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Propulsion Gear Units for Gas Turbine Naval Installations

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The gas turbine is established as a Naval Marine propulsion power unit and the number of ships at sea using the high power gas turbine in association with diesel engines, smaller gas turbine or steam turbine is increasing. Gear unit designs have been evolved to meet the conditions dictated by the engine/propeller shaft positions and the requirements of ship designers. The involvement of the gear designer in the analysis of shaft vibration characteristics is accepted, and the advantage of costly shore testing has been proven in that design modifications could be difficult and expensive to carry out during trials.

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INTRODUCTION

The marinized version of the aircraft derived gas turbine is not a well-established marine propulsion medium and the number of vessels at sea using the gas turbine as part, or the whole, of the power source is growing at an increasing rate. This paper is intended to look at some of the gear units designed for these installations and, where possible, to discuss operating experience either at sea or on a shore-based test facility.

The generally accepted advantages of the gas turbine, when compared with a steam turbine, of light weight and reduction of auxiliary services, e.g., boilers, condensers, etc., are offset, to some extent, by the fact that in the current generation of engines the power turbine is unidirectional, and certainly with some engines, the specific fuel consumption characteristic does not encourage their use under conditions which deviate markedly from the optimum. These characteristics have had a significant effect on the design of gear units for main propulsion purposes.

The uni-directional feature can be accommodated by either the use of a uni-directional gear in conjunction with a controllable pitch propeller, or of a reversing gearbox in conjunction with a fixed pitch propeller. Both systems have been used, the choice depending, to some extent, on the power to be transmitted and the type and desired performance of the vessel. Controllable pitch propellers have been produced which meet the power output of the current series of high power gas turbines, although, at that time, this represented an appreciable step forward, but experience is now being gained in their operation and will no doubt lead to larger and more efficient propellers. A very recent U.S. Navy vessel uses a controllable pitch propeller in a drive using two turbines, and no doubt this is an indication of the way this form of drive will develop. On the other hand, a recent propulsion system designed for the Royal Navy, which combines two gas turbines to drive one shaft, is based around the use of a large reversing gearbox and a fixed pitch propeller.

The performance characteristic has led to the use of multiple engines with, say, two engines together for high-speed operation and one engine for cruise power, or alternatively, one high power engine for high speed and one or more smaller powered engines for cruise conditions. The smaller prime mover may be another gas turbine, steam turbine, or diesel engine. Each of these combinations has been used successfully, some installations using the "or" configuration, where the engines are used independently of each other, others with the "and" configuration where the engines are used in combination for high-speed operation.

A desirable feature with combined drives is that the change from one driving mode to another should be made without loss of propulsion and with the minimum of control involvement in the change, a situation which can be readily achieved by the inclusion in the drive of a clutch or clutches which provide automatic engagement and disengagement. A number of forms of clutch have been used mainly of the self-synchronizing type or ones incorporating a sprag device. The most widely used clutch is the Synchro Self Shifting overrunning clutch, the operating principle of which, together with typical mounting arrangements, is described fully in the paper presented to the 1972 Conference entitled "Operational Experience of the S.S.S. (Synchro-Self Shifting) Clutch particularly in Naval Propulsion Machinery" by H. A. Clements. Suitable clutches are incorporated in the drive from each gas turbine and in operation are engaged and disengaged by control of the engine speeds.

This type of clutch will engage immediately on start-up from rest if the driven side is stationary, therefore; it is not suitable for inclusion in a diesel engine drive line of a

