ROLL STABILIZATION OF WARSHIPS

BY

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ABSTRACT

The world's first successful active roll stabilization of a warship took place in 1938 in the Royal Navy. This paper firstly examines the history of stabilization from that time, through World War II to the present day, based on Royal Navy and U.S. Navy experience. The operational requirements for stabilizers in the various ship types of present day navies are then discussed and the types of stabilizer systems available to meet the requirements of modern warships are described and compared in terms of operational performance and cost-effectiveness. Finally the paper looks to the future and suggests some different stabilization ideas which, although not new in themselves, may with the aid of modern technology, become practical propositions and be successfully developed for future warship applications.

Introduction

Unlike the merchant ship, whose role is to voyage uneventfully and economically from port to port, the warship's role is to go to sea and to stay there, live there, and work there. This special role heightens the impact that wave-induced ship motions have on the overall effectiveness of a warship. It is therefore the operational requirements of various warship types and their size that govern both the degree of motion control that should be applied and the nature of the stabilizer system that should be employed. Heave, pitch and roll are the motions that most influence operational effectiveness and of these roll is usually of the greatest magnitude. Fortunately, the forces that induce roll are relatively small and it is practical to counteract these with a roll stabilizer device. Furthermore, having controlled roll, there is then scope to manoeuvre the ship to reduce and to optimize these two motions.

There have been many studies and experiments in the past to reduce the other critical motions of pitch and heave by the direct application of counteracting moments and forces, the most recent example being the study of bow fins for the French Navy aircraft carrier *Charles de Gaulle*[1]. These have, however, all proved to be impracticable because of the very high powers and stresses involved. The discussion in this paper will therefore be confined to roll stablization in the historical context and that of the present day, but other degrees of freedom will be examined in the context of future developments.

HISTORY

Several unsuccessful attempts were made to provide ships with roll stabilization in the late nineteenth century, including such bizarre devices as gigantic flywheels and gimballed saloons, but it was not until 1935 that the first practical and successful system appeared in the Cross Channel steamer *Isle of Sark*. This was an active fin system designed and developed by Brown Brothers and Company Limited of Edinburgh in conjunction with Denny Brothers Ltd of Dumbarton and was the first of many hundreds of Denny-Brown stabilizers.

During this same period of the late 1930s the Admiralty developed a new class of warship to become known as anti-aircraft sloops. These ships, designed specifically to provide anti-aircraft cover for convoys, displaced 1190 tons and had a principal armament of six four-inch high-angle guns. The gun fire control system was somewhat rudimentary and based on goniographic principles with an unstabilized sight line. Following Admiralty involvement in trials on the *Isle of Sark*, it was decided to fit Denny-Brown stabilizers in the anti-aircraft sloops to improve their gun fire accuracy, commencing with H.M.S. *Bittern* in 1938. During the immense R.N. shipbuilding programme of the Second World War over one hundred sloops, frigates and destroyers were fitted with similar stabilizers. By the end of the Second World War developments in naval gunnery had led to tachometric fire control systems with their rate-measuring gyros simultaneously providing a very accurate stabilization of the sight line against roll, pitch and yaw motions. Thus the gunnery requirement to provide roll stabilization for the whole ship was diminished and stabilizers were no longer fitted in R.N. ships.

The Denny-Brown stabilizers of the Second World War era had fins of about 2 square metres in area and a high aspect ratio of about 2.1. They were of the retractable type which could be withdrawn athwartships into the hull when not in use, and were thus protected when the ship berthed alongside. During the late 1940s and early 1950s these stabilizers virtually disappeared from the British Fleet, the notable exception still giving good service today being those fitted in H.M.Y. *Britannia*.

It was not until the advent of the naval helicopter and the requirement to use it in an anti-submarine (ASW) role from small ships that the roll stabilizer made its re-appearance, this time as an aid to naval aviation. The COUNTY Class guided missile destroyers were built with three pairs of active fins each, the LEANDER Class frigates with one pair, whilst the Type 12 frigates were retrofitted with one pair each and no less than five pairs were used when H.M.S. *Blake* converted to a helicopter cruiser. Since that time all combatant ships for the R.N. have been designed with fin stabilizers from the outset.

