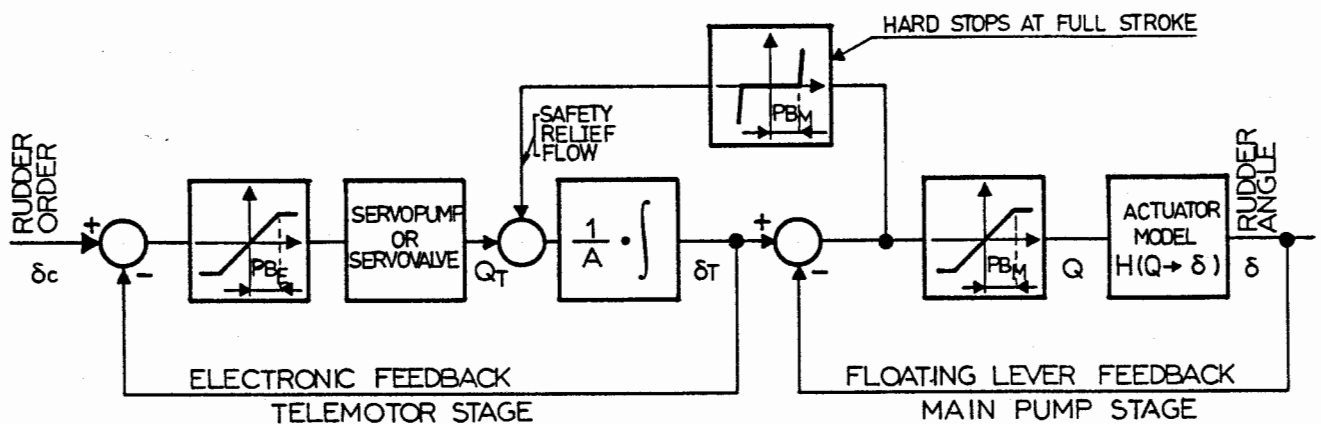
MAX TELEMOTOR SPEED : δ_T = 6 deg/sec.

ELECTRONIC PROPORTIONAL BAND: PB_E 1 deg $\leq PB_E \leq$ 3 deg

MAIN GEAR PROPORTIONAL BAND : PB_M = 6 deg

RUDDER SPEED : 65 deg IN NOT MORE THAN 28 sec.

Fig. 9 Type 4 Control Loop. Analog controlled Telemotor.
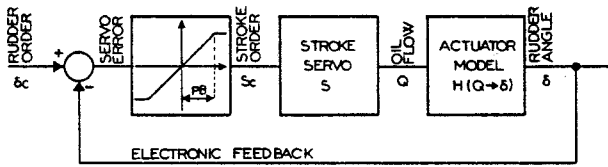
PB : PROPORTIONAL BAND   1deg ≤ PB ≤ 5deg

Sc : STROKE ORDER

RUDDER SPEED: 65deg IN NOT MORE THAN 28sec.

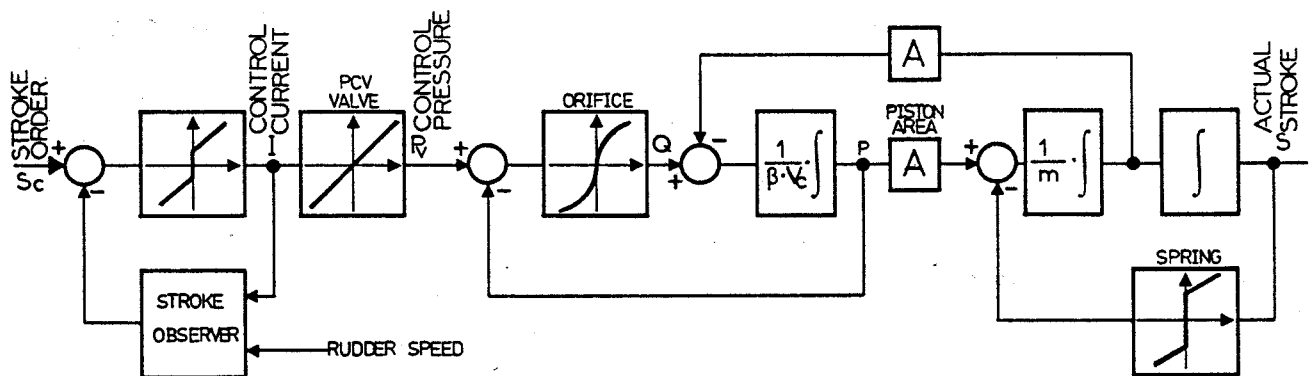Fig. 10   Type 5 Control Loop.

