RECENT RN GEARING EXPERIENCES

BY

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ABSTRACT

This article presents a summary of recent RN experiences with marine propulsion gearing. The causes of RN gearing failures are now well understood and we have demonstrated that we can design and manufacture gears that will withstand the applied stresses and operate very quietly. Despite the move to Integrated Electrical Propulsion systems, there is a continuing need to support gearing for the foreseeable future in the current surface and current/future submarine fleet, though with a shrinking industrial base this presents a significant challenge. Gearing remains a viable option for future submarine propulsion systems and indeed for future surface platforms, particularly if there is a requirement to achieve high speeds.

Introduction

Currently, the most serious naval gearing problems are associated with main gear wheel tooth fractures. These have never caused a catastrophic failure, but such defects require power limitations to be applied to reduce the risk of further degradation in performance and replacement of the damaged gear elements to restore operational capability.

The most recent failures, of CVS and T23 mainwheels, have occurred on legacy equipment, designed and manufactured before lessons had been learnt from the submarine gear failures in the late 1980's and before the results of the subsequent research work initiated in the early 1990's were available.

Over-stressing of components is clearly the cause of incipient tooth fracture and can normally be attributed to a combination of the following:

- Excessive contact and bending stress resulting from a combination of poorly designed gear geometries with high sensitivity to misalignment, build misalignment and alignment shift at power.
- Weaknesses in material strength however slight or localized.
- Changing operating regimes that challenge design assumptions.

Gearing Research and Development (1950-1980)

To set the scene we should first consider the development of today's RN gearing. In response to gearing problems in the Second World War the RN embarked on a comprehensive programme of collaborative gear research and development between the 1950's and the 1970's. Much useful work in the fields of fatigue strength, scuffing and gear noise was carried out, as well as work focused on investigating heat treatment and distortion. Relatively little effort was expended in refining gear stress procedures and no significant work was directed toward understanding reliability.

This resulted in the introduction of finish-ground case-hardened gears for main propulsion gearboxes. This facilitated a large increase in torque (and power) density and a commensurate reduction in gearbox size and weight and a reduction in gear noise and vibration, with no apparent adverse effect on reliability. By the early 1980's the RN considered that gearing was mature, without significant performance problems, although work remained to refine noise performance.

History of Gear Failures (1970-1990)

1970 – SSN Gearbox explosion at VSEL's shore test facility (ADEB).

1970's – T21/42 Primary Wheel tooth failures.

1986 – HMS *Illustrious* gearbox explosion.

1987 – CVS Primary Wheel tooth failures.

1989 – S/T Primary pinion tooth failures.

1989 – SSBN Pre- Production Prototype (PPP) mainwheel tooth failure at VSEL's shore test facility (Submarine Machinery Test Establishment (SMITE).

1990 – HMS *Vanguard* secondary mesh scuffing in SMITE.

The SSN explosion in VSEL's shore test facility occurred because the mainwheel forward bearing suffered a major wipe, exposing the steel backing which contacted with the steel shaft. The frictional heat produced from this contact was sufficient to produce a flammable oil mist and ignite it, resulting in the major explosion. The subsequent investigation revealed that in this particular gearbox design, during port ahead and starboard astern operating modes, the main wheel shaft moves toward the bearing oil inlet resulting in oil starvation. As a result many design changes were introduced and a speed restriction was imposed in some vessels to maintain an adequate oil supply to the bearing. Although this incident did not result in loss of life it prompted the MoD to launch a working party to investigate the causes and mechanisms of gearbox explosions with the aim of reducing the risk of future explosions.

The precise cause of the T21/42 primary wheel failures was not conclusively identified but it is probable that the nitriding process was not well controlled, resulting in low fatigue strength. While it would have been possible to develop high strength nitrided gears the pragmatic solution adopted was to revert to better understood (and higher strength) case carburised gears.

