GEARING TECHNOLOGY IN THE NAVAL MARINE CONTEXT

BY

LIEUTENANT COMMANDER S.N. DAY MSC, CENG, MIMAREST, RN
COMMANDER P.D. GILBERT, MSC, MA, CENG, FIMECHE, FIMAREST, RN
(Warship Support Agency Marine Propulsion Systems IPT)
AND
PROFESSOR D.A. HOFMANN, OBE, CENG, MIMECHE
DR B.A. SHAW, PHD, BENG, MIM
(Design Unit, University of Newcastle)

This is an edited version of the paper that was presented at INEC 2004 – Marine Technology in Transition. *Organized by the Institute of Marine Engineering Science and Technology and held in Amsterdam, 15 – 19 March 2004.*

ABSTRACT

The trend towards Integrated Full Electric Propulsion has led some commentators to infer the demise of geared propulsion solutions in naval platforms. The widening scope of design considerations, specifically the development of multihull platforms and the requirement to propel vessels in excess of 35 knots, bring the Marine Engineer to the limitations of electric motor technology. This article outlines the research work conducted under the management of the Marine Propulsion Systems Integrated Project Team, part of the UK MoD's Warship Support Agency, to support and enhance in-service geared solutions. It also discusses, in broad outline, the advances in technology available to tailor gearing designs for noise-critical applications. It is the intention to demonstrate how benefits derived from in-service applications can contribute to the inclusion of gearing in marine propulsion systems for future platforms. Current naval combatant applications have demonstrated the success of pull-through from fast ferry type systems with direct-mechanical drive Waterjet and various Prime Mover combinations. The article explores the possibilities of geared electric designs and how these hybrid options may offer effective solutions when considering the weight and volume limitations in a frigate sized (5,000 tonnes) high-speed vessel.

Introduction

The Marine Engineer in Transition: does this statement really need to be made? Transition is the constant in marine engineering – coal to oil, piston to turbine, mechanical to electric to name a few of the key themes. The philosophical commitment to Integrated Full Electric Propulsion (IFEP) has prompted the thought that mechanical power transmission in the Royal Navy will be eradicated from 'Frigate and greater sized vessels' by the end of the current tranche of acquisition programmes.

At this point yet another transitional theme emerges: 'Fast Ship'. This emerging need from the operating communities lend weight to requirements that specify a top-speed in excess of 35 knots. To support this the Marine Propulsion Systems Integrated Project Team (MPSIPT) is currently managing a development strand with the University of Newcastle to look at high speed propulsion; prime mover to propulsor encompassing electrical and/or mechanical power transmission systems under Marine Engineering Development Programme (MEDP) funding. The initial drive of this work will be discussed later in the article.

The Through-Life Costs (TLC) of currently installed geared systems are proving to be significantly higher than originally anticipated and it is undeniable that the perceived disadvantages and weaknesses of mechanical power transmission in the Royal Navy have formed part of the supporting case towards IFEP. In mitigation, the Transmissions Group of the MPSIPT have invested in a series of programmes to reduce TLC whilst also enhancing the capability of main propulsion gearing for future platforms.

Gearing Issues – Reliability

With the pressure to increase power density, the reliability of geared propulsion systems in Royal Naval service has fallen short of the expectation of the operators. In the case of, say, gas turbine engines, the life between overhaul, the overhaul procedures and the expected reliability (hours between significant failures) are well defined. Main propulsion gearing pre-dates this rigorous approach to the assessment of life and reliability. It is clearly a false assumption that 'gearing' would somehow have an infinite life with 100% reliability. However, very high reliability, in excess of 10^7 hrs between significant failures, can be achieved. Indeed, it is regularly achieved by merchant marine gearboxes. In the Naval context, this would represent a probability of failure of less than 1% in a 30 year ship life. However, to achieve this reliability of the total gearbox system, gears, bearings and other components must be designed to stress levels commensurate with the required reliability, that is to 4 (or even 6) sigma stress levels (Mean fatigue strength less 4 to 6 standard deviations). It is now recognized that there must be a change in the philosophy of Naval gearbox design from the past emphasis on achieving very high power density to a design strategy which considers reliability as a principal objective. Research in support of the design of high reliability, high availability gearing has been conducted.[1] The work carried out for the UK MoD has identified that the weight, size and initial purchase cost penalty for such high reliability gearing is in the range 5-15%[2] relative to current Naval gearboxes. Small changes to gearbox design generate significant improvements in reliability. The technologies are proven and available for future marine gearboxes.

Bearing problems were a major issue with Naval gearing in the 1980's, due largely to poor control of bearing clearances, lubrication entry and journal roundness. Bearing maintenance, in some cases unnecessary, is a major TLC for Naval gearboxes. In 2003 MPSIPT initiated a programme of work to develop new bearing materials with enhanced life and reliability to reduce the TLC of gearbox bearings in current and future gearboxes. However, as COOPER[3] wrote in 1987:

> '... probably the single cause of the biggest loss in operational time is...poorly locked fasteners'.

To this could be added power take-offs, interlocking, micro-switches and other small standard components that were not selected or fitted with sufficient regard for reliability.

Naval Gearing defects

Currently, the most serious naval gearing issues are associated with gear teeth. Gear tooth degradation has never caused a catastrophic failure of a gearbox, that is a failure that has resulted in a gearbox transmitting power. However, such defects require power limitations to be applied to reduce the risk of further degradation in performance. In most cases the replacement of the damaged gear elements has also been undertaken to restore operational capability.

Over-stressing of components is clearly a cause of their failure. This over-stressing can be attributed to the operating regime, component interaction (particularly under dynamic loading) or weaknesses (however slight or localized) in material strength. Failures are seldom attributable to single factors yet the drive for increased power density has identified areas of gear performance and operation that were not comprehensively charted at the time key design assumptions were made. Due regard is also required to the constantly evolving operating envelope of ships which can occasionally challenge these design assumptions. Notwithstanding this evolution it is also apparent that the comparison of 'idealised' operating profiles with those actually experienced in the live systems are crucial in maintaining reliable and available plant.

In addition to these operational factors; component interaction and material weakness causal factors include:

- Gear mesh misalignment.

  This is discussed in greater detail later under research, but has the effect of increasing bending and contact stress in gears significantly, in some cases more than doubling gear stressing.

- Micro-pitting

  This has been a significant factor in failures of case carburised gears run in high specification EP oils. Micro-pitting and the associated small cracks have been identified as precursors to tooth failure (FIG.1).