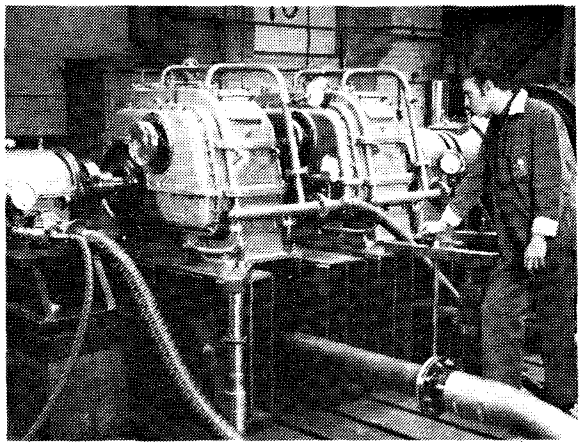

Fig. 1 Tyne gear units on test rig for full load "back to back" testing

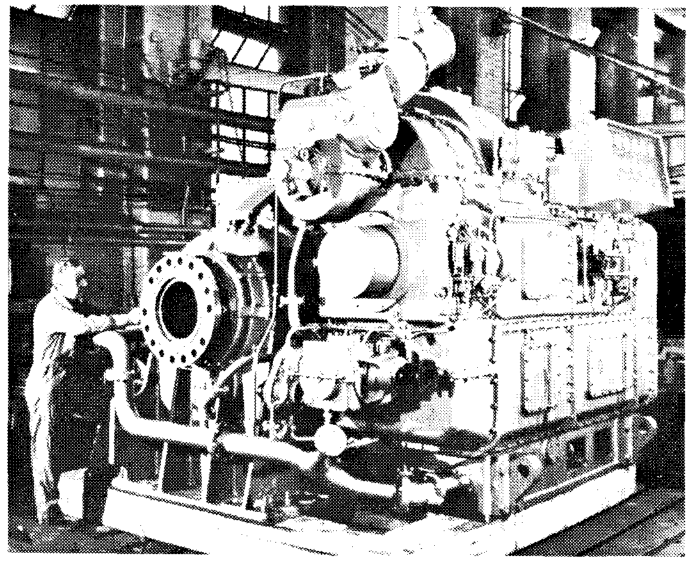

Fig. 2 View from aft end of R.N. Type 42 main gear unit

combined installation as the engine must be allowed to run up to some speed before putting on load. Friction clutches or hydraulic couplings are preferred in this case, with the operation of the clutch being achieved through the ship control system. In order to prevent overspeeding of the hydraulic coupling runner when in turbine drive, an overrunning clutch can be incorporated in the gear unit or be made integral with the hydraulic coupling.

COGOG SYSTEMS

The historical background to the Royal Navy's decision to equip the Type 42 "Sheffield" Class of destroyers with a COGOG arrangement has been stated on a number of occasions. A paper entitled "Machinery Installation in the Type 42 Destroyer" presented recently to the Institute of Marine Engineers (2)[1] makes reference to the gas turbine operating experience gained with the Combined Steam and Gas (COSAG) installation in the Guided Missile Destroyer and General Purpose Frigates (4) contributing to the Board of Admiralty decision that all future surface ships should be gas turbine driven. Further experience has been gained with the all gas turbine Combined Gas or Gas (COGOG) conversion applied to H.M.S. "Exmouth."

The gas turbines chosen for the Type 42 are the Rolls Royce Marine Olympus TM3B for main drive and the marine version of the Rolls Royce Tyne RM1A engine for cruise power. The high rotational speed of the power turbine of the Tyne engine make necessary the inclusion of a primary reduction stage, and, after careful consideration, it was decided that rather than have a single complex gear unit incorporating the whole of the Olympus and Tyne gearing, it was preferable to use a main gear unit and a separate primary gear to be fitted to the Tyne as part of a module, the gear ratio chosen to suit the gearing included in the main unit. With this arrangement, as long as the ratio of powers between the Olympus and Tyne engines remains the same, the Tyne module can be used with other main units whatever the propeller speed concerned.

The Tyne engine drives the primary unit through a torque tube and diaphragm type flexible coupling. Diaphragm couplings are also used between the primary unit and the main unit to accommodate the misalignment possible between the flexibly mounted engine module and the rigidly mounted main gear unit. In order to keep the machinery length as short as possible, the length of torque tube necessary to accommodate the relative movement possible under shock conditions has been pased through the low-speed shaft, thus allowing the two units to be close coupled.

The double helical gears are gas carburize hardened, and the teeth profile ground to a standard of accuracy at least equal to AGMA 390.03 Grade 12 on Maag machines. Tip, root, and end reliefs are applied as appropriate. As the power turbine is only available for one direction of rotation, an idler gear is introduced into the gear train for the port set, thus providing

1 Numbers in parentheses designate References at end of paper.

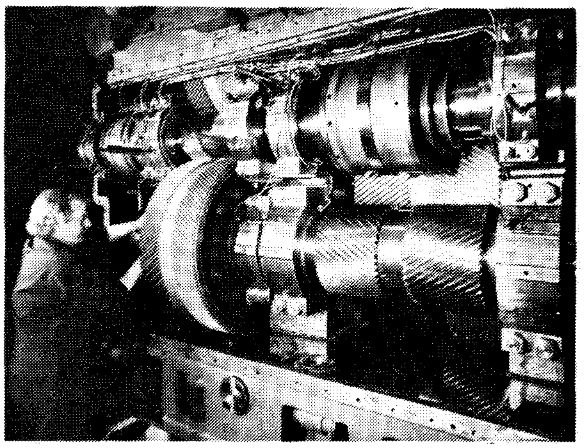

Fig. 3 R.N. Type 42 unit with side covers removed

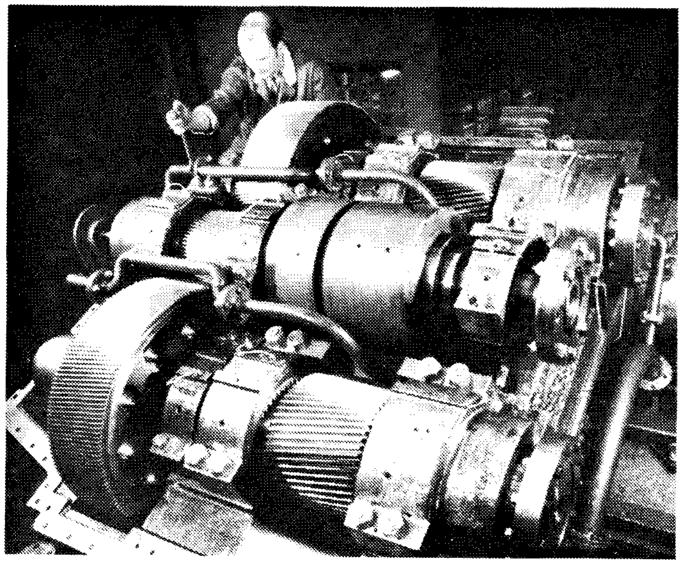

Fig. 4 Open view of unit for Vosper Thornycroft Mark 5 and Mark 7 fast destroyers

a reversed rotation into the main unit. The positions of the input and output shafts are not changed and externally the port and starboard primary units are identical (Fig. 1).