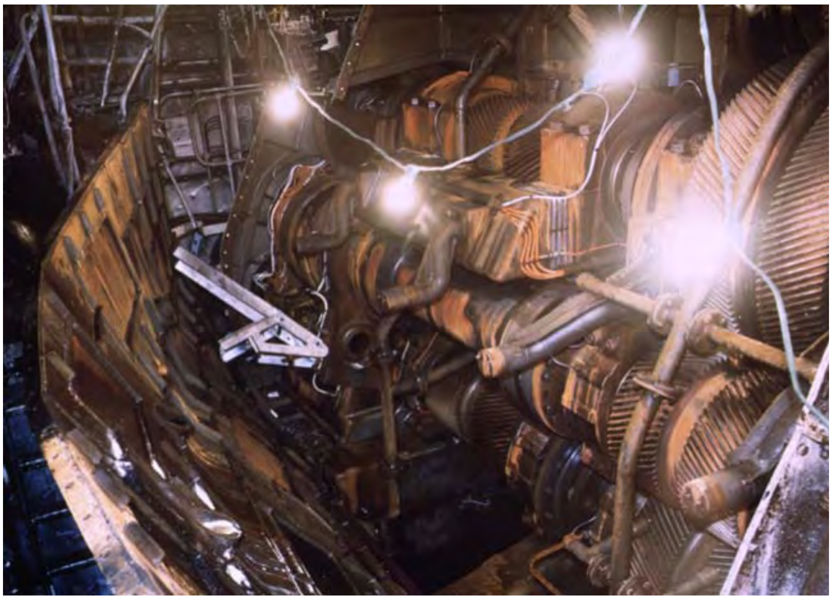

FIG.1 – HMS *ILLUSTRIOUS* GEARBOX EXPLOSION

The gearbox explosion in HMS *Illustrious* (FIG.1) was caused by insufficient clearance between an SSS clutch controller shoe and the clutch following maintenance. This produced the frictional heat necessary to generate a flammable oil mist, which then ignited producing a small primary explosion. The primary explosion fractured the gearcase, allowing fresh air to ingress and feed the much larger secondary explosion. Although there were no casualties *Illustrious* was unavailable for three months and repair costs totalled £4M. As a result of this incident the running clearances of all in-service SSS clutch actuators were checked and procedures introduced to ensure that acceptable minimum clearances were achieved and recorded during maintenance and new build. A review of all potential steel/steel contacting components was also undertaken across the fleet that resulted in the modification of some seals. The board of enquiry also recommended a review of the Gearbox Explosion Working Party findings.

FIG.2 – CVS BROKEN PRIMARY WHEEL TOOTH

FIG.3 – SSN PRIMARY PINION FAILURE

Detailed investigations into the S&T primary pinion failures (FIG.3), making use of strain gauging, identified the cause to be a combination of dynamic misalignment and excessive tooth profile reliefs. The solution was replacement pinions with improved tooth profiles and strain gauging to enable dynamic load distribution to be measured and improved where necessary by re-alignment.

The SSBN PPP mainwheel suffered two failed teeth on it's induction hardened mainwheel in SMITE. Heavy markings at the forward end of the teeth suggested misalignment and it was established that the generated end reliefs used were not as good as chamfered end reliefs for tolerating misalignment.

FIG.4 – HMS *VANGUARD* SECONDARY GEAR SCUFFING

HMS *Vanguard*'s mainwheel and secondary pinions scuffed during trials in SMITE (FIG.4). The failure was not investigated in detail at the time but the cause was believed to have been misalignment and poor tooth profiles. These issues were addressed in SSBN 06-08, which all operated successfully in SMITE and in-service. *Vanguard* completed her first commission with a power restriction in place and the gears were replaced in LOP(R). The geometry of the replacement pinions was optimized for low noise at critical speeds and the pinions were crowned to reduce end loading and to reduce the sensitivity to misalignment. Strain gauging was fitted to enable load distribution to be assessed. These gears were successfully tested during the post LOP(R) sea trials, when gearbox vibration analysis showed the gearbox to be significantly quieter than any other of the class.

Gearing Research and Development (1990-Present)

New research was instigated in the early 1990's resulting in a programme of collaborative work carried out by key UK Universitys and QinetiQ, via the British Gear Association (BGA). This work has been directed, and continues so to be, at understanding the root causes of gear defects and at developing solutions to enhance the reliability, availability and noise performance of current and future main propulsion gearing. The principal strands in this work have been:

- Developing robust techniques for measuring in-service gear stressing and gear mesh misalignment (strain gauging).
- 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 DU-GATES and proving the correlation between calculated Transmission Error (TE) and gear noise using the 8MW Marine Gear Research Rig (FIG.5).

FIG.5 – MARINE GEAR RESEARCH RIG

- Understanding bending fatigue strength of case carburised and induction hardened gears.
- Understanding surface fatigue strength, in particular micro and macro-pitting.