4.9   Type 5.   Single Loop.   Analog Control Variable Capacity Main Pump

A variable capacity pump working into a closed hydraulic circuit and stroked by a servovalve composes the pump unit of the type 5 gear. To stabilize servo, some form of stroke feedback is required: Either directly to the servovalve, or via a potmeter or a nonlinear stroke obser-ver to the servoamplifier.

The observer principle will give the lowest bandwidth, but will have the longest life, as there is no stroke potmeter or feedback arm that could be worn out. As in the type 4 case, the EMRI developed systems include a small 3-way valve for NFU emergency control. The NFU valve bypasses all electronics and the servo-valve and stroke the pump directly. It is a safety feature, but due to the high reliability of microelectronics and of servohydraulics it is seldom or never used.

Fig. 10 shows the block diagram of the type 5 gear, and fig. 11 is a simplified diagram of the stroke servo S.

Performance of the type 5 systems is excellent. It has the advantage over the type 4 analog sy-stems of fewer moving parts on high force level. Seen from the autopilot, the type 5 system re-presents 1 lagging state, compared to 2 of the type 4 systems. (Lagging state = time constant). Each lagging state is destabilizing to the au-topilot control loop.

4.10   Type 6.   Single Loop Analog Controlled Full Flow Servovalve

High power servovalves are available, and since at least one steering gear maker uses this prin-ciple, it should be mentioned. Since a servo-valve is used in the power stage, the heat prob-lems must be solved through the application of pressure compensated pumps or pumps with "load sensing", or through the application of a large oil cooler.

If very high bandwidth were required in the sy-stem, an oil cooler and a fixed capacity pump at full safety relief pressure should be used together with the servovalve-

The block diagram looks like fig. 10.

Used in a steering gear, performance of the type 6 system is expected to be like that of type 5. Due to the heat problems the type 6 system is unlikely to appear on large ships.
Type 6 is the only system, that so far has not been performance tested by EMRI through compa-rison to other systems.

5.   DISCUSSION OF STEERING QUALITY

The term steering quality includes 3 dimensions:

1. Reliability and availability.
2. Precise manoeuvring.
3. Fuel economy.

All 3 dimensions are important for the ship operators. To some extent the reliability aspects are taken care of through the classifi-cation process.

Regarding manoeuvring accuracy and fuel economy no international standards exist. It is the responsibility of the ship operators (owners and charterers) to specify. The survey of sec-tion 4 could be a help in the specification of the steering gear parts of the control loop.

NOTE: THE MODEL SHOWN APPLIES A PRESSURE CONTROL VALVE (PCV)
PUMP STROKE IS ZERO WHEN −3 bar ≤ R_v ≤ 3 bar (BY SPRING)

Fig. 11   Simplified Model of Analog Stroke Servo.   (The Center Block, S, of fig. 10).

Table 1
Estimated rudder activity in relation to steering gear principle

Control Principle	Loop Configuration	Main Pump	System Type	Rudder Activity (δ^2)
Bang-Bang	Single loop	Fixed	1	3 deg^2
Bang-Bang	Twin loop	Variable	2	2 deg^2
Bang-Bang	Single loop	Variable	3	1.5 deg^2
Analog	Twin loop	Variable	4	1.2 deg^2
Analog	Single loop	Variable	5	1 deg^2
Analog	Single loop	Servo Valve	6	1 deg^2

Fuel economy and precise manoeuvring require two different autopilot controllers, but both are optimised through the use of analog control in the steering gear servo.

A long range of installations and sea trials have supported this statement. Some of the sea trials are reported in section 7 of this paper.

A good measure of steering performance is the mean squared rudder angle, here defined as the "rudder activity". Table 1 list the theoretic situation of a marginally stable ship under autopilot control at low seastate, and equipped with the 6 types of steering gears described in section 4. The resulting differences in the rudder activity is thereby caused by the steering gear principles. It is recognized from the table, that the performance increases with the type number, as the rudder activity decreases.