Full load testing was carried out on development gear units prior to dispatch, and considerable running has since been undertaken by Rolls Royce. Some of the problems experienced and the remedial work carried out are discussed in the paper presented to the 1974 Conference and entitled "A Cruise Gas Turbine for Naval Ships" (3).

The main gear unit is the conventional dual tandem, articulated, locked train arrangement, and, in order to meet the conditions imposed by the shaft position in the ship, the primary gears have been moved around the main wheel to a vertical position. Having matched the input speed from the Tyne engine by the primary unit, the inputs from both the Olympus and Tyne engines are fed to the same primary pinion, the Olympus at the forward end, and the Tyne at the aft end, with synchronizing clutches in each drive; therefore, all the gears in the main unit are under load when in either main or cruise drive and there are no unloaded "idling" gears (Fig. 2). The double helical gears have gas carburize hardened pinions with the teeth profile ground, the primary wheel rims nitride hardened, and the main wheel rim of through hardened steel. The primary wheels are of welded construction with the rim welded to sideplates and the sideplates welded to a flange formed on the shaft. Careful attention to the design and the development of a manufacturing procedure has resulted in it being unnecessary to carry out any tooth profile or helix rectification after hardening. The main wheel is of bolted construction with the rim bolted to sideplates and the sideplates bolted to the shaft (Fig. 3).

The main gearcase is fabricated using a combination of steel plates and castings to provide a structure which will carry adequately all the loads expected during service. The structure has been analyzed using finite-element techniques to determine stress levels and deflections, and panel sizes analyzed so as to avoid, as far as possible, critical resonances in the running range. Support in the vessel is through three areas located around the main thrust block and at the forward corners in the area of the main wheel.

At the time of writing this paper, the first ship of the class, H.M.S. "Sheffield," has been commissioned and is in service with the fleet. Problems encountered and operating experiences are recounted in the previous Reference (2). The Type 21 "Amazon" class of frigate, also being brought into service at this time, has a propulsion system which is, with minor exceptions, chiefly related to pump drives identical to that described. Three ships are already commissioned with others to follow shortly. H.M.S. "Amazon" was, in fact, the first ship with this machinery to undertake trials and, therefore, experienced the early problems, some of which are referred to in the foregoing paper. The remedies adopted have been applied to the other ships of the class and to "Sheffield" and subsequent vessels of that Class. The comparatively trouble-free setting to work of the later ships is a measure of the effectiveness of the remedies employed.

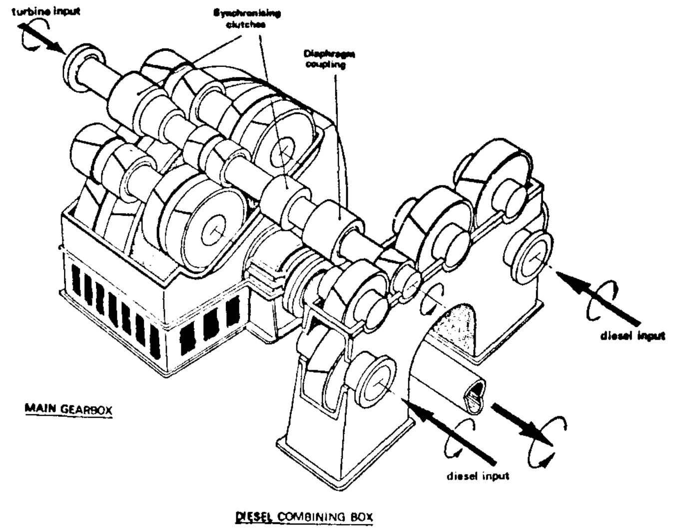

Fig. 5 Gearing arrangement for Vosper Thornycroft Mark 10 destroyer

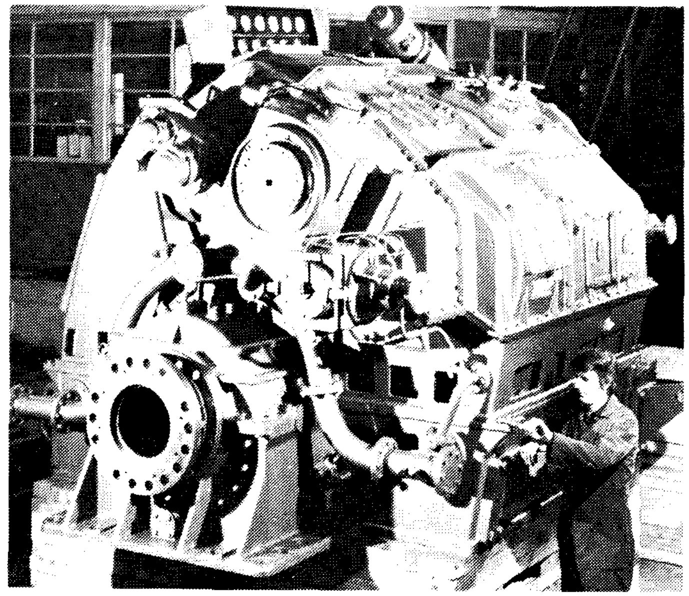

Fig. 6 Mark 10 gear unit from aft end

CODOG SYSTEM

Combined "diesel or gas" systems are usually similar in concept, generally using the same type of high power boost engine and with a diesel engine, or in some cases a number of diesel engines, for cruise power. The diesel engines can be either medium or high speed, and examples are quoted of installations where each type has been adopted.

