H.M.S. 'INVINCIBLE'

THE CASE OF THE KNOCKING SHAFT

BY

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Introduction

This article tells the story of *Invincible's* port shaft problems in 1983/84 and their remedy. It is an important story because, not only did it result in considerable loss of operational time for the ship, but it also exposed an Achilles heel in the design of under-water (UW) bearings and shafting in R.N. ships. The effects of deposits on shaft liners, shaft alignment, the dynamic behaviour of shafts and propellers, and the factors influencing UW bearing wear were all understood individually and to a degree in combination. The combining action of these factors in *Invincible* was disastrous and most difficult to diagnose. The causes are now much better understood and bearing and shafting design in future ships will benefit from the UW bearing development programme which has been given fresh stimulus and direction from the *Invincible* troubles.

Many agencies were involved at various times in the *Invincible* story,without whose participation the solution would not have been achieved. Success was attained by a remarkable co-operative effort between the ship, the Dockyard, the administrative authorities, contractors, and others, all of whom displayed degrees of toleration and patience beyond the call of duty in the face of the demands of the men from the Ministry! This article seeks to tell the story of the technical investigation, analysis, and remedy. Apologies are offered in advance for any glaring omissions of specific reference in the text to the contribution of individual organizations.

Beginnings

Problems with the port shaft were first reported in October 1983 as a combination of excessive shaft TIR (Total Indicated Reading, i.e. twice the shaft eccentricity) at the first bulkhead inboard (see FIG. 1) and a high rate of weardown at the port intermediate 'A' bracket bearing (IAB). Neither of

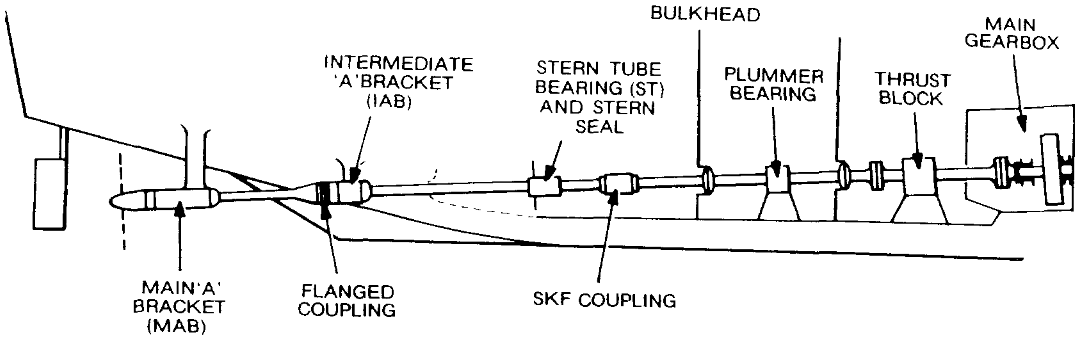


FIG. 1—H.M.S. 'INVINCIBLE' PORT SHAFT

these problems is entirely unknown to MEOs. Cathodic chalk and other shaft liner deposits are the scourge of underwater bearings and large shaft runouts (TIRs) are not unheard of in aircraft-carriers with relatively long shafts. One of the features of the early stages of the *Invincible* investigation was the plethora of 'good' advice and encouragement from those senior citizens, serving and retired, who remembered the 'good old bad old days' of multi-shaft 'real' aircraft carriers and their unique vibrational characteristics!

FIG. 1 shows the configuration of the port shaft of the INVINCIBLE Class. Conventional wisdom says that 0.001 inches per foot shaft distance from the nearest bearing is the maximum tolerable TIR. *Invincible* rapidly achieved over 0·1 inches at the first bulkhead inboard at 160 r.p.m. Deflections of this magnitude must be accompanied by a similar amplitude somewhere in the outboard (i.e. UW) shafting, the IAB being the most likely position from simple geometrical considerations. This could only be harmful and at this stage it was uncertain whether the observations were the cause or effect of the rapid weardown measured at the IAB.

Poker gauge readings are not noted for their accuracy, repeatability, or general trustworthiness. However, by the end of November 1983, in the face of repeated requests from Headquarters for more and more corroborative readings, *Invincible*'s divers were accomplished in the art and a consistent and incontrovertible trend had emerged. The wear (more than 7 mm) was over the allowed limit of 5.265 mm (total clearance allowance 6.94 mm) and 3.5 mm of this wear had been achieved in about 6 weeks. Calculations in Bath showed that the IAB would be unloaded in the static condition at this weardown of over 7 mm. Put in another way, the IAB was no longer supporting the shaft statically or at low speeds. At this stage in the investigation, although the influence of propeller offset thrusts on shaft dynamics and bearing loads was recognized, its magnitude and direction were not known. It was clear, however, from basic consideration of the transverse vibrational frequency of the now unsupported length of shaft between the stern tube (ST) and main 'A' bracket (MAB) bearings, that whirling would commence at about 135 r.p.m. This would cause excessive deflection at the IAB with reflections in the inboard shafting, amplitude diminishing in the forward direction.

At this stage technical advice for C.-in-C. Fleet and the ship was being generated by the newly created Sea Systems Controllerate, whose sections were grappling with their own new identities and responsibilities when confronted with the *Invincible* problem. The priority and seriousness of the problem is reflected in the requirement for almost daily consultations in the latter part of October and November.

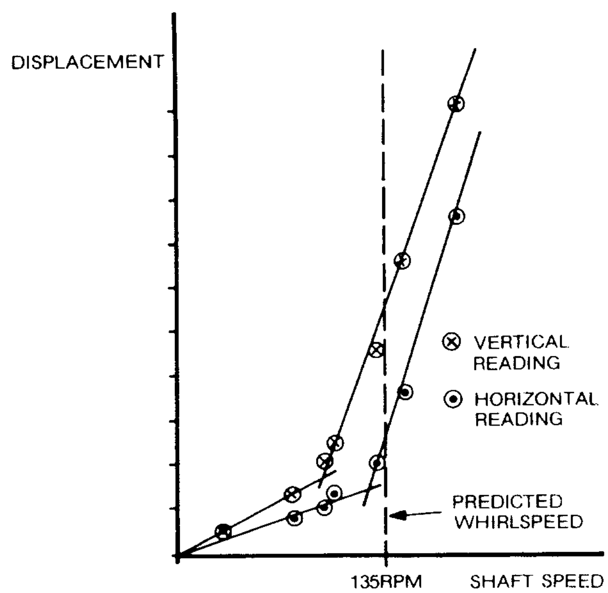


FIG. 2