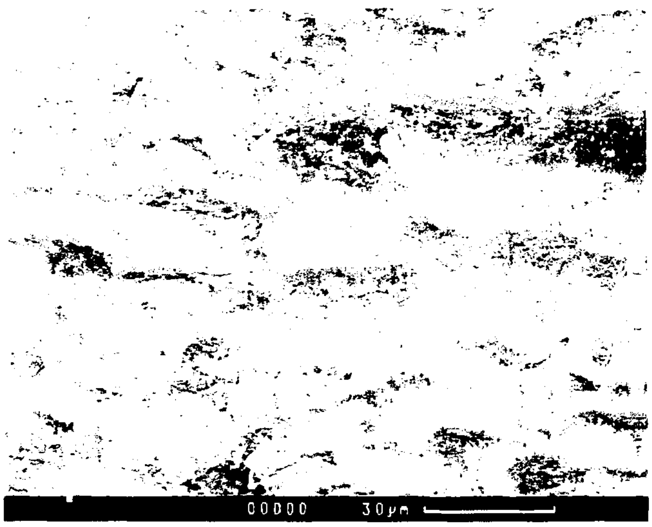

FIG.1A – MICRO-PITTED SURFACE

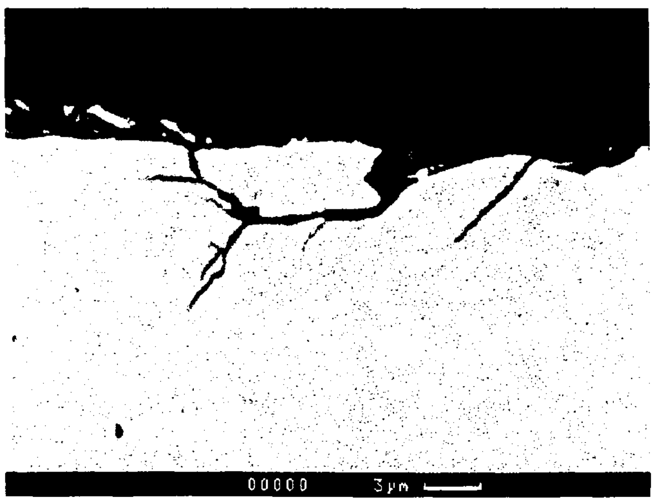

FIG1B – SECTION THROUGH MICRO-PITS

- Macro-pitting and machining marks (hobbing tears) have been implicated in the only case of 'classic' root bending fatigue failure witnessed in the failure of through hardened main wheels, (FIG.2).

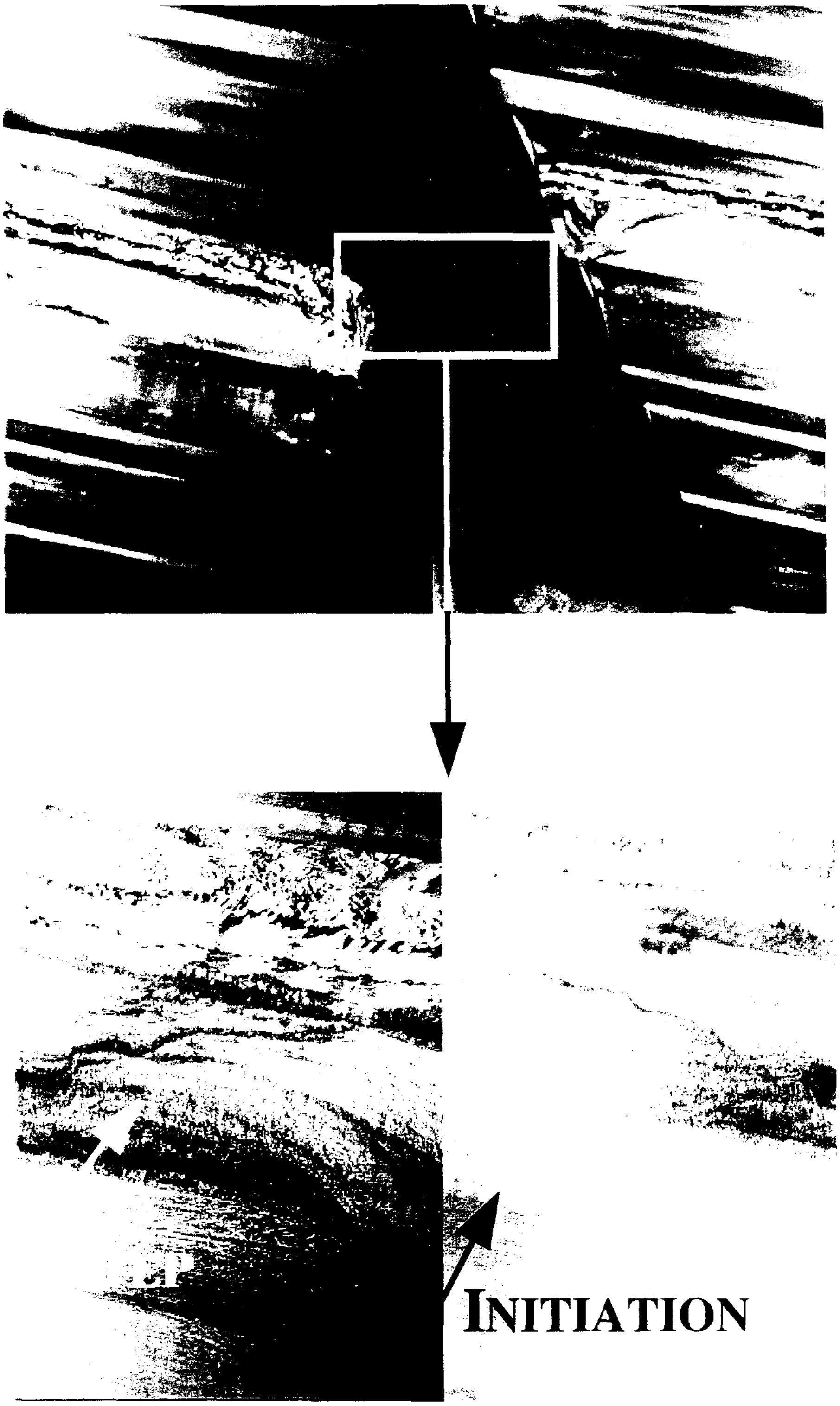

FIG.2 – TOOTH FRACTURE INITIATING FROM MACHINE MARKS

- Case-core junction failure, due to insufficient case thickness or excessive residual stress gradients, has been contributory to the failure of induction hardened main wheels. (FIG.3) shows a typical tooth fracture of an induction hardened gear tooth with case-core junction initiation.