- Improving understanding of heat treatment and developing better quality assurance using magnetic inspection techniques (BARKHAUSEN Noise) and ultrasonic measurement of induction hardened case depth.
- Developing new gearbox designs that are less sensitive to mesh misalignment, have intrinsically low noise levels, high reliability and low through life cost.
- Developing techniques for preventing gear case explosions.

Recent History of Gear Failures (1990-2005)

1996	–	T23 Mainwheel tooth failure (*Norfolk*).
1999	–	CVS Mainwheel tooth failures (*Invincible* and *Illustrious*).
2002	–	T23 Mainwheel tooth failure (*Lancaster*).
2003	–	T23 Mainwheel tooth failure (*Marlborough*).
2003	–	OPV Primary gear tooth failure (*Anglesey*).
2004	–	*Astute* Secondary gear mesh scuffing.
2004	–	T23 thrust cone failure (*Lancaster*).
2005	–	T23 Mainwheel tooth failure (*Westminster*).

T23 Mainwheel Failures

The T23 gearbox was designed and manufactured by GEC, to commercial standards. Thrust cones were used for the first time in a RN application to react the axial force generated by the single helical secondary gears. Detailed inspections of the thrust cone surfaces have been undertaken on all T23s since build by QinetiQ and no significant problems have been identified. This use of thrust cones prompted a package of R&D work by Cardiff University and QinetiQ, which resulted in the development of the Thrust Cone Design Aid Package for use on future applications.

The *Norfolk* mainwheel tooth cracking failure developed from a sub surface crack at the case/core interface that developed into a large surface breaking flaw. The cause of this failure was assessed as excessive end loading due to misalignment and the secondary gears were replaced, with a strain gauged pinion enabling alignment to be optimized. This resulted in the re-alignment of all T23 secondary gears to reduce end loading and the risk of failure.

The subsequent failure in *Lancaster* (FIG.6) cast doubt that misalignment was the sole cause of a potential class deficiency. As a result a wide examination of design, material, manufacturing and operational issues was implemented and a class wide visual inspection regime introduced for every 50 cumulative running hours. Following palliative repairs *Lancaster* continued to operate, with a power restriction in place to reduce the risk of further degradation.

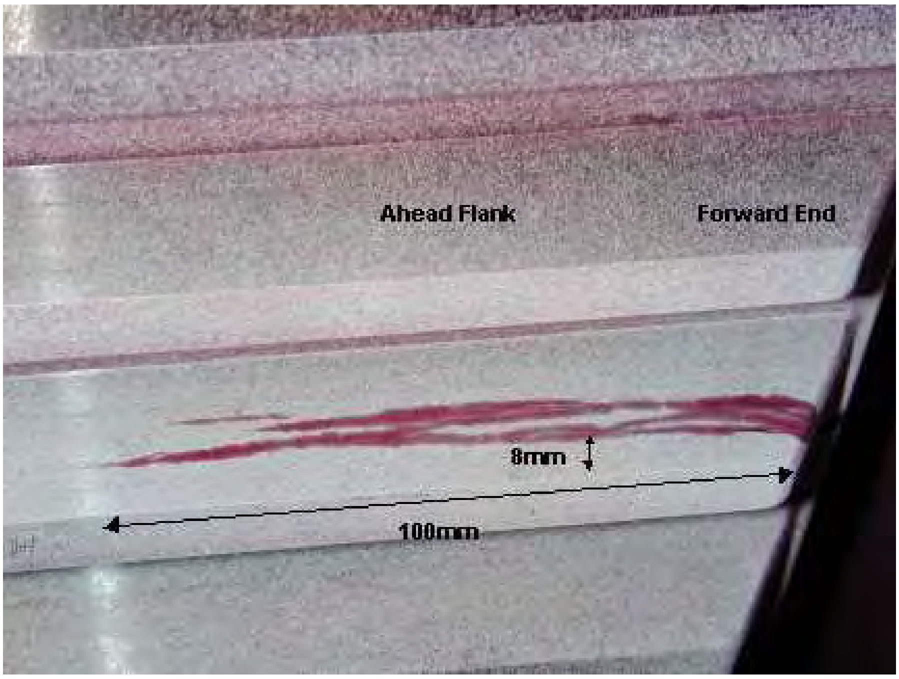

FIG.6 – HMS *LANCASTER* MAINWHEEL TOOTH CRACKING

After the *Marlborough* failure a class wide torque restriction was agreed with DCINC to reduce the risk of imminent failure.

The cause of these failures has now been confirmed as a combination of:

- Low main wheel strength due to insufficient case depth, especially at tooth ends.
- High contact stresses due to less than ideal pinion geometry leading to high end loading.