During this second era a new design of fin was introduced. The athwartships retractable type had always been vulnerable to damage from underwater shock and could be a considerable embarrassment if it jammed in the extended position. The space required for retraction within the ship was already more than the designers wished, and to strengthen this design for shock would have made it even less acceptable in terms of space requirement. The new design fin was non-retractable and driven by a fin shaft passing through a gland in the ship's hull. This is now the generic design of fins for warships and is illustrated in FIG. 1.

This fin unit can be designed to the highest current shock standards, but because it cannot be retracted its outreach must be restricted to the docking line of the ship, if the ship is to berth alongside without damaging the fins. The fin aspect ratio is therefore very low, typically about 0.6:1, and the trapezoidal shape was adopted to minimize as far as possible the adverse lift/area ratio caused by the low aspect ratio. It was the outreach limitations and consequent low lift/area ratios that led to the multi-fin installations.

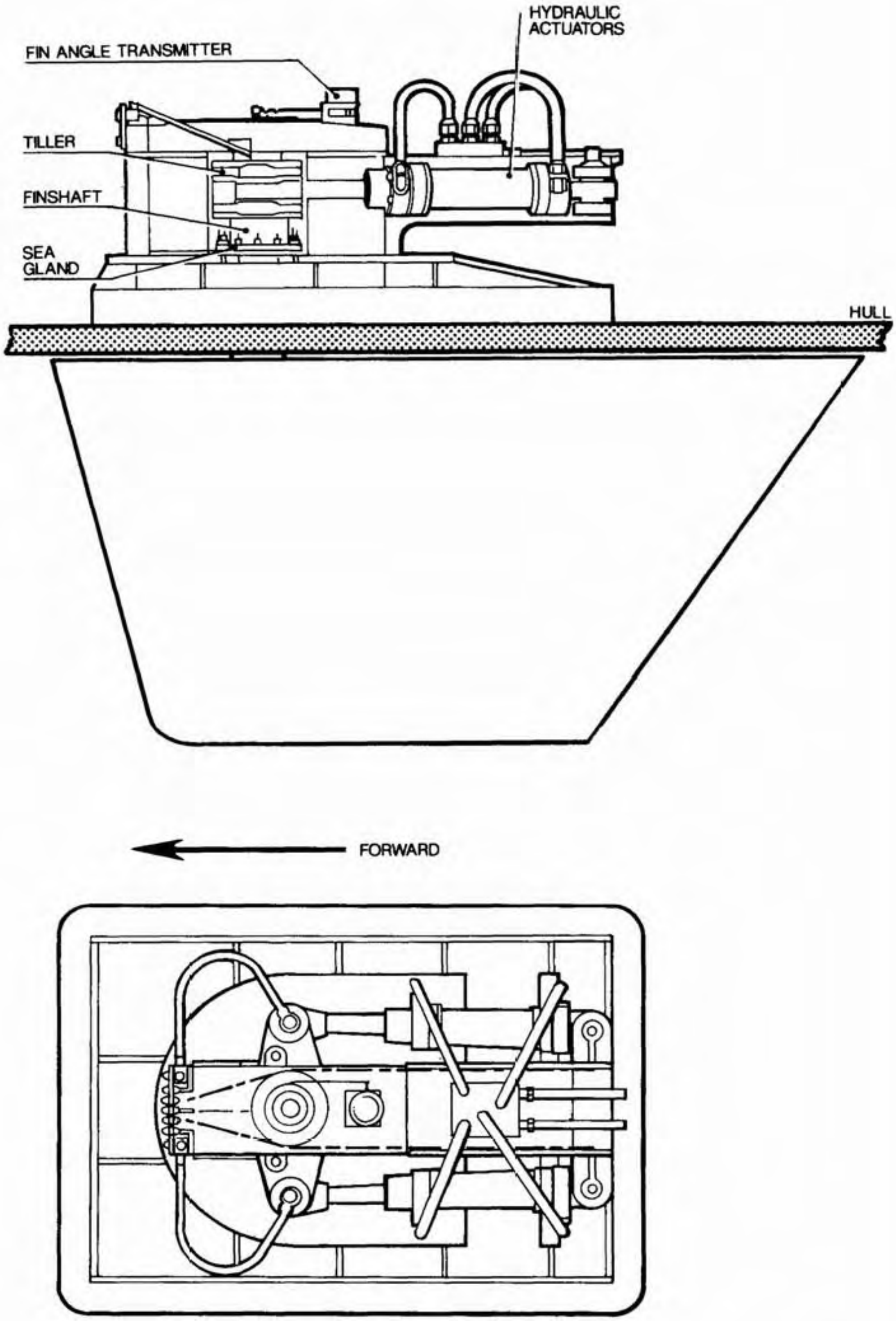

FIG. 1—TYPICAL NAVAL STABILIZER FIN UNIT (FIN NOT SHOWN IN LOWER VIEW)

Because of the large aircraft carrier force of the U.S. Navy, ASW helicopters were not introduced into small escort warships until much later than in the R.N. Following some unfortunate experiences with unreliable stabilizer systems in the DD 1052 class destroyers during the 1960s there was considerable resistance to fitting any more in the U.S. fleet. As a result however of considerable work by Captain James Kehoe, U.S.N.,[2] and by Dr Juliana Gatzoulis and Mr Robert Keane,[3] U.S. opinion swung in favour of fin stabilizers for the 70 ships of the FFG 7 class of frigates with their large LAMPS helicopters, which were built in the early 1980s. This active fin stabilizer system, again from Brown Brothers and built to very exacting U.S. Navy standards, represent the 'best that money can buy' and sets the benchmark for systems built to full military standards. Paradoxically however, by the time the FFG 7 stabilizer system completed development very few navies of the free world, other than the U.S.N., could afford equipment built to such high standards due to rapid changes in the world economic climate.

PRESENT DAY

During the 1960s and early 1970s most countries in the free world enjoyed a fairly steady economic growth and the trend in the design of equipment for warships was the pursuit of excellence in performance and reliability, this resulted in increasing technical sophistication and a steady increase in unit purchase costs. With the world trade recession that followed the quadrupling of oil prices during the Arab-Israel War of 1974 most nations were forced to review and reduce their defence expenditure and it soon became clear to the naval authorities that future warships would have to be designed down to a cost and every feature of the new designs closely scrutinized for cost-effectiveness. Thus the current situation arose in which the naval requirement is not simply the best equipment regardless of cost, as typified by the FFG 7 stabilizer system, but is now the best equipment available for a given cost.