FIG.3A – FRACTURED TOOTH

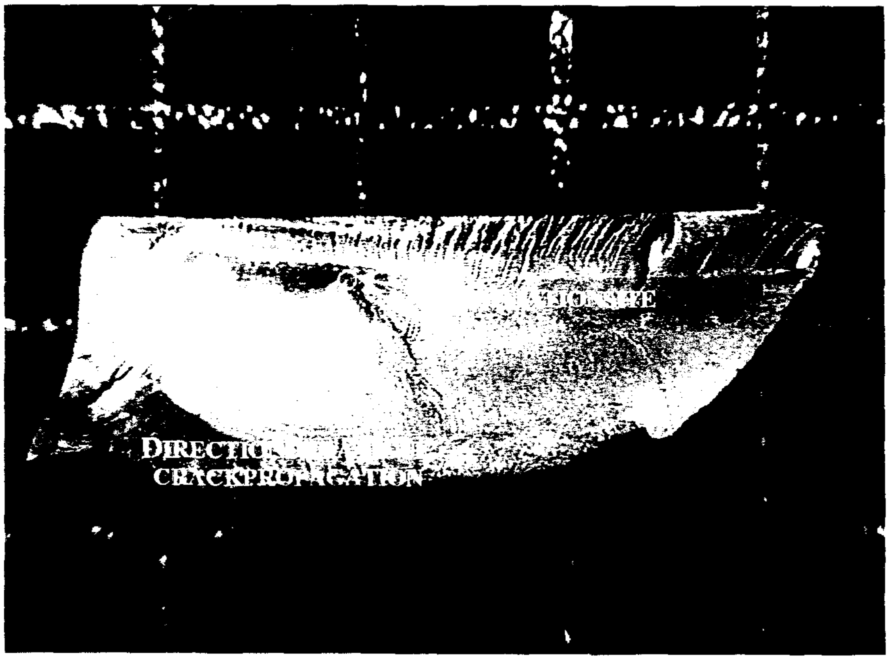

FIG.3B – INITIATION SITE AT CASE/CORE JUNCTION

- The drive for high power density exposed shortcomings in the metallurgical cleanliness of the steel, the detailed tooth profile geometries and the quality assurance processes followed.

Naval Gear Research – 1950...1978

The Royal Navy embarked on a comprehensive programme of gear research and development between the 1950's and the 1970's in response to gearing problems that had occurred in HM ships in the Second World War. This research was carried out collaboratively with the UK gearing industry. Much useful work (over 500 reports) in the fields of fatigue strength (bending and surface), scuffing and gear noise was carried out, as well as work focussed on investigating heat treatment and distortion. Relatively little effort was expended in refining the gear stress procedures, which continued to be based on the 'K Factor' (surface fatigue), and no significant work was directed toward understanding gear and gearbox system reliability.

This research resulted in the introduction of finish-ground case-hardened (case carburised and induction hardened) gears for main propulsion gearboxes. This facilitated a large increase in torque transmission (and power density) and a commensurate reduction in gearbox size and weight and a significant reduction in gear noise and vibration, with no apparent adverse effect on reliability.

By the 1980's the Royal Navy considered that propulsion gearing was mature, without significant noise or performance problems. In 1987 COOPER had the confidence to write that,

> 'Gear problems in Royal Navy warships are infrequent....'

Naval Gear Research – 1992...present

New research was instigated in the early 1990's resulting in a programme of work being carried out by UK University research groups and Government research agencies. This work has been directed, and continues to be directed, at understanding the root causes of incipient gear defects, and at developing solutions to enhance the reliability and availability of current and possible future main propulsion gearing. The principal strands in this work have been:

- Developing robust techniques for measuring in-service gear mesh alignment and assessing gear stressing levels.
- Developing an accurate, comprehensive gear stress analysis and gear noise prediction technique – Design Unit Gear Analysis for Transmission Error and Stress (DU-GATES).
- Experimentally validating the gear stress analysis procedure DU-GATES and proving the correlation between calculated Transmission Error (TE) and gear noise.
- Understanding bending fatigue strength of case carburised and induction hardened gears and developing higher bending strength gears.
- Understanding surface fatigue strength, in particular micro and macro-pitting and developing gears with higher surface fatigue strength.
- Improving understanding of gear heat treatment and developing better quality assurance using micro-magnetic inspection techniques in 'Barkhausen Noise' (BN).
- Developing new gearbox designs that are less sensitive to running misalignment, have intrinsically low noise levels, high reliability and reduced TLC.
- Developing techniques for preventing gear case explosions.

These research topics are outlined below.

Running Misalignment

The design codes for naval gearing have been based on the assumption that in operation the misalignment between gear teeth is of similar magnitude to the manufacturing tolerances for individual gear elements.

Investigations of gear failures since 1989 have shown that operational mesh misalignment has been a significant factor in a number of failures, with measured operational mesh misalignments up to 10 fold greater than assumed in the design. This resulted in gear stressing up to 100% greater than permitted by the design codes as illustrated in (FIG.4).