Therefore a simple technical assessment would suggest that replacement wheels and pinions are required to restore capability.

In conjunction with MPS211 and Design Unit, DAVID BROWNS developed a methodology that enabled an assessment of the relative risk of failure to be made. This took account of:

- Actual case depth (measured in-situ using state of the art ultrasonic equipment).
- Stressing (from an assessment of historical running alignment).
- Running hours (current and future).

It also allowed the user to assess what action would be required to restore full capability; i.e. a replacement modified pinion alone or a replacement pinion and wheel.

The class recovery programme, agreed with FIPT and FLEET involves the replacement of all secondary pinions with modified items that will significantly reduce end loading and therefore the risk of wheel failure (FIG.7). They will be fitted with strain gauging to enable load distribution to be measured and then optimized by realignment. Replacement pinions have already been purchased and fitted in *Lancaster* and *Kent*, at a cost of approximately £200k per gearbox.

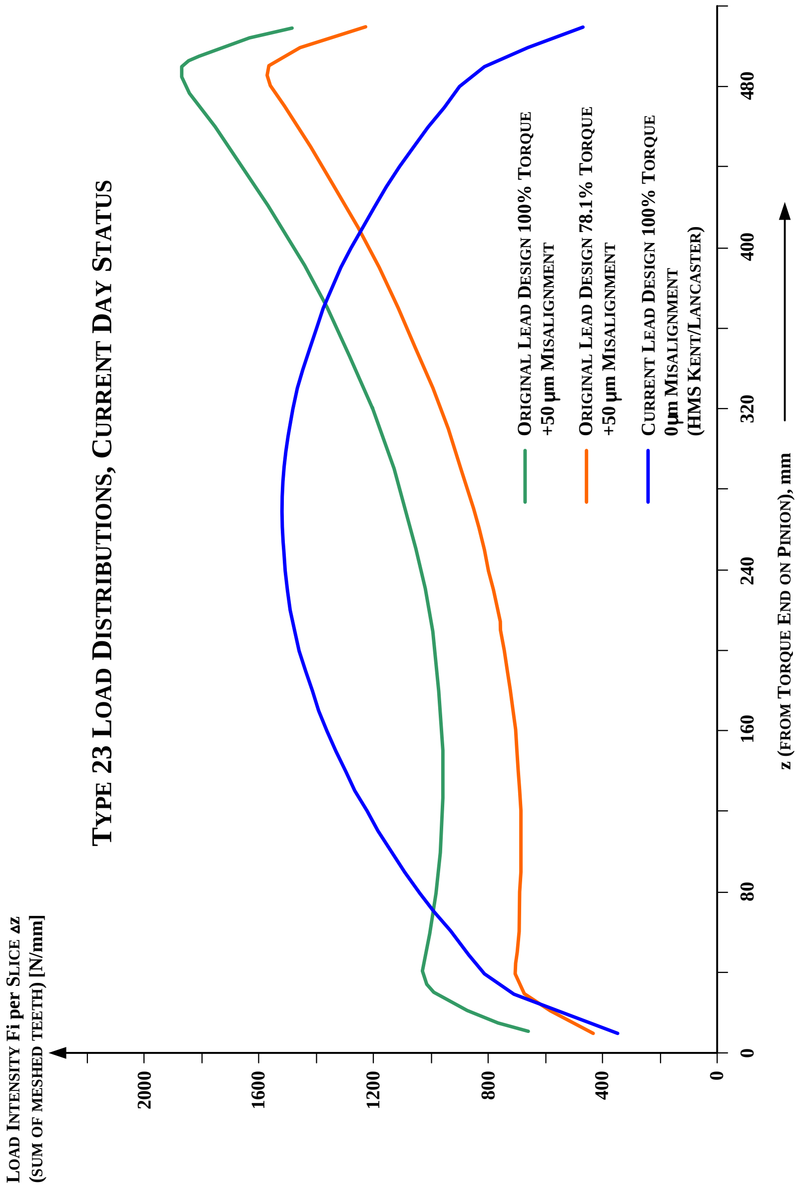

FIG.7 – T23 SECONDARY GEAR STRESSING

Replacement main wheels have been fitted in *Norfolk* (port) and *Lancaster* (stbd) to replace the failed originals. To restore full capability it is also planned to replace the failed *Westminster* port wheel, *Montrose* (stbd) wheel which has some damage, and the *Iron Duke* (port) wheel, which has particularly low case depth. Replacement wheels will incorporate deeper case depth to increase strength and thicker rims to reduce flexure. The cost of purchasing and fitting a replacement wheel and pinion is approximately £500k per gearbox.