Even with these economies in design many of the smaller nations realized that the true warship with its military features of high shock resistance, high speed and low noise characteristics was still too expensive and indeed too sophisticated for their needs. Their requirement is for coastal defence and offshore patrol, not an ocean task force. Thus was born the concept of the large Offshore Patrol Vessel (OPV). These ships are usually in the range of 1200 to 1800 tonnes displacement, with full helicopter facilities, and reasonable power. They are, however, to commercial standards and lack the shock, speed and noise characteristics which contribute greatly to the high cost of the true warship.

Recognizing this situation Brown Brothers embarked on a private venture development programme for stabilizer systems for both warships and OPVs which would meet the changed requirements. As one way of reducing costs whilst retaining as much as possible of the previous high technical standards, they adopted a policy of 'complete system engineering' in which they took control of the design and manufacture of the whole system embracing sensors, electronic computation, power amplification, and the heavy mechanical actuation. To achieve this policy they set up their own Control System Division whose digital-based hardware and software products are marketed as Vickers Marine Controls (VMC). In re-examining the operational requirements Brown Brothers concluded that the essential ingredients for a stabilizer system were the stabilizer power or degree of stabilization achieved, the effect of ship's speed on stabilizer power, and the role of the ship.

Stabilizer Power

This is usually defined in terms of 'wave slope capacity' (WSC), in which the maximum heeling moment provided by the stabilizer system is equated to the heeling moment that would be applied by the appropriate value of wave slope, and is therefore expressed in degrees. Obviously the WSC required to stabilize a 20 000 tonne aircraft carrier in Sea State 6 would be much less than that for a 3000 tonne frigate in the same sea state, simply because the basic disturbance of the larger ship is much less in the first place. The stabilizer power specified for a given class of ship is somewhat subjective and should certainly vary with the role of the ship. For example, a case may be made for less stabilizer power in a ship without aviation facilities than for a ship of similar size which carries organic helicopters. For their private venture work therefore, for ships with organic aviation Brown Brothers have concluded in general terms that the values of stabilizer power given in TABLE I will give satisfactory cost-effective operation.