(Actually table 1 list the results from 9 ships, each carrying two different types of steering equipment, that was compared. Measurements were carried out on the following pairs:
Types: 1 to 5; 2 to 5; 2 to 4 and 3 to 5.)

6. ASSESSMENT OF PERFORMANCE IN THE PRESENCE OF LIMIT CYCLES

While the previous sections have presented a survey of different steering gear designs, and pointed to the existence of limit cycles associated with the Bang-Bang type control systems, this section briefly discuss the assessment of limit cycle amplitudes, and of the associated propulsion losses.

The assessment of limit cycle amplitudes may be approached through either theoretical analysis of the nonlinear steering system, or by time-domain simulation studies of the yaw-sway-surge coupled motions of the ship.

The more complete models of the steering gear control loops, figures 2 to 11 are by far too complex to cope with analytical treatment of limit cycles. we have instead used a rather simplified description with a nonlinearity and one integration in each loop for the analysis. {17}. Of the theoretical methods available, a multiple input describing function technique is manageable for both single and twin loop systems. However, the prerequisite when using this technique, that signals transmitted through the remaining dynamical system to the nonlinearity

have only a minor content of frequencies higher than that of the limit cycle, is violated in the present case, {17}. The only usefull approach is therefore to use time domain simulations.

Results from such investigations confirm the practical experience, that Bang-Bang controlled steering gears (types 1 to 3) display a limit cycle with an amplitude and period that, for each particular system, depends upon adjustment of the autopilot parameters, {19}.

With adjustements like those commonly used in practice, the simulations showed the amplitude of the rudder angle to be 2 to 5 times the deadband of the steering gear control loop. This is in fairly close agreement with actual findings.

Propulsion losses associated with limit cycles are assumed to result from the variable force of inertial origin due mainly to the cross-coupling between yaw rate and sway velocity during yawing, and from the retarding force induced by the rudder during self-sustained oscillatory behaviour of the ship/steering system.

The propulsion losses associated with the limit cycle was found to be somewhat smaller {19}, than the figures measured on the seatrials. {16, 18}.

7. SEA TRIALS

Extensive series of sea trials have been conducted with the purpose of measuring possible improvements in propulsion efficiency when improved control equipment was installed.

The series of test trials commenced with a set of controlled manoeuvring experiments. These were used for identification of the nonlinear speed equation. {14, 16, 18}.

In the following two groups of tests are reported:

a. Measurement of propulsion efficiency during normal operation of the ship, but with alternating use of one servo principle or another. The purpose was to compare the performance of Analog steering with different Bang-Bang systems. (Trials with 5 ships). Analysis of these experiments have included both statistical data processing and analysis of the time history of the ship's course, rate of turn, rudder angle, speed and power consumption.

b. Statistical analysis of regular speed reports from ships where Analog steering and in some cases new autopilots were installed. The purpose has been a long term evaluation of steering performance.
(11 ships were analysed).

7.1 Comparison of Control Principles

A series of tests were conducted with 5 ships where both Analog and Bang-Bang servos were installed. The installations include a change-over switch between Analog and Bang-Bang. Two cases have been selected for this presentation because on both ships, the two control systems had been installed at the same time. Hence improved quality of one system could not be caused by wear of the other. Test trials were conducted as a series of short experiments of either 30 min or one hour duration.

One experiment involved a 4,200 tdw bulk carrier. Two sets of experiments were made. In the one, ship's speed was found through radar observations every 20 min. In the other, a patent log was used to find the ship's speed through the water. The ship's normal instrumentation was otherwise used. Results of the tests are given in table 2 and in fig. 12. The term res.spread denotes the spread on results after removing influence from f.ex. wind, by the least squares regression.

Table 2
Results from Tests with 4,200 tdw ship

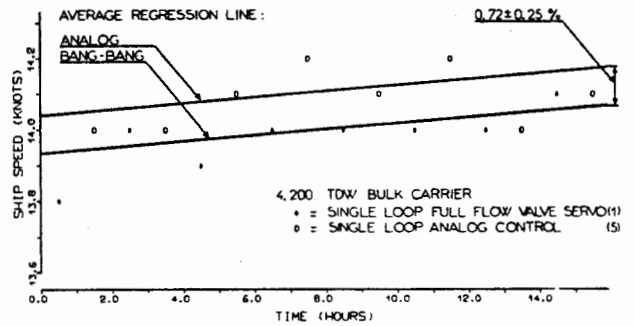|	radar obs.	patent log
number of runs	48	48
average speed (m/s)	6.70	7.16
spread (m/s)	0.43	0.15
res.spread (m/s)	0.11	0.12
impr.by Analog(m/s)	0.040±0.032	0.044±0.038
rel.imprvment (%)	0.60±0.48	0.62±0.53

Fig. 12 Results from one Day's Experiment with Bulk Carrier. Data are corrected for Weather.