FIG.8 – HMS *LANCASTER* THRUST CONE DAMAGE

Following the replacement of *Lancaster*'s secondary pinions in 2004 the starboard thrust cones failed during a basin trial (FIG.8). The subsequent investigation identified that the angle of the replacement pinion cone track had not been well matched to that of the replacement starboard wheel, which resulted in poor contact and breaking up of the nitrided surface of the pinion cone track. The repair required replacement thrust cones to be fitted to the pinion and in-situ honing of the mainwheel. The correct angle for the replacement pinion thrust cone track was accurately established by checking the contact between a selection of mandrels with the wheel. As a result of the failure comprehensive measurements and installation checks have been introduced for the thrust cones on future replacement pinions and wheels. Replacement pinions were subsequently fitted in *Kent* in 2005 and no problems were encountered.

As this article goes to print, a further mainwheel failure has occurred in *Westminster* (port), prompting a review of the class situation and of the get well programme.

CVS Mainwheel Failures

Designed and manufactured by DAVID BROWNS in the late 1960's to Naval Engineering Standards, these gearboxes are the largest and most complex in service with the RN.

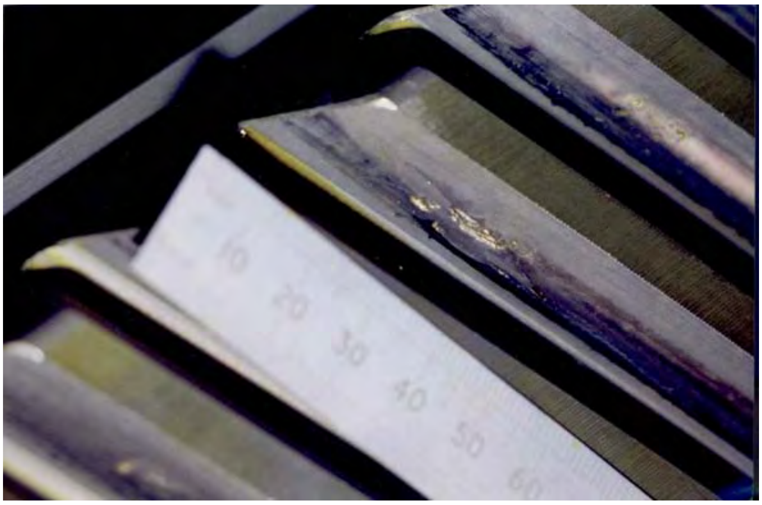

FIG.9 – HMS *INVINCIBLE* MAINWHEEL PITTING

During a routine inspection in 1999 ship's staff discovered apparently minor cracking originating from pitting on HMS *Invincible*'s starboard mainwheel (FIG.9). During the subsequent specialist inspection and palliative repair the true extent of the problem became apparent, with some cracks extending the length of the tooth. This resulted in the removal of 9 whole teeth and the ends of 2 teeth (FIG.10).

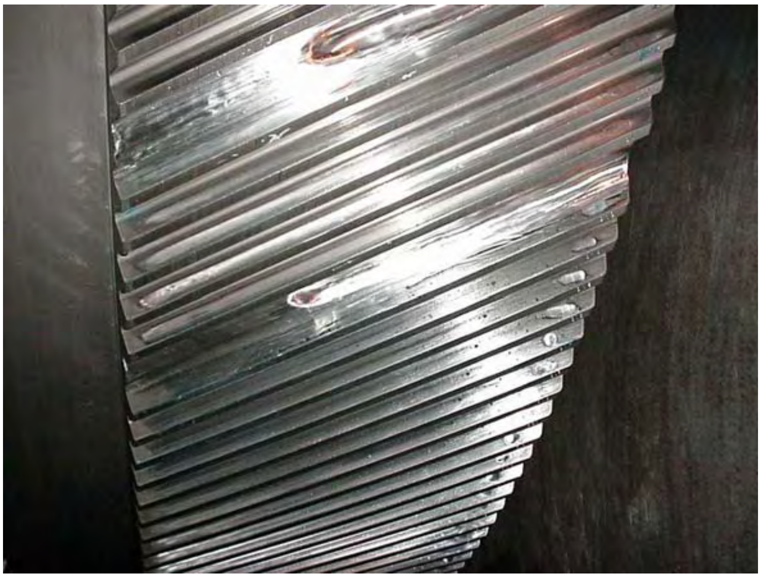

FIG.10 – HMS *INVINCIBLE* PALLIATIVE REPAIR

Subsequent inspections of the other CVS gearboxes identified that the ends were missing from 2 teeth on HMS *Illustrious'* port mainwheel (FIG.11).