A typical example of one type of CODOG installation is that fitted in the Vosper Thornycroft Mark 5 and Mark 7 vessels supplied a few years ago to the Iranian and Lybian naval authorities, respectively. In each case, the ship is a twin-shaft ship with each shaft driven by an Olympus TM3B engine for high speed or by a Davey Paxman Ventura 16 YJCM high-speed diesel engine for cruise.

As with the COGOG installation described in the foregoing, the gearing arrangement is the dual tandem, articulated locked train configuration and again, to accommodate the shaft position in the ship, the primary gears have been rolled inboard relative to the main shaft. The diesel engine is placed outboard of the main shaft and aft of the gear unit. The gear ratio required when in diesel drive is such that a primary unit is not required and the cruise drive pinion can be meshed directly with the main wheel (Fig. 4).

The ship is a comparatively small, high-speed vessel and in keeping with the idea of making the gear unit as small as possible a number of features are incorporated. The arrangement of the gears has the primary trains placed aft of the secondary, allowing the main drive synchronizing clutch to be located alongside the primary gears. Thus, the total assembly of gears and clutches is fitted within the length of unit required for gears only. The unit incorporates single helical gears and the gear thrusts are contained with tilting pad thrust bearings. The connection between the primary wheel and secondary pinion is by a cardan shaft rigidly coupled at each end and with the gear loads opposed. A small residual unbalance of loads keeps the line toward the aft end in order to provide stability under running conditions.

All the gears within the unit are hardened, the primary and secondary pinions and the primary wheels are gas carburize hardened and have the teeth profile ground, and the main wheel is gas nitride hardened. The wheel is 1.87 m in diameter and approximately 300 mm facewidth and is constructed as a forged steel rim welded to a center, this assembly then bolted to flanges formed on the mainshaft.

The first of these vessels went to sea about five years ago and is, at the time of writing, in a British Naval dockyard for the first major overhaul. It is too early to assess the condition of the gears, but apart from some clutch trouble caused by mal-operation of the locking control by the operator, no repair work has been called for at any time.

Higher cruise powers are possible by the use of larger engines or, to provide greater

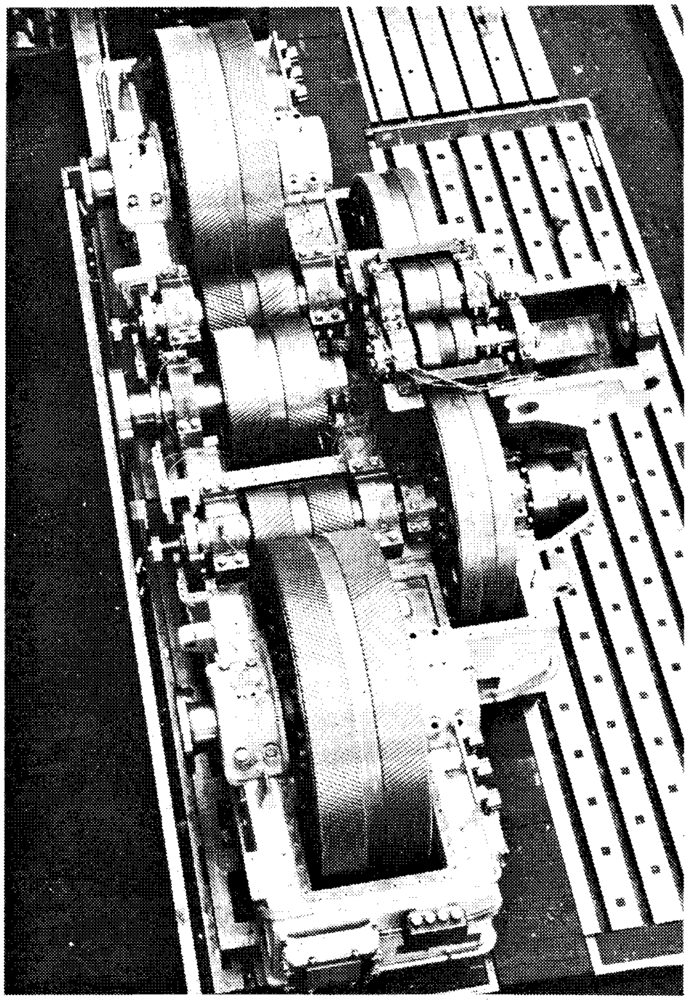

Fig. 7 Yarrow frigate propulsion unit during assembly

flexibility of operation, by a combination of engines. In the Vosper Thornycroft Mark 10 Destroyer, which is being built for the Brazilian Navy, the total cruise power requirement is met by the combining of two diesel engines per shaft, with the ability to run these engines singly or as a pair. Each engine is coupled to a combining gear through a hydraulic coupling and cardan shaft with pin type flexible couplings at each end (Fig. 5).