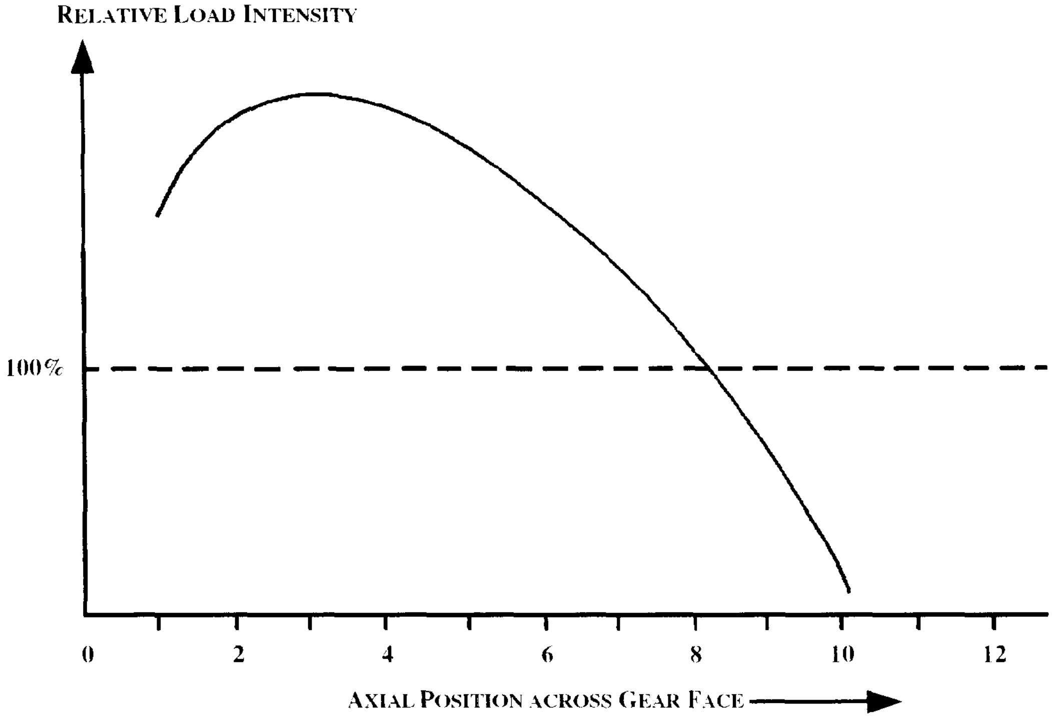

FIG.4A – LOAD/STRESS DISTRIBUTION ACROSS FACE WIDTH – MISALIGNED

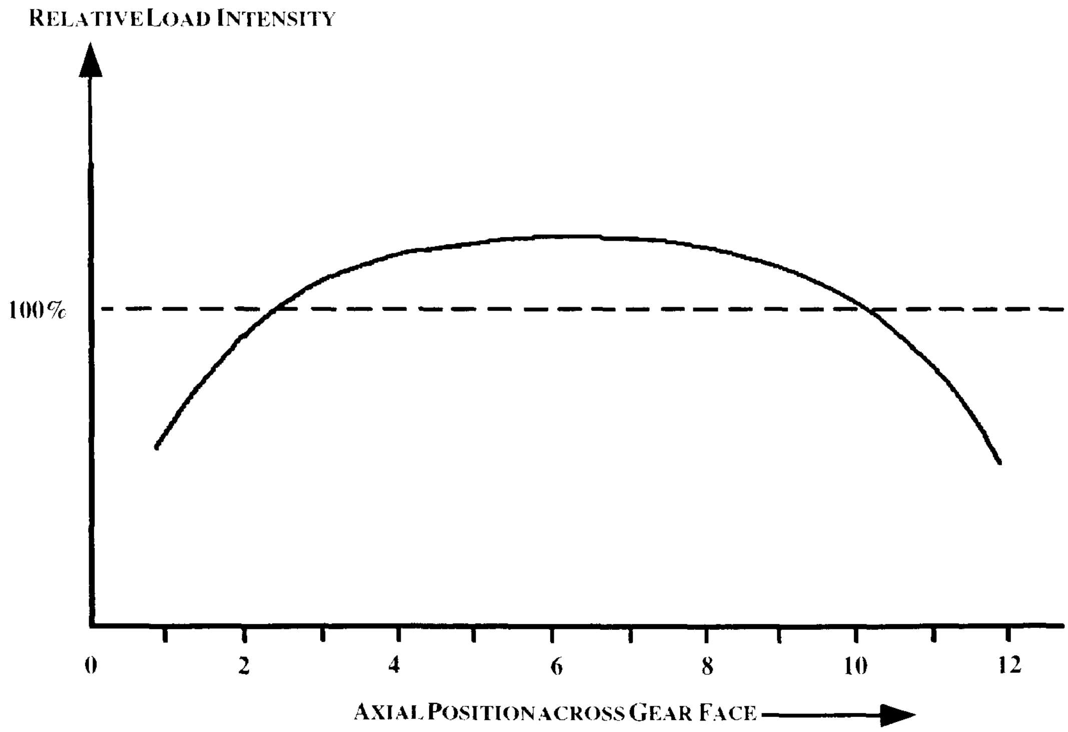

FIG.4B – LOAD/STRESS DISTRIBUTION ACROSS FACE WIDTH – ALIGNED

Gear Stress Analysis – DU-GATES

DU-GATES is a hybrid analysis technique based on Finite Element (FE) Analysis for calculating gear stressing and TE.[4] This can take account of the very fine detail of gear geometry, crowning, lead correction, tip and root relief as well as mesh misalignment, which all significantly affect gear stress and TE. A block diagram of the calculation procedure is shown in (FIG.5).