FIG.11 – HMS *ILLUSTRIOUS*' MAINWHEEL FAILURE

The investigation into the *Invincible* failure confirmed the most probable sequence of events leading to failure to be:

- Loosening of the mainwheel aft side plate fasteners in 1983 led to a lack of radial support, transferring the load to the forward end of the forward helix.
- This overload resulted in localized pitting.
- Replacement of the side plate nuts and tightening of bolts in 1984 arrested the pitting.
- Changing deployment patterns in the 1990's (operating with high ambient temperatures and lower winds) necessitated higher ship speed to achieve safe aircraft launch.
- Fuel restrictions led to more high power single engine running and with each engine driving onto the mainwheel through a separate drive train the maximum tooth loading is the same in single engine operation as twin engine operation. It is worth noting that the design codes would only have assumed maximum tooth loading for a small percentage of the time.
- This increased usage at high power, exacerbated by transient over-torques, resulted in cracks developing from the pitting.

The investigation into the *Illustrious* failure confirmed the most probable sequence of events leading to failure to be similar to *Invincible*, except that the initiating damage had been caused by part of a failed primary gear wheel tooth going through mesh. The main wheel had been dressed in-situ but stress raisers had remained. The two failed wheels were effectively more fragile than others of the class due to existing damage.

The damaged wheels have been replaced in refit with a stronger induction hardened design, where the stiffer rim is welded to the sideplates (FIG.12). Replacement pinions have improved profiles to reduce end loading and the total cost of each repair was in the order of £2M.

FIG.12 – HMS *INVINCIBLE* MAINWHEEL REPLACEMENT

To reduce the risk of failure across the class, the torque at which the next engine is introduced (change up criteria) has been reduced. A lower (routine operational maximum) twin engine torque has also been introduced and the original maximum operating torque is retained but for urgent operational use only on 4 engines. Transient overtorques are now more carefully controlled by ship's staff and are recorded by the Guardian system. The condition of the gears continues to be monitored by a 6 monthly MPS211 inspection.

OPV Pinion Failure

Gear tooth failures are not isolated to larger platforms. In July 2003, during her final RN passage, several teeth fractured on HMS *Anglesey*'s port input pinion, with consequential damage to the mainwheel and starboard pinion (FIG.13). The fractures were classic bending fatigue initiated close to the end face, caused by misalignment. A replacement set of gears were fitted prior to the sale of *Anglesey*.