TABLE I—*Recommended values of stabilizer power*

Ship Type	*Displacement* tonnes	*Power (WSC)* degrees
Aircraft Carrier	20 000 – 40 000	2 – 3
Cruiser	8 000 – 12 000	3 – 4
Frigate/Destroyer	2 000 – 5 000	4 – 5
OPV	800 – 1 800	5 – 7

Effect of Ships' Speed

In accordance with the laws of hydrodynamics, the lift generated by stabilizer fins such as those illustrated in FIG. 1 is proportional to the square of the ship's speed, and therefore the wave slope capacity of a given installation will vary in the same manner. For this reason a stabilizer installation is designed for a specified service speed which for a warship is usually in the region 18 to 22 knots. The WSC is quoted for that speed and is that which will be generated with the fins at their maximum angle of attack, which is usually 25° to 30°. When the ship exceeds the service speed the stabilizer controller automatically reduces the applied fin angle according to the square law to maintain a constant value of WSC and prevent undue fatigue stressing of the fin unit. When the ship reduces below the service speed a reduction in the WSC is inevitable, and at very low speeds, say below 6 knots, the WSC is practically zero and the fins automatically zeroed to prevent them cycling from limit to limit with virtually no benefit. If however the ship's role includes slow speed operation, such as sonar array towing or minehunting, some other form of stabilization is required that is independent of speed.

Controlled Passive Tanks

Having examined and rejected the possibilities for active tank stabilizers[4], passive tanks, and moving weights in modern warships, Brown Brothers pursued a compromise between the passive and active tanks systems to control the natural transfer of fluid through the flume (the link between the port and starboard tanks) of a passive system. This is illustrated in principle in FIG. 2. The motion of fluid is controlled by opening and closing butterfly valves to the airspace above the fluid in the tanks. By sensing the ship's roll angle velocity together with the instantaneous direction of fluid flow in the flume, the stabilizer controller drives the valves so that the fluid motion opposes the roll by being in phase advance of it, ideally a phase advance of 90° for optimum performance. The frequency response bandwidth of the controlled passive system is much greater than the purely passive and the additional weight and space requirements are negligible compared with an active tank system. Controlled passive tank systems are now in service in the R.N. seabed operations vessel, H.M.S. *Challenger*, and coastal survey vessels, and in the new mooring and salvage vessel of the Royal Maritime Auxiliary Service (RMAS).

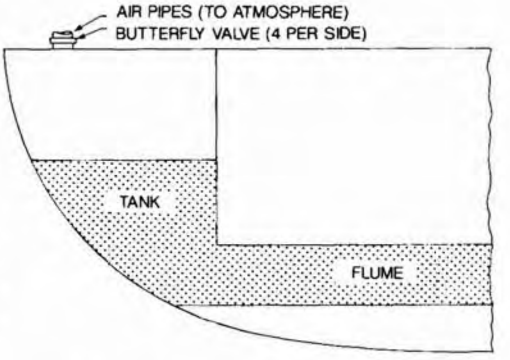

FIG. 2—CONTROLLED TANK STABILIZER

The Performance of Fins and Tanks

The graph of FIG. 3 shows the roll response of a ship plotted against the frequency of roll disturbance of a sinusoidal form that approximates to Sea State 5. Without any form of stabilization the 'out to out' roll would be some 25° at the ship's natural frequency of 0.7 radians per second (roll period 9 seconds). If stabilized with controlled passive tanks as in FIG. 2, the roll would be reduced to about 8°, not only over the wide frequency spectrum illustrated, but also at any ship's speed down to zero. If in addition one pair of fin stabilizers were installed in the ship, a further reduction to something less than 2° would be achieved but only at speeds of 18 knots and above. At, say, 12 knots the roll would probably be 4 or 5° at the natural roll frequency. Below 6 knots the fins would make no contribution and be zeroed.