The propulsion machinery on each shaft of a two-shaft ship comprises an Olympus TM3B turbine at the forward end of a main gear unit and two MTU-16V-956-TB91 high-speed diesel engines coupled to a combining gear which is, in turn, coupled to the main unit. The main unit is, from a gearing aspect, identical to the Type 42 unit described earlier so from a consideration of ease of production, and as the two contracts were going

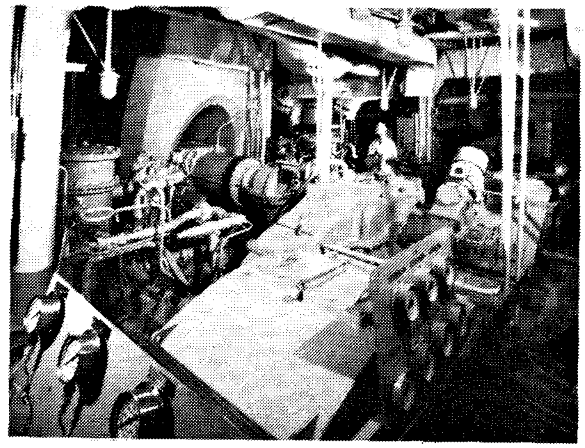

Fig. 8 Machinery room of Yarrow frigate

through the works at the same time, the rotating elements and bearings are made identical, only the gear case being re-designed to suit the ship conditions.

The two diesel engines are placed aft of the main unit and one on each side of the propeller shaft. The combining gear is made to bridge the shaft and the single output shaft is coupled to the main unit by a double diaphragm unit flexible coupling to allow for relative displacements between the two units. The main unit takes the drive through a synchronizing clutch at the aft end of the primary pinion in exactly the same manner as with the Type 42 assembly (Fig. 6).

The high power capability of the Olympus and similar engines has made possible a form of drive for smaller or lower speed vessels in which one main engine is made to drive two propeller shafts. Installations of this type using either one diesel engine for cruise power operating on a CODOG basis have been built and are at sea, while ships using the same general principle but with two diesel engines have been in service for some considerable time.

A typical example of an arrangement using one diesel engine is that fitted in the Yarrow frigate built for the Imperial Thai Navy. In this unit, the gas turbine drive is split in a primary gear section which incorporates an idler gear to give reversed rotation of one side, the split power then being transmitted through cardan shafts to the secondary gear section pinions which, in turn, mesh with their respective main wheels. The diesel engine, in this case a Crossley Pielstick 12 PC2V medium-speed engine, is positioned aft of the unit and inboard of the propeller shaft and drives through a pinion meshing with one main drive secondary pinion. A synchronizing clutch