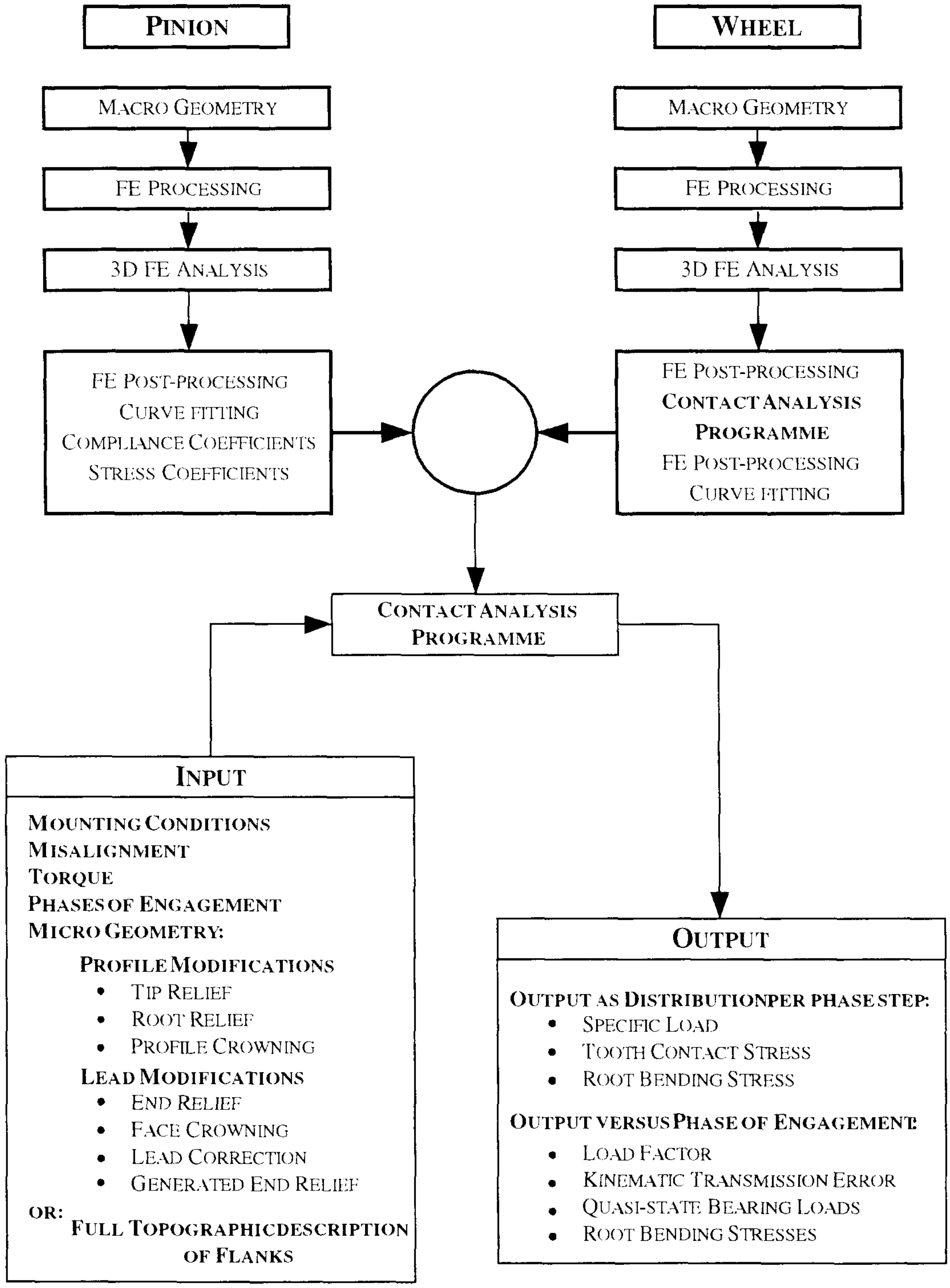

FIG.5. – DU-GATES SOFTWARE PACKAGE – BLOCK DIAGRAM

The principal uses for DU-GATES are as a design tool to optimize the gear macro and micro-geometry for:

- Minimum stress.
- Minimum TE and hence gear noise.

It was the first time that gearing could be optimized for low noise at patrol speed and maximum load-carrying capacity at full power.

It is also a useful tool for investigating failures and the effect of gear damage on stress and hence on in-service life. Design optimization for low noise with DU-GATES can result in a reduction of TE and hence gear noise and vibration by as much as 20 dB, and reductions of contact and bending stress by up to 25%.

Experimental Gear Noise and Vibration Research

A unique resource for gear noise and vibration research was established by the MoD in Newcastle in 1994. The Marine Gear Research Rig (MGRR) is the largest and most refined facility worldwide for experimental gear stress and noise research.[5] It is capable of testing gears of up to 600mm diameter and 250mm facewidth at powers up to 8 MW at peripheral speeds up to 60 m/s. A general view of the rig is shown in (FIG.6).

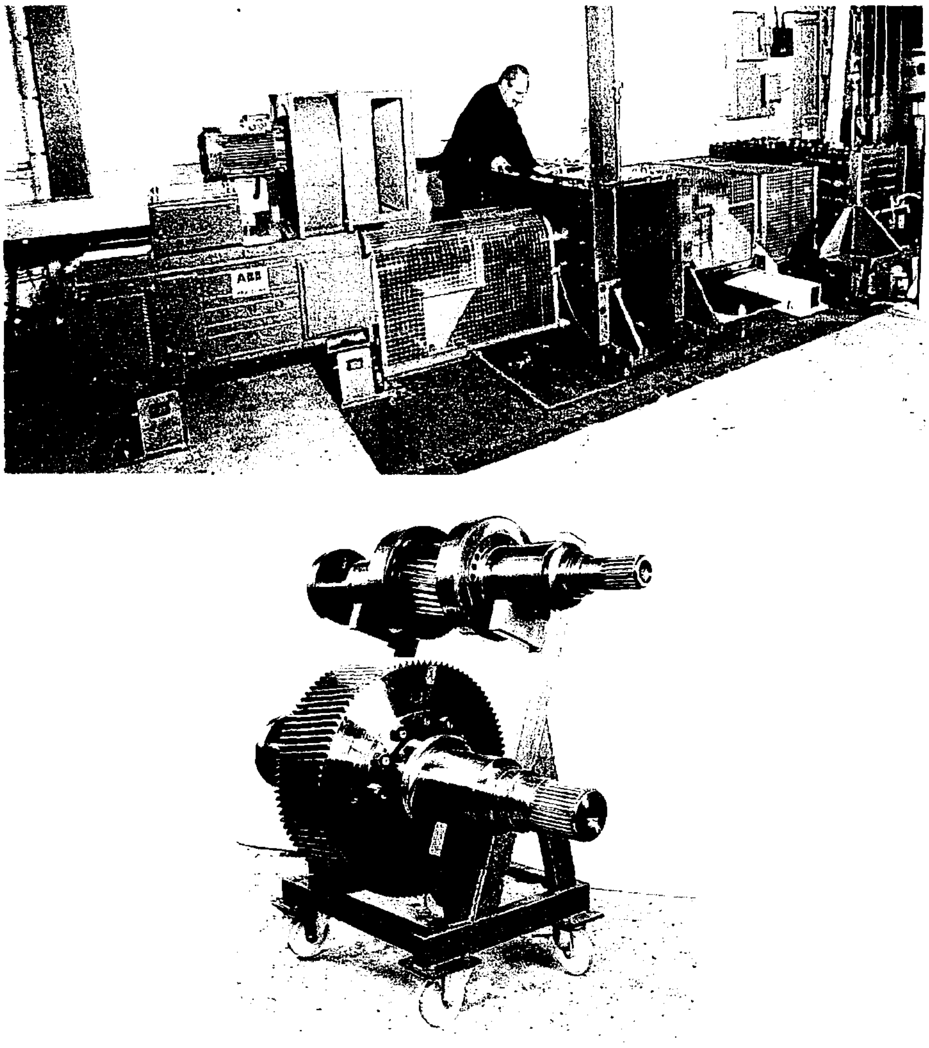

FIG.6 – MGRR RESEARCH RIG AND TYPICAL TEST GEARS

The principal objective for the research with the MGRR has been the validation of the theoretical gear analysis program, DU-GATES. A range of gear designs, double helical and single helical with and without thrust cones, have been analysed with DU-GATES, and subsequently tested on the MGRR. Tests have been conducted over a wide range of torques (0 -15kNm) and speeds (0-5500 rpm) and mesh misalignments in the range ± 100 μm/800mm. (FIG.7) shows the relationship between the dynamic bearing force at Tooth Contact Order (TCO) and the calculated TE for these tests, showing a clear correlation between calculation and measured gear noise excitation. The different point icons are attributable to different specific data sets from representative gears under test.