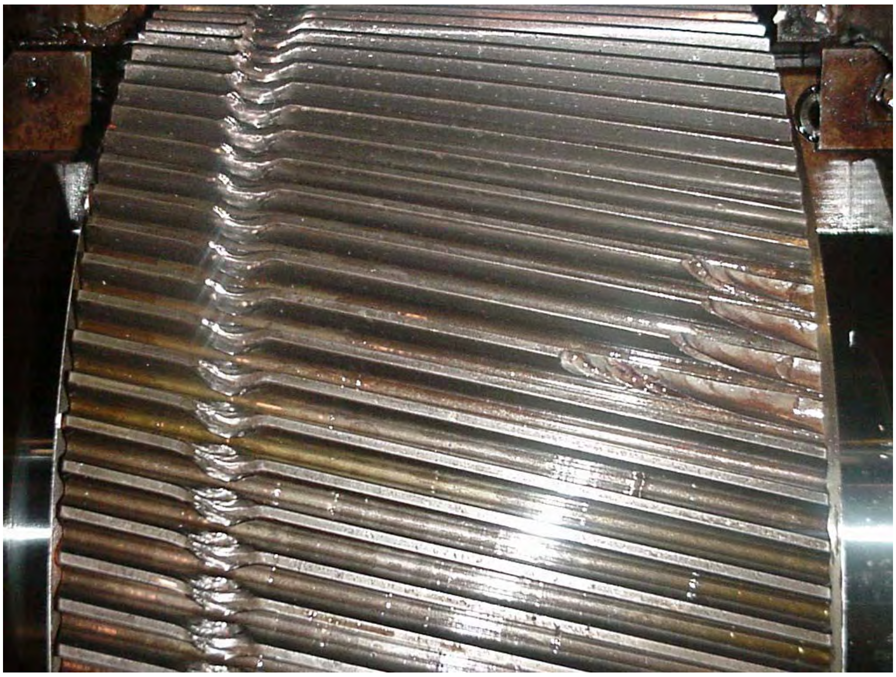

FIG.13 – HMS *ANGLESEY* PINION FAILURE

ASTUTE

The ASTUTE gearbox design was developed from that of previous SSN gearboxes by BAe Systems (formerly VSEL). The design process was facilitated by the gearing peer group, embodying lessons learnt from earlier RN gearing failures and recognizing the deficiencies in the in-service performance of S/T/V classes.

The most notable improvements can be summarized as:

- Increased tooth size and hence strength of primary and secondary gears.
- Use of thrust cones to eliminate the overturning moments that cause inherent misalignment at the gear meshes (lesson learnt from '89 pinion failures).
- Optimized gear tooth geometry (using DUGATES).
- Improvements in manufacturing technologies leading to improved accuracy.
- Improved gear wheel construction eliminating swash.
- Tilting pad mainwheel bearings to overcome oil starvation in port ahead/starboard astern operation.
- Strain gauging of primary and secondary gear meshes.
- Separation of primary and secondary gearcase structural elements and improved flexibility and articulation between primary and secondary gear elements.
- Stiffer structure to reduce flexure and therefore misalignment.

Shore trials in SMITE (FIG.14) culminated in a 6 hour run at full load in June 2004. The trial ran very smoothly and gearbox was the quietest ever tested at Barrow.

FIG.14 – SMITE

These achievements were partly overshadowed by a scuffing incident that occurred on the secondary gear elements part way through the full power trial (FIG.15). The damage was remarkably similar to that experienced in *Vanguard* (1989). In addition during the dismantling of the gearbox damage was discovered on the secondary gear thrust cones.

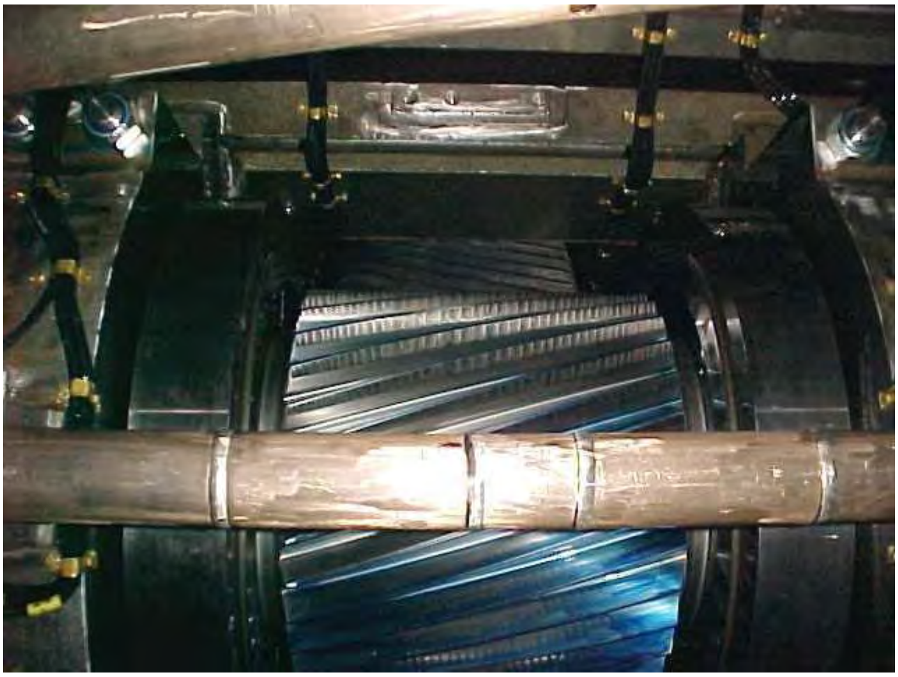

FIG.15 – HMS *ASTUTE* SECONDARY GEAR SCUFFING

Investigations by members of the gearing peer group identified that the most probable cause of the *Astute* scuffing failure (and with hindsight the *Vanguard* failure) was poor oil supply to the gear mesh. The secondary gears were replaced with those destined for boat 3, which embodied very subtle tooth profile modifications. The most significant change was an improvement to the oil spray arrangements for the gear teeth and thrust cones.