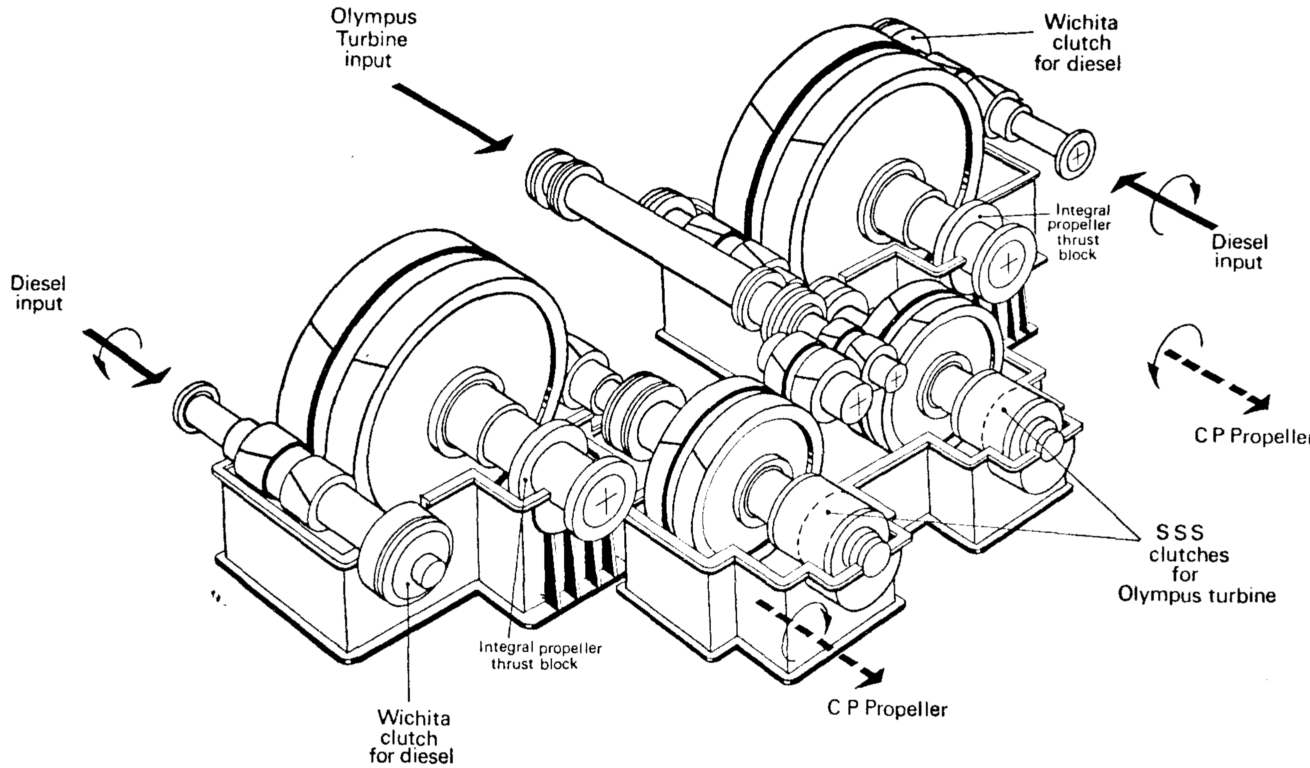

Fig. 9 Diagrammatic layout of gearing for Belgian Navy Escort Vessels

is fitted between the main turbine and the primary pinion and a pneumatically operated friction clutch provides connection and disconnection of the diesel engine (Fig. 7).

The gearing is double helical, the primary and secondary pinions and the idler gear are gas carburized hardened with the teeth profile ground, and the primary and secondary wheels are of bolted construction with the rims of through hardened steel (Fig. 8).

The arrangement of the gearing is, to a great extent, determined by the power requirement for cruise and the configuration within the ship, but one problem with the arrangement described is that the whole gear trains must be accelerated by the one diesel engine when starting in cruise drive. The resulting high torques required to accelerate the primary gears have, on a previous installation with which we were not concerned, created starting difficulties for the diesel engine and vibration problems in the system. We considered that failure to appreciate the possibility of trouble had been primarily due to the fact that the system had not been analyzed as a complete entity but had been treated as a number of unrelated components. In this instance, therefore we insisted that we were involved from the beginning in consultations with the shipbuilder, the diesel engine maker, and a consultant retained by the shipbuilder. We carried out an extensive theoretical torsional and transverse vibration analysis during the design stage which resulted in some modification to torsion shaft diameter and flexible coupling characteristics. To verify the results, an equally extensive experimental analysis was arranged to be carried out during basin and sea trials. Strain gages were attached to the torsion shafts, the signal being relayed by telemetry equipment to a recorder mounted outside the unit. Accelerometers were attached to the bearing caps to measure critical vibrations, the signals being taken to a tape recorder and multi-channel oscilloscope. Two displacement transducers were fitted at 90 deg on each bearing cap to measure radial shaft displacement, these signals also being taken to the tape recorder and oscilloscope.

The results obtained showed the theoretical analysis to be remarkably accurate, and the absence in this ship of any associated problems during the trials and setting to work completely vindicated the trouble and expense of carrying out

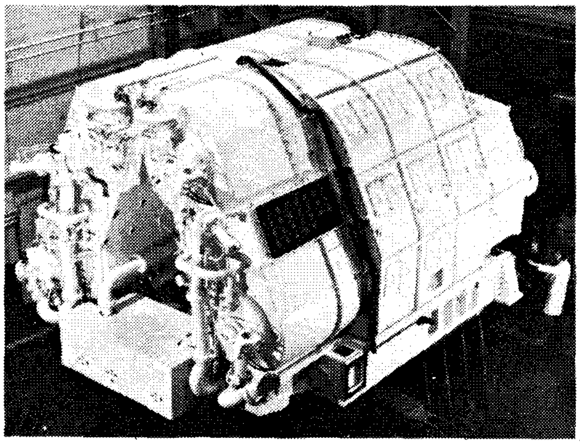

Fig. 10 Reversing gear unit for A/S Cruiser (CAH)

such an exercise.

For a propulsion system requiring more power under cruise condition, and to give greater flexibility in operation, a second diesel engine can be added to what is basically the same gearing arrangement. This is the case with the gearing at present being constructed for Escort vessels of the Belgian Navy. In this instance, the two cruise engines are placed outboard of the propeller shafts, one in the forward engine room with the Olympus engine, and one in the gear room aft of the gear unit. As it is necessary to be able to drive each shaft only with its own associated engine, the gearing is on a three-module basis comprising a primary unit coupled to the gas turbine and two suitably handed secondary units each coupled to a diesel engine. With synchronizing clutches on each output shaft from the primary unit, each secondary can be run independently and the primary gears are only in operation when the gas turbine is in use (Fig. 9).

Again, in this instance, full cooperation between the engine builders and the gear maker in determining the vibration characteristics of the complete system has been achieved and some minor modifications were made to the original proposal, emphasizing the importance of such cooperation at an early stage to avoid possible major problems later.

The double helical gears are hardened throughout, the pinion and idler gears are gas carburize hardened and then profile ground, and the primary and secondary wheels are nitride hardened. Profile grinding is carried out before nitride hardening to produce a good surface finish and the standard of tooth pitch and profile accuracy appropriate for this class of drive.

These examples are representative of the types of units which are possible using the CODOG combination. Many more are sure to be designed depending upon the preference of individual navies and shipbuilders for certain engines and the requirements of ship performance and duties.