CORRELATION BETWEEN CALCULATED TE AND MEASURED PINION AFT BEARINGLOAD (OUT OF RESONANCE)

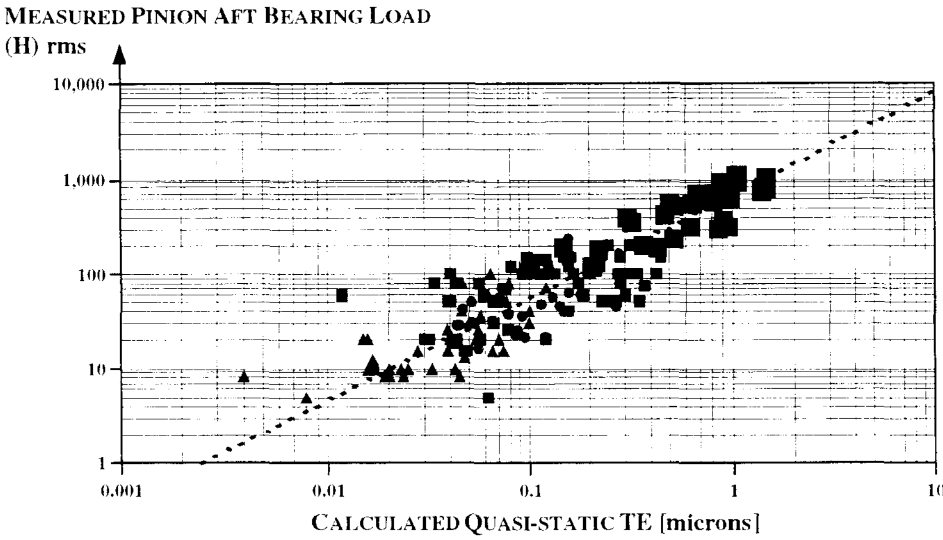

FIG.7 – MEASURED BEARING FORCE AT TCO (PINION AFT BEARING) V COMPUTED TE

A programme of MEDP funded work is currently underway to confirm the performance of special 'compliant' bearings, which have been designed to significantly reduce mesh misalignment, reduce gearcase excitation at TCO, reduce gearbox build and maintenance costs and improve gear reliability in the next generation of Naval gearboxes.

Material Improvement – Bending and Contact Fatigue Strength

The work undertaken has also made it clear that the gear material fatigue strength achieved in naval gears was not as great as had been assumed in the design. The drive to increase power density in marine gearing which dominated the early research resulted in the use of statistical stress distributions for the design of gearing approximating, at best, to a one sigma fatigue strength. Current design practice would suggest 3 to 4 sigma strength for high reliability and integrity gearing. These factors led the MoD to initiate a significant programme of research into both bending and contact (surface) fatigue strength.

Bending Fatigue Strength

A number of MoD research programmes and collaborative research with the UK gearing industry, co-ordinated through the British Mechanical Power Transmission Association (BMPTA), have investigated the bending fatigue strength of case carburised and induction hardened gears. These have shown that the bending fatigue strength stipulated for gear design in the Naval Engineering Standard and also the international gearing standard ISO 6336 was significantly optimistic, and could not be achieved even with current, clean steels. At the time the RN's current gearboxes were manufactured, the steel would have been of lower quality, and hence even less strong. It was found that, irrespective of the steel and the case hardening process used (carburising, induction hardening, nitriding) very significant improvements in gear fatigue strength, up to 70%, could be achieved by controlled shot peening which imparted high compressive stress in the gear root. This also had the beneficial effect of reducing the variability of fatigue strength, so that the standard deviation of strength was reduced from typically 6-10% to 3-6% of mean strength. When the design of high reliability gearing is considered, where the permissible stress level should be the 4 sigma strength, the benefits of shot peening can exceed 100%. This work has led to a better understanding of bending fatigue strength and gear reliability in respect of this type of failure as well as the development of higher strength gears.

One weakness of the completed research is that fatigue testing was terminated at 10^7 load cycles. That is at 50 times the bending fatigue strength endurance limit ($\approx 2.10^5$ load cycles). There is evidence from recent failures that fatigue strength drops off at very long life. Further work is planned to investigate bending fatigue strength at lives in excess of 10^8 gear revolutions, with the tests conducted in hot oil.

Surface Fatigue Strength

Micro-pitting ('grey staining' or 'peeling') is the most widespread factor limiting gear performance across all fields of application – aerospace, automotive, industrial, power generation. A programme of research has been carried out collaboratively with the BMPTA to investigate and quantify this problem. Disc and gear testing has been supported by the development of a sophisticated 3D micro-elasto-hydrodynamic lubrication (μEHL) model by the University of Cardiff. This has enabled the calculation of lubricant film pressures and thickness for typical ground gear surfaces and the prediction of local asperity contact. The modelling of pressure distribution in a typical gear mesh predicts peak pressures two to three times greater than the nominal Hertzian contact pressure.[6]

This work has shown that micro-pitting is a fatigue related phenomena, with a defined fatigue strength threshold below which micro-pitting does not occur for a given set of gears and a specific lubricant and operating temperature. Unlike bending fatigue it is not, however, strictly a gear material property, but is significantly affected by small changes in surface finish, oil additive chemistry and operating temperature.

One outcome has been the identification of areas of plastically deformed tempered martensite at the asperity scale. These appear to be the result of plastic deformation of the surface during initial running. The profile and scale of these tempered regions bear a strong resemblance to the geometry of typical micro-pitting – as shown in (FIG.8).