In fig. 12 results from one day's measurements using the patent log are plotted. The data shown are corrected for influence by wind, but because weather informations is being somewhat arbitrarily judged and given in the terms of the Beaufort scale, the scatter due to wind and sea can not be entirely removed.

Both results taken over 48 runs show 0.6 % speed increase at constant propeller thrust in favour of the Analog system.

The other experiment selected for presentation involved a ULCC tanker at full load. In this case a twin loop Bang-Bang and a twin loop Analog steering gear were compared using the same autopilot. The signals measured were conditioned and averaged by the EMRI "SPICE" signal processing unit. Results are listed in table 3, and raw (not weather corrected) speed readings over 9 hours are plotted in fig. 13.

Table 3
Results from Tests with 330,000 tdw tanker

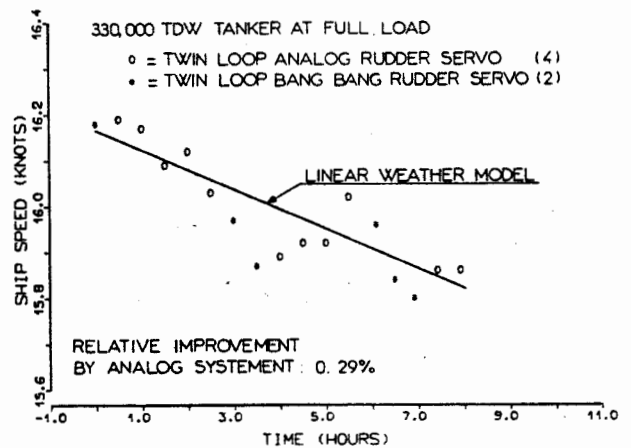| number of runs		57
average speed	(m/s)	8.157
spread	(m/s)	0.17
res.spread	(m/s)	0.05
improvement by Analog	(m/s)	0.019±0.017
rel. improvement	(%)	0.23 ±0.21

Fig. 13 Results from Test Trials with ULCC Tanker. Data shown are standardized to 36.000 hp, but are not corrected for weather influence.

- 9 -

On the particular day which relates to fig. 13, weather became gradually worse, as reflected in decreasing average speed. Each run lasted 30 minutes. The values plotted in fig. 13 are the raw consecutive data gathered without allowing ship speed to settle after a change of rudder servo. Points following a servo changeover are therefore disregarded in the analysis. These points are included in the plot anyway, because they show how speed changes following each change of steering gear servo. The results of 57 runs as listed in table 3, show an improvement in speed of 0.2 % in favour of the Analog system.

In this case both steering gear servos were new, and the performance of the Bang-Bang system was quite satisfactory. A significant reduction in rudder activity (~ 50 %) was nevertheless found when changing to the Analog system. From a judgement of steering quality therefore, the Analog system also appeared to be superior.

In the analysis it has been experienced to be rather difficult to remove weather influence entirely from the speed data. Weather informations are given as the impression of seastate during the runs. A least squares fit is carried out to minimise the correlation. Weather influence is present in the data anyway, and only direct measurement of the average wind speed and direction over the run could improve the results.

7.2 Analysis of Speed Reports over extended Periods

Analysis has been made of regular speed reports from ships where Analog steering and in some cases, new autopilots were installed. The speed reports are measurements of the average speed over several hours at the current operating condition of the ship. In addition to the ship's speed, approximate averages of shaft speed, shaft power, seastate, wind speed and the angle of attack from waves and wind are provided. Furthermore parameters as ship's draught and trim are available. Based on these figures the speed data can be converted to some standard operational condition. In this process results are rather sensitive to measurement uncertainty, and as hardly any ship have long term averaging instruments for providing the readings, some scatter in the results is unavoidable. In order to obtain statistical significance, a considerable number of observations are then required. Results for two different container ships are presented in fig. 14 and 15.