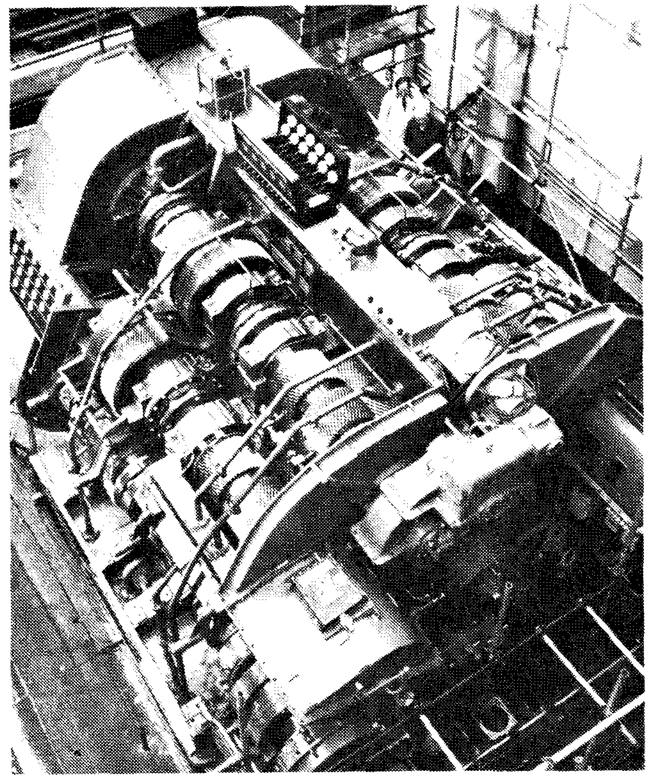

Fig. 11 A/S Cruiser gear with covers removed

COGAG SYSTEMS

Combined systems using more than one prime mover on an "and" basis would appear to provide the best use of the available power. In an "or" configuration, one engine and its ancilliary equipment is being carried at anytime without doing useful work and so must be considered a negative in relation to ship performance. In the "and" configuration, all the engines are combined for the full boost or high-speed condition.

Examples using two gas turbines are, of course, now well known in the "Spruance" class of vessels at present under construction. Two high power engines are coupled through one gearbox, either engine to be used separately for cruise condition and both engines for boost. Reversing is provided by a controllable pitch propeller, although experience with propellers capable of absorbing such large powers did not exist prior to this installation. It will be of great interest to see how the application of current technology and practice works out under these conditions of power and speed.

The Royal Navy has now accumulated considerable experience with the combined steam and gas installation in the County Class guided missile destroyer and Tribal class general-purpose frigates. These transmissions have been discussed at length (4), and any comment which could be made here would be superfluous.

The COSAG systems referred to are associated with a reversing gear unit, although, except for the Type 82 which includes an Olympus turbine, the power capacity is within the experience of controllable pitch propellers. However, when the propulsion requirements for the A/S cruiser (CAH) were being considered, the high power requirement was outside the then proven design capacity of the controllable pitch propeller and the decision to adopt a reversing gear was, to some extent, a foregone conclusion. As discussed in the paper, "Shore Testing of Gas Turbine Ship Propulsion Machinery," presented by Capt. O'Hara at the Conference in 1975 (5), the COGAG reversing gearbox represents the largest unit of its kind designed for use at sea (Fig. 10).

The principle used in this gearbox is relatively simple. From each engine, a maneuver drive ahead is provided through a hydraulic coupling and a direct drive ahead through an S.S.S. clutch, the two alternative drives on separate gear lines which are driven from an intermediate gear train. A speed differential between the two is such that when in maneuver drive, and allowing for the designed slip in the hydraulic coupling, the speed sense across the direct drive S.S.S. clutch is negative, i.e., the clutch cannot engage. To engage direct drive, the coupling slip is increased by emptying the circuit to the point at which the speeds of the two sides of the clutch are synchronized causing the clutch to engage. Further emptying of the coupling completes the disconnection of the maneuver drive. A reversal of the process, i.e., filling of the ahead coupling, will cause the relative speeds of the clutch to become negative with the resultant disconnection of the clutch, thus reverting to maneuver drive.

Also driven from the intermediate gear train is a further line incorporating a hydraulic coupling to provide reverse rotation of the main shaft. Ahead to astern operation is done in maneuver condition and is achieved by filling and emptying the appropriate couplings (Fig. 11).

With a primary gear train in the drive from each engine, the triple reduction gear unit

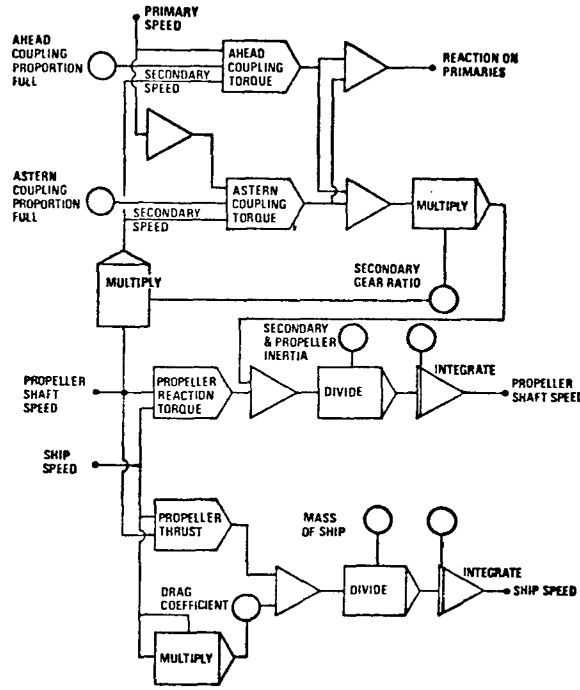

Fig. 12 Block diagram of ship performance simulation

has a total of 19 gears, 55 journal bearings, four hydraulic couplings, and two S.S.S. clutches. As reported in the paper referred to, the gear box weighs approximately 170 tons. Comment has been made that it would seem to be ludicrous to use lightweight aircraft derived gas turbine and then a gearbox of such size and weight, but it must be appreciated that a major feature in fixing the gearbox size is the minimum centers at which the gas turbines can be located while still allowing access between them for servicing.