A programme of work undertaken by Design Unit has demonstrated a significant improvement in the scuffing performance of test gears with these modifications incorporated. In March 2005 trials in SMITE re-commenced and the gearbox was successfully tested without further incident.

As a result of the *Astute* scuffing incident a revised operating regime has been agreed for all 'V' boats, which have a similar oil spray arrangement to the original ASTUTE design. Modifications to the 'V' class oil supply arrangement are being implemented during LOP(R).

Industrial Base

There were originally 4 players in the UK Naval gearing industry:

- DAVID BROWNS (T21/22/42 and CVS gearbox design and manufacture, ASTUTE gear manufacture).
- VSEL (SSN/SSBN gearbox design and manufacture, ASTUTE gearbox design and build).
- GEC (T23, RFA, *Ocean* and CASTLE class gearbox design and manufacture).
- ALLEN GEARS (HMS *Roebuck* gearbox design and manufacture and manufacture of spare gears).

DAVID BROWNS bought the GEC and VSEL manufacturing facilities in the late 1990s, acquiring personnel, knowledge and manufacturing machinery. They are now part of the US corporation TEXTRON and are now the only UK based company who can manufacture large (mainwheel size) high quality marine gears. ALLEN GEARS, owned by ROLLS-ROYCE, specialise in epicyclic and smaller parallel axis gearboxes but have successfully manufactured spare SSN and T23 pinions. VSEL maintain a small body of gearing expertise, principally for the ASTUTE design and manufacture.

There are other European manufacturers (e.g. RENK in Germany and MAAG in Switzerland) who have the experience and capability to manufacture high quality marine gearboxes and others who could supply spare gears and smaller gearboxes. The worldwide gear manufacturing base is in a fragile state with several of the major US players having disbanded their gear manufacturing facilities.

For specialist independent advice, research and test facilities and strain gauging work MPSIPT have an enabling arrangement with Design Unit (Newcastle University). QinetiQ provide independent advice on lubricants and Cardiff University provide specialist advice on thrust cone.

Gearing Peer Group

The gearing peer group was established after the SSN failures in the early late 1980s.

Comprising experts from MoD, BAe Systems, DAVID BROWNS, Design Unit, Cardiff University, QinetiQ and independent specialists the group continues to meet as required to facilitate the resolution of gearing issues. They also facilitated the ASTUTE design process and continued to meet to resolve issues during gear manufacture and trials. The group continues to work well but is becoming fragile because several of the main contributors are due to retire soon

Summary

This article has provided a summary of the previous and current gearing issues in the RN. Investigations managed by MPSIPT have identified the causes of these failures, usually a combination of the following factors:

- Historically reliability issues were not adequately considered at the design stage.
- Excessive contact and bending stress resulting from a combination of poorly designed gear geometries with high sensitivity to misalignment, build misalignment and alignment shift at power, factors which the historic design codes did not take account of.
- Weaknesses in material strength however slight or localized.
- Changing operating regimes that challenge design assumptions.

These failures prompted a comprehensive gearing research and development programme managed by MPSIPT. This work has been directed, and continues so to be, at understanding the causes of gear defects and at developing solutions to enhance the reliability, availability and noise performance of current and future main propulsion gearing.

The development and validation of the gear stress and noise analysis programme DU-GATES has given gear manufacturers a powerful tool for designing ultra quiet, high reliability marine gearing. New designs have been extensively validated on the Marine Gear Research Rig and this has given the MoD and industry the confidence to implement the results into the ASTUTE class gearboxes and HMS *Vanguard*, where significant reductions in noise have been realized.

The techniques developed, and validated, for measuring in-service gear stressing with strain gauges not only identified a major shortcoming of in-service gearboxes, but will also ensure that the new ASTUTE class gearboxes and replacement T23 secondary gears will operate at ideal alignment and hence minimum stress and noise.

The worldwide Naval gearing industrial base is in a fragile state and whilst the gearing peer group continues to work well it too is becoming fragile because several of the main contributors are due to retire soon.

Conclusions

- The causes of naval gearing problems that have occurred in the last 15 years are well understood.
- With a shrinking industrial base and the imminent retirement of several key members of the gearing peer group, the continuing support of legacy gearing remains a challenge.
- New design and stress analysis and measurement techniques for high reliability, ultra low noise gearing have been developed and extensively validated, enabling the design and manufacture of reliable and very quiet gears.
- For any future geared applications the priority must be to design for reliability, rather than the past emphasis of achieving very high power densities with minimum size and weight.

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