In fig. 14, 97 observations taken over one year illustrate the performance before and after modification of the steering gear servo. (From a type 2 to a type 5, 230 days into the period). Despite the relative large standard deviation of the measurements, a statistical significant improvement of 1.32 % ± 0.54 % is obtained after the change.

Fig. 15 shows a plot of 49 observations on another ship over a two years period. In this case the autopilot was changed from a PI to a PID type, and at the same time the steering gear was modified to Analog control. (From a

type 2 to a type 4 servo). By the combined change, an increase in ship speed of 1.92 % ± 1.44 % was achieved, referring to the ship's nominal operating condition.

The speed reports have been randomly selected over the periods considered, and all observations (except some with less than 40 % of nominal shaft power) have been included in the analysis. The figures obtained therefore express the actual performance for the particular ships.
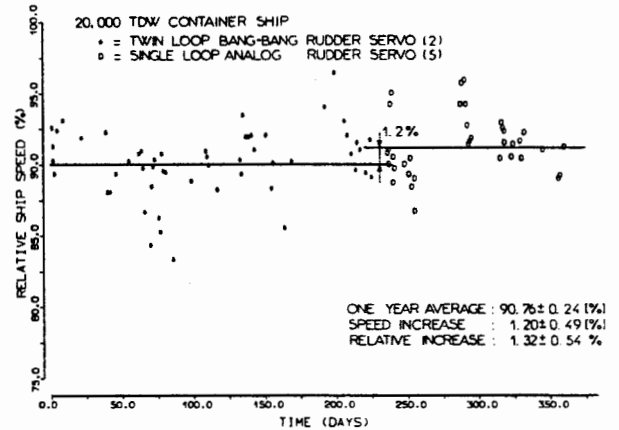

Fig. 14 Relative Ship Speed during one Year. Data are corrected for ship's draught, trim, shaft power and weather. Rudder servo was changed after 230 days.
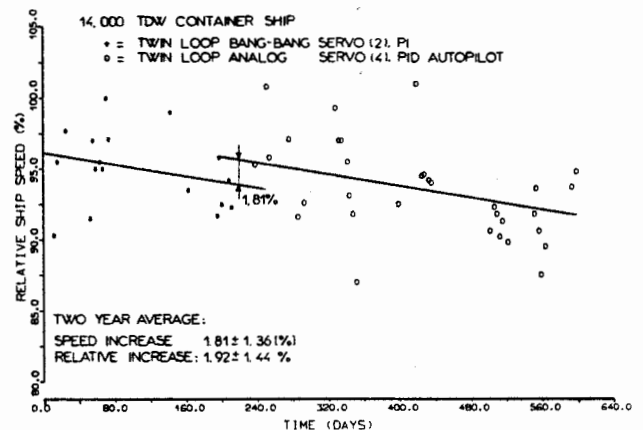

Fig. 15 Relative Speed referred to constant Power Level. Data are corrected for draught, trim, shaft power and weather.

7.3 Discussion of Recordings from Test Trials

In addition to the statistical analysis, recordings from the test trials, where different steering gear servos are used, provide a valuable means for visual inspection of the steering quality.