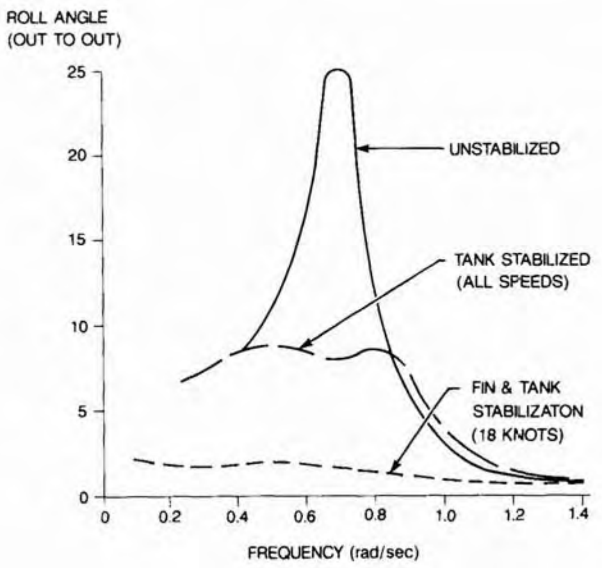

FIG. 3—STABILIZER PERFORMANCE, WITH ±3° SINE WAVE INPUT (c. SEA STATE 5)
ship length: 110 m
beam: 14 m
displacement: 3000 tonnes
G.M.: 1.5 m

For an aircraft carrier a 'fin only' installation would suffice, although for the *Charles de Gaulle* considerable augmentation is being considered.[1] Similarly fins alone should suffice for the AAW or ASW frigate with organic helicopters but no towed array. If however the ASW frigate has a primary role of array towing then a combined fin and tank installation would be more satisfactory. For a minehunter a 'tank only' installation would be most suitable. In the case of OPV there is no reason why the warship non-retractable stabilizers should not be fitted provided the ship's speed is high enough. Most OPV operating navies however do not have a Fleet Air Arm manned by experienced maritime aircrew and use Coastguard or even Army helicopters at sea. This necessitates a higher degree of stabilizer power as suggested in TABLE I. Because the OPVs are normally low speed vessels with service speeds no higher than 10 to 14 knots and maximum speeds rarely exceeding 20 knots, the size of non-retractable fin required to generate this power would be much too large for the ship.

The solution available today is the modern version of Denny-Brown commercial stabilizer which is illustrated in FIG. 4. Because the fins are folded into the hull when the ship berths alongside, their outreach is virtually unlimited and a high aspect ratio can be employed. This design also facilitates the use of a tail flap the effect of which, combined with the high aspect ratio, results in highly efficient generation of lift. In general terms this design of fin is approximately twice as powerful as a non-retractable trapezoidal fin of the same area and is thus very suitable for the slow speed OPV which does not have the military high shock requirement.

THE FUTURE

Rudder Roll Stabilization (RRS)

It has been known for many years that the difference in natural response frequency between the roll and yaw motions of a given ship is quite considerable and that in theory a single set of control surfaces can be used to provide both the steering and stabilizer functions. Considerable theoretical work was carried out in the 1970s[5,6], and in more recent times developments in the control systems field have furthered practical demonstrations of controlling this 'non-minimum phase' system[7,8,9], with the references quoted covering only a small portion of this work. There are however areas in which RRS has yet to be fully proven and user confidence established, particularly the dynamic performance of the machinery, integrity of the system, and modes of operation.

In considering dynamic performance it must be recognized that the 'rudders' must now operate in the frequency regime of stabilizers, which is roughly one order higher than for steering. From the performance viewpoint, therefore, the equipment must be to stabilizer standards. Indeed the description 'Steer by Stabilizer' might be more accurate than RRS, it also emphasizes the fact that such stabilizers must be designed and built to the integrity of steering systems. Because they are not essential for sea-going capability, current stabilizer systems are built with virtually no redundancies or facilities for manual or emergency control. The new combined system therefore must combine the dynamic performance of stabilizers with the integrity of steering, which makes it far more expensive than at first sight. It is also significant that, unlike stabilizers which act only as regulators correcting induced roll, steering systems must respond to steering orders as well as regulating against induced yaw. There are also occasions of close manoeuvring in warship operations, such as Replenishment at Sea, when a combination of manual steering with automatic stabilization is used for safety reasons, and the interactions of these two motions in differing modes will require considerable proving trials for RRS.