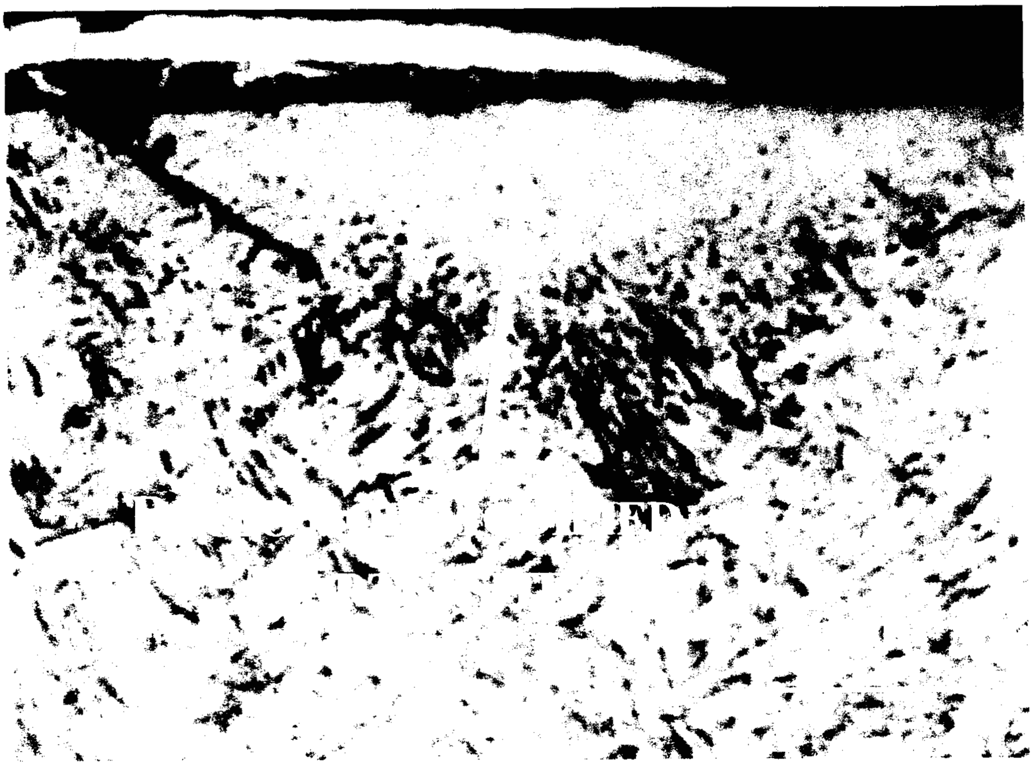

FIG.8A – AREA OF TEMPERED MARTENSITE

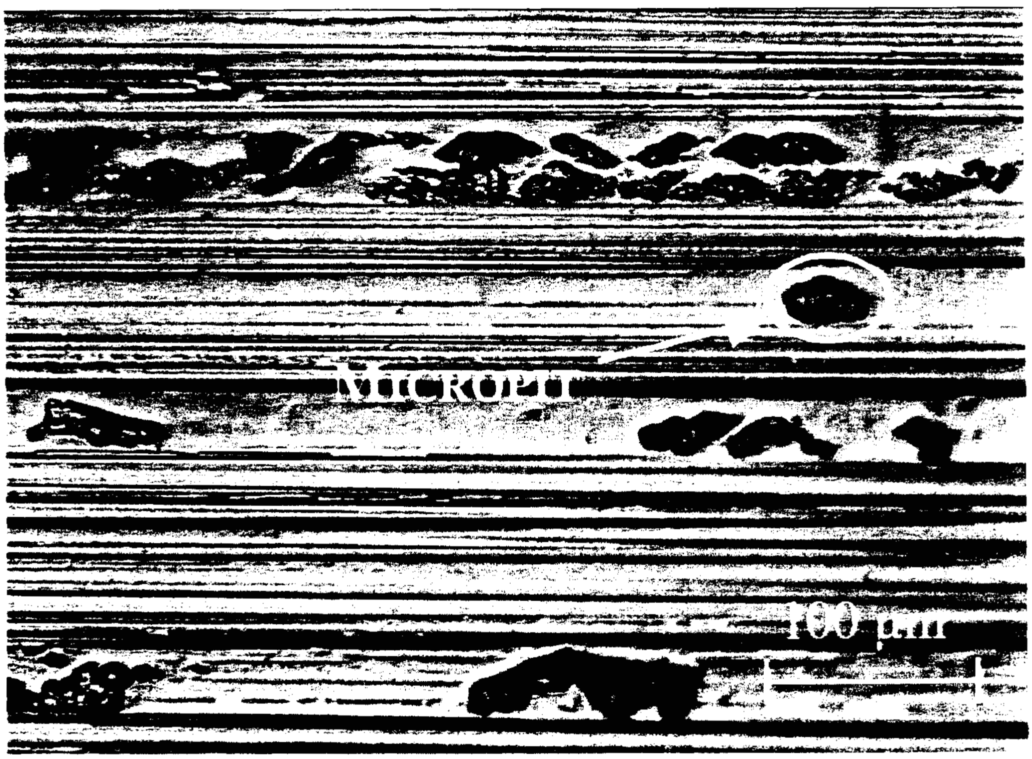

FIG.8B – TYPICAL MICROPIT

These observations are being further investigated by the Universities of Newcastle and Cardiff with the objective of better understanding the mechanism of micro-pitting and the development of surface treatments and new lubricants which could prevent the onset and progression of this type of failure.

Gear Alignment

The traditional method of setting the alignment of gears in the gearbox during initial build has been to set the bearings to achieve a defined contact marking pattern using soft engineers blue in the static case and a hard marking-off lacquer, typically 'Talbot Blue', at full power. Unfortunately the discrimination of the process is poor. Significant mesh misalignment, sufficient to double gear tooth stressing, could not always be identified. The use of strain gauges to measure load distribution is the only accurate method of quantifying mesh misalignment. Nevertheless, effort has been expended seeking to improve the accuracy and repeatability of the traditional contact marking technique, which is cheap and quick and can be carried out by any appropriately trained person.

Heat Treatment and Grinding Burn

Heat treatment and grinding problems such as thin case, low hardness and temper burn have been implicated in a number of failures of Naval gearing. MPSIPT has instigated a substantial package of work to develop non-destructive quality assurance techniques based on the ferro-magnetic properties of the steel. The technique used is called BN and is based on the analysis of the magnetic response of a steel to an applied, varying, magnetic field. The rate and frequency of alignment of the magnetic domain with the applied magnetic field is a function of hardness (metallurgical composition) and residual stress of the gear. Its use for detecting grinding burn is already well proven and it is being routinely used for the QA of the ASTUTE class gears. (FIG.9) shows the relationship between BN and the change in residual stress due to grinding burn.