The design of this unit presented a challenge in that having devised an operating principle and decided the general proportions of the gear elements with regard to diameters, we had no experience of units of this size and type from which to determine peak transient conditions of loading during the reversal operation. This information was necessary to enable use to effectively size gear facewidths, bearing proportions shaft diameters, hydraulic coupling oil flow characteristics etc. To obtain this information experimentally was clearly impossible, so we had to devise an analytical basis from which to derive the necessary data. A ship performance simulation was carried out on the company's design and research department IBM 1130 digital computer. It was apparent that a more comprehensive simulation could be carried out using an analog computer, but as this type of installation was not readily available to us and in the interest of speed and economy, it was decided to proceed on the digital machine. The exercise is discussed as an example of using simulation techniques in a paper (6) presented to the International Marine and Shipping Conference 1973 in London (Fig. 12).

The operation of the ship was simulated using a program based on the IBM 1130 continuous system modeling program where the model can be treated as if for an analog computer. The block diagram for the major part of the simulation is shown and centers around the three acceleration equations:

1 For the turbine and primary gearing
2 For the propellershaft and associated gearing
3 For the ship as a whole

Information relative to turbine, propeller, and hull characteristics and properties of hydraulic couplings, gear inertias, etc. were fed into the program. Various modes of operation were analyzed and the results provided useful information relating to:

1 The maximum torques to which the gears will be subjected during crash reversals; hence, tooth safety margins can be determined.
2 Using the above, the elastohydrodynamic conditions at the tooth contact, i.e., the oil film thickness and temperature under full load and transient reversing condition.
3 The optimum oilflow rate and speed of operation of coupling scoops to avoid overheating of the couplings.
4 The heat to be dissipated from the coupling oil and the size of cooler to be employed.

This exercise produced values which were used at the design stage, and although a more sophisticated analysis has since been carried out by a consultant on behalf of the Ministry of Defense, no fundamental changes were found to be necessary.

As reported by Capt. O'Hara (5), the first completed gear unit has been the subject of an intensive shore testing program and a full description of the plant and the progress and achievement to the date of his article is included therein. It is sufficient here to record that, at the time of writing, testing has been virtually completed. The power-injection trials have been completed successfully and the only trial still outstanding is the endurance running. This trial has been re-scheduled to be carried out after the unit has been refurbished and brought to the same standard as the ship gears, which have had any modifications found advisable at Ansty incorporated during manufacture.

Running, which has taken place since the preparation of Capt. O'Hara's paper, has proved the modifications carried out to the high-speed bearings, but some trouble has been experienced with a location bearing on one hydraulic coupling drive line due to a wrongly adjusted shaft position during assembly. The partial remedy referred to in relation to the main shaft bearings has been totally effective and we suspect could have been adopted in the ship boxes without it being necessary to make the radical change which has, in fact, been carried out.

There is little doubt that the value of shore testing has been well proven in this installation, and it is felt that we can now proceed with confidence to the ship installation.

CODAG SYSTEMS

In spite of what would seem to be the advantage of using both cruise and boost engines simultaneously, very few such installations exist. The only examples which come to mind are the Federal German Navy's "Koln" class and the Italian Alpino class. The reason for this is not very clear, the engineering of the transmission is not difficult, but it may be that the complexity of the control to be applied to ensure power matching could be a deterrent.

The design of unit to be employed will depend on the relative powers of the two engines, e.g., with two prime movers of the order of 4000 to 5000 hp a scheme using a torque converter for matching the speeds has been proposed, but with a cruise engine of the same order of power combined with a boost engine of Olympus or equivalent power, a two ratio arrangement in the diesel drive would appear to be a better proposition. Schemes have been prepared on this basis, but as yet no requirement to complete the design has come forward. No obstacle, which cannot be overcome, can be foreseen should the need for this form of drive arise.

FUTURE DEVELOPMENT

The development of transmission systems has been dictated, to a great extent, by the development of turbines and other types of engines, the development of ships, and their operational characteristics.

With the present generation of high power gas turbines the need for combined systems will still exist and combinations of gas and nuclear steam, gas and multiple diesel, and multiple gas turbines are still a possibility.

The development of the new range of large turbines with considerably improved fuel characteristics could eventually remove the need to provide a cruise drive, the main engine being sufficiently effective at low power and speed operation. It only remains then to develop the reversing turbine and the gearing requirement will revert to that previously required for steam turbine operation and with no requirement for reversing drive, controllable pitch propeller, or combined machinery installation.

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