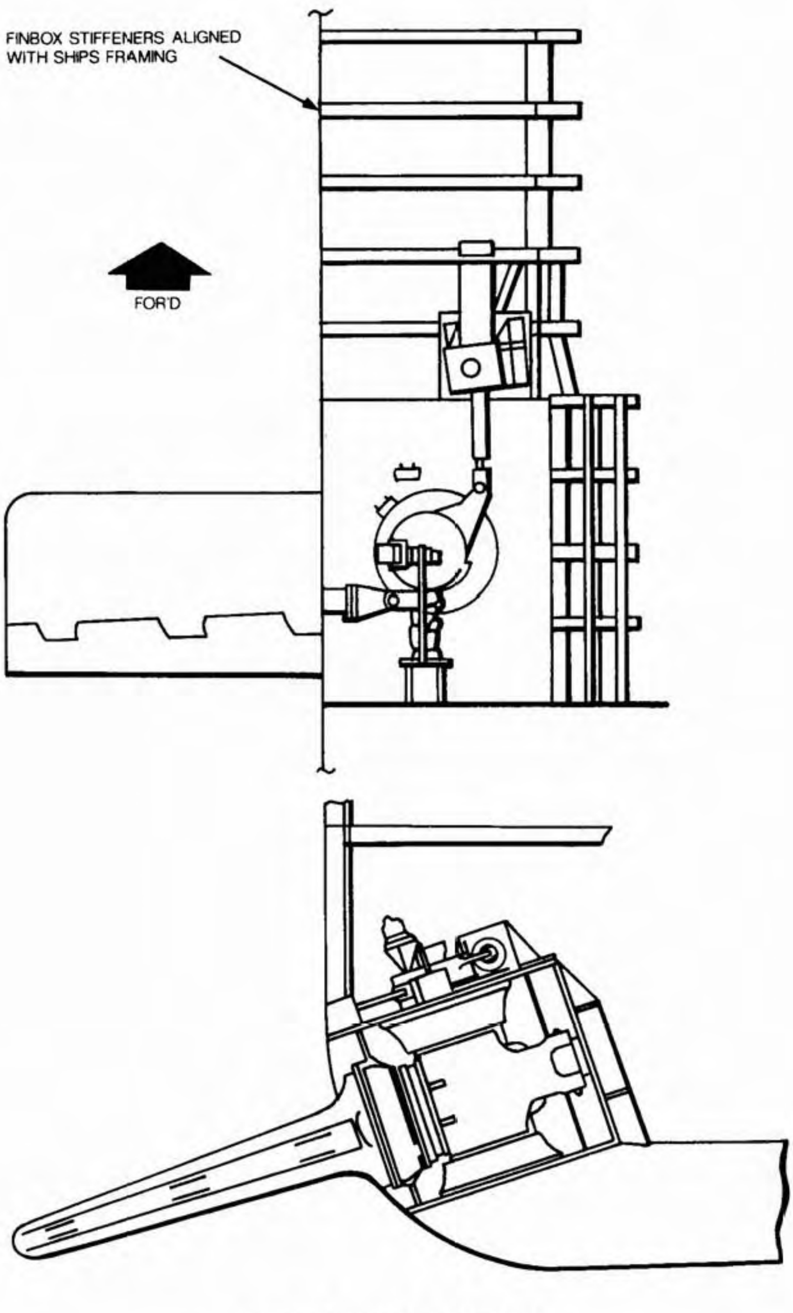

FIG. 4—FOLDING FIN STABILIZER

An interesting solution to these problems is being adopted for the Royal Danish Navy's STANFLEX 300 Class, which has three propellers with a 'rudder', which is basically a stabilizer unit, behind each. This is illustrated in FIG. 5. In the cruise mode the outboard propellers only are used and their rudders operated in RRS. In the high speed mode all three propellers are used but the centre rudder is operated for steering only. This arrangement of three independent units provides the redundancy required for the steering function and the facility to separate the functions when required to eliminate the possibility of interaction.