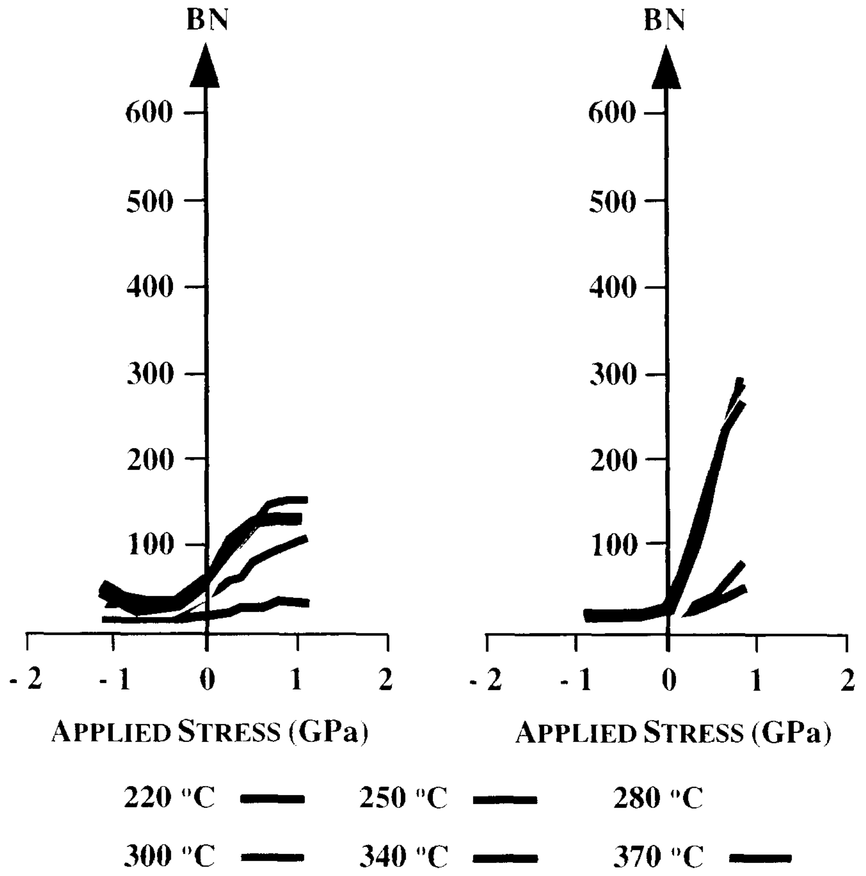

FIG.9 – RELATIONSHIP BETWEEN RESIDUAL STRESS AND BN FOR TWO GEAR STEELS

The BN technique is currently being investigated by the University of Newcastle to develop QA procedures for:

- Case depth.
- Hardness profile.

BN is being evaluated as a non-destructive technique for quantifying cumulative contact fatigue damage, which could be applied to life assessment of all types of highly stressed components. The work conducted under this programme has achieved widespread recognition as being at the forefront of the development of this technique in this application. Recently published work[7,8] illustrates the promise that BN shows when scanning with different magnetisation frequencies and the depth of penetration that can occur on increasing the amplitude of the signal.

Modular Self Aligning Gearcase

The philosophy behind the design of current RN gearboxes has been to make the gearcase as stiff as possible so that mesh alignment is maintained under all conditions. However, within the reasonable constraints of size and weight, it has proven to be impossible to achieve the required gearcase stiffness. Bearings are having to be misaligned statically to compensate for operational mesh misalignment at high torque. A project has been undertaken directed toward the development of a self aligning, modular gearcase, which will more closely allow for perfect gear mesh alignment at all operating conditions while still being inexpensive to manufacture.

A concept design for a dual input, single output three stage gearbox of this type is shown in (FIG.10).

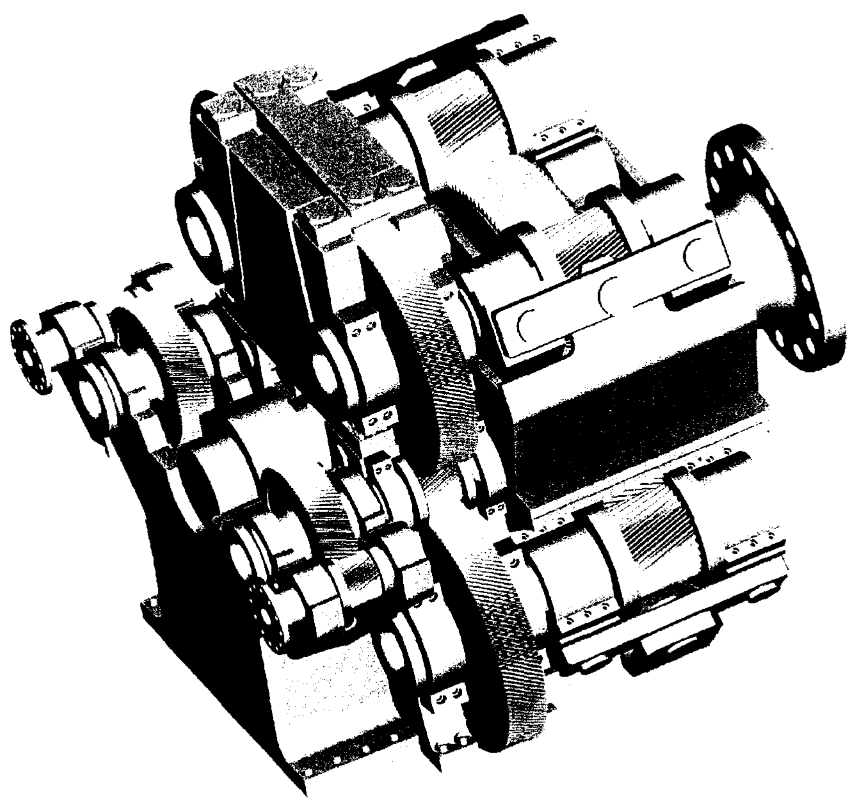

FIG.10 – MODULAR SELF– ALIGNING GEARBOX ASSEMBLY