A clearcut and rather dramatic evidence of the difference in steering quality between an Analog type 4 system and a Bang-Bang type 2 system, is presented in fig. 16. The figure shows a consecutive recording of two experiments. Run no.8 is with the Analog servo system , run no.9 is with the Bang-Bang system. There is no time difference between the runs, and the no.9 recording starts at the instant where the pumps are changed. In the Bang-Bang mode, a limit cycle starts,
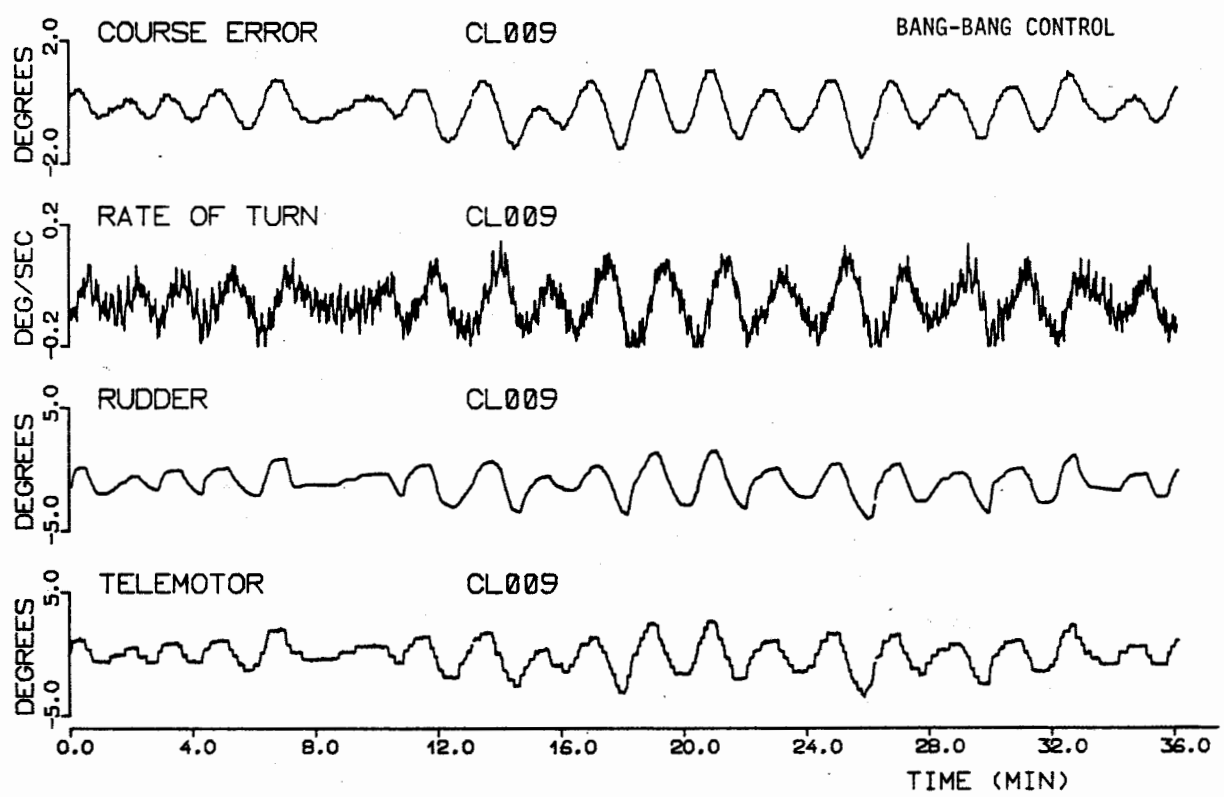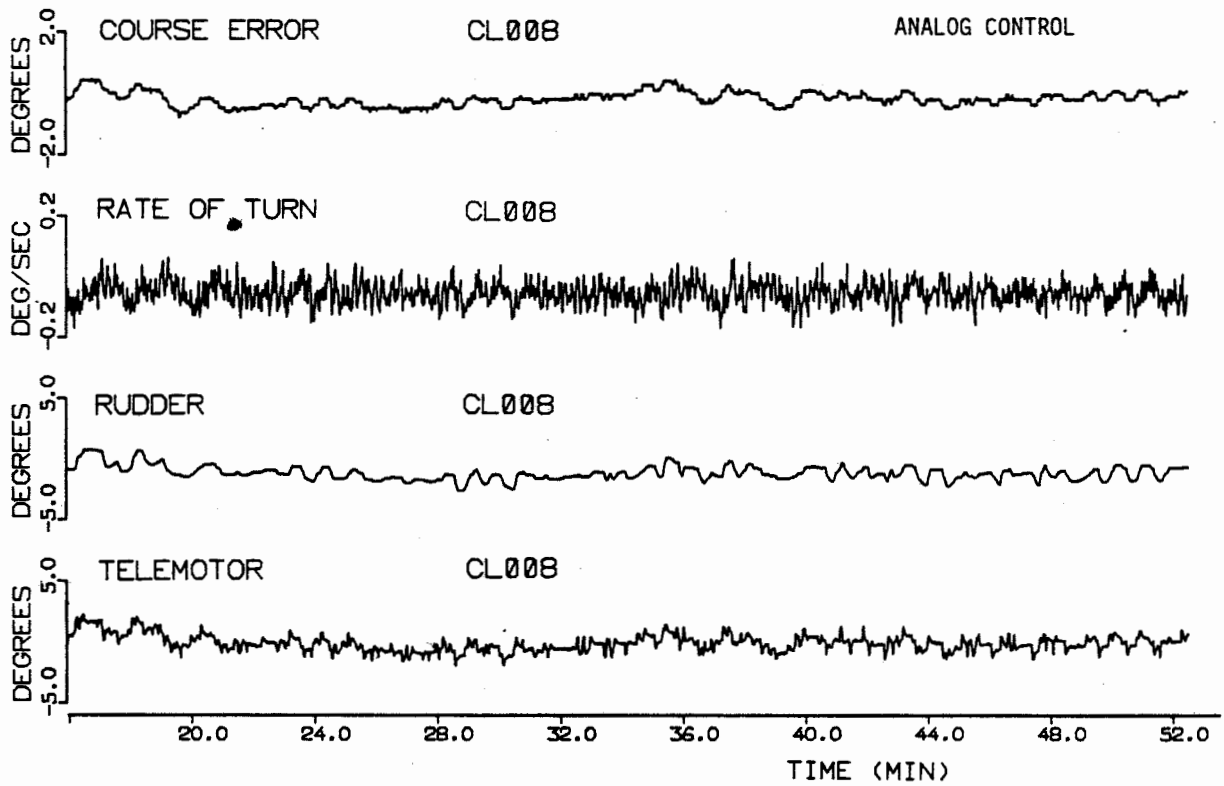
Fig. 16   Recordings from a test trial with Analog Steering gear of type 4 (RUN: CL008) and a Bang-Bang system of type 2 (RUN: CL009). Container ship with displacement 30.000 m³ at 18.8 knots. The weather is calm, seastate 1.
RUN: CL009 follows immediately after the end of RUN: CL008.

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Table 4
Measured Steering Performance: 30.000 m³ Containervessel - February 1982

Run no	Rudder Servo Type	Rudder Activity	Mean Square Heading Error	Average Speed through Water	Average Shaft Torques	Time (min)
CL008	ANALOG type 4	0.188 deg²	0.033 deg²	18.77 knots	72.85 % of max	$40 \rightarrow 52$
CL009	BANG-BANG type 2	1.783 deg²	0.495 deg²	18.43 knots	73.15 % of max	$24 \rightarrow 36$

and reaches its full amplitude within a quarter of an hour. The period of the limit cycle is about 120 seconds. The autopilot in control was a standard PID type, and its settings were left unchanged during the experiment.

It is evident from the time history of the tele-motor angle in fig. 16, that the two rudder servo systems behave quite differently. Where the Analog servo gives a smooth signal with small, rapid corrections, the Bang-Bang system is characterized by changing its state in discrete steps of 2/3 degree. The limit cycle gives excursions of ± 4 steps of this quantization. This compares with theoretical predictions.

It could be argued, why the rather ideal Analog system gives spikes of about 1.2 degree rudder order at the telemotor level, when these signals are smoothed by the power stage anyway. The cause of this phenomenon is not found in the rudder servo system, but in the compass transmission system, which has a step motor with 1/6 degree quantization. The steps can be seen on fig. 16. Each step in the compass transmission system of 1/6 degree is followed by a spike of 1.2 degrees on the telemotor. The amplification takes place in the autopilot controller, which has a high frequency gain of approx. 8.

Averaged results from the performance measurements during the two runs are summarized in table 4. It is not surprising to find as well a speed drop (-1.8 %) as a rise in shaft torque (+0.4 %) in the Bang-Bang period.

8. CONCLUSIONS

This paper has presented a unique survey of the different types of steering gear control systems, which are presently in use, including the newer systems with analog control. The simulation studies that so far have used very much simplified models, have shown the existence of limit cycles, with Bang-Bang systems, while superior performance is achievable with the Analog systems. {19}.

These observations were supported by the results from a series of test trials with several ships, where different steering gear remote control systems were installed and successively used. Statistical analysis of the experiments demonstrated the impact on fuel economy of Bang-Bang and Analog systems, and the analog control was found to improve the fuel economy at a certain speed by 1,5 to 2 %.

Steering quality of the Analog system was found to be superior too. Better course keeping and

less rudder activity are important for specific applications such as hydrographic vessels. {20}.

With the bunker prices of today, the fuel economy will concern any shipowner or charterer. Being only about 2 to 4 %, propulsion losses due to unideal steering are only a small part of the total fuel consumption, but of course of prime importance in the selection of manufacturers of autopilot and steering gear equipment. So much the more as the right combinations can reduce the losses substantially.

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