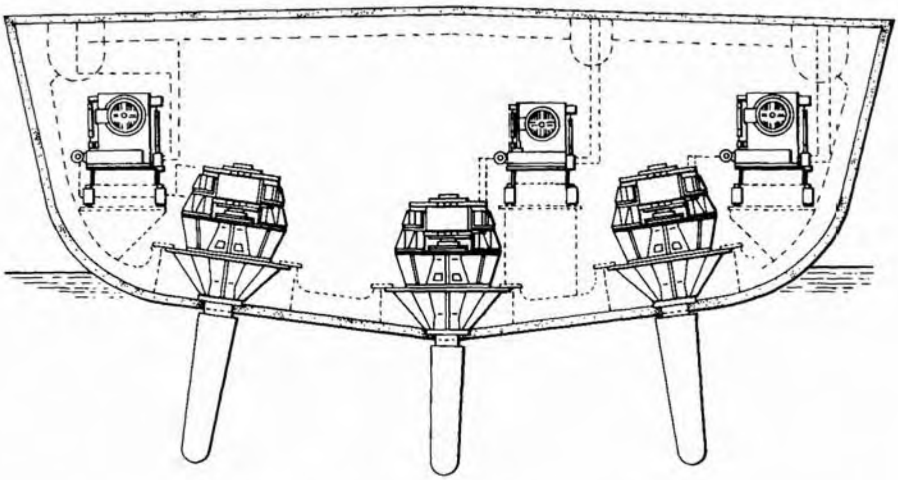

FIG. 5—THREE RUDDER RRS INSTALLATION

Small Waterplane Area Twin Hull Vessels (SWATH)

Considerable interest is now being shown in SWATH applications for warships such as illustrated in FIG. 6. The attractive feature of this ship type is its inherently low reaction to wave motion which arises from the small waterplane area and deep immersion of the pontoons. In broad terms it has been suggested that a SWATH displacing some 5000 tonnes would have about the same motion as a 20 000 tonne monohull in the same sea state. This advantage is however offset by the low self-righting effects. Following extensive sea trials of a small experimental SWATH vessel by the U.S. Navy, it has been accepted that passive motion control is insufficient and that active control of roll, and particularly of pitch, must be adopted.

From their studies of this control problem Brown Brothers suggest a four fin configuration as in FIG. 6. The after fins provide the basic pitch stability and are fixed. They are however provided with controllable tail flaps for the adjustment of trim which is required with variation of wave height. The forward fins are fully movable and, being driven independently, can control both the roll motion and the induced pitch variation. The steering function is quite separate and is provided by rudders. A SWATH vessel of about 3500 tonnes is currently under construction for the U.S. Navy and will create tremendous interest when the results of sea trials are available.

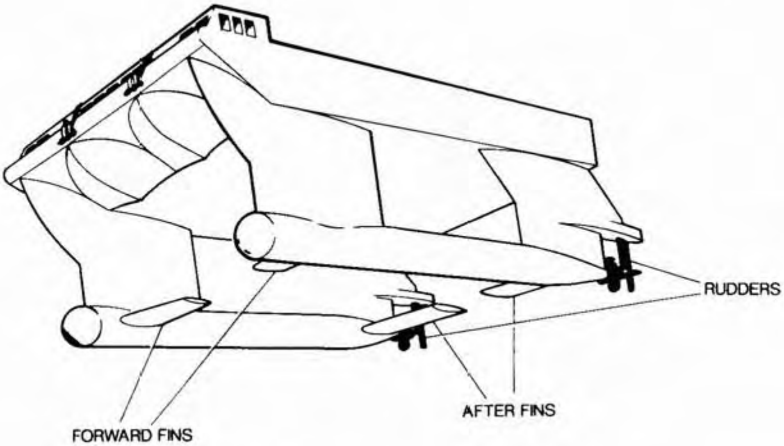

FIG. 6—FIN CONFIGURATION FOR SWATH

CONCLUSIONS

This review of fifty years of ship motion control has indicated that whilst wave induced forces on warships have remained unchanged, the need for counteracting them and the technologies available to do so have been the subject of continuous change. Such changes will continue into the future and, far from being a closed subject on which everything is known, the problems of ship motion will continue to tax the minds of marine engineers as long as ships continue to go to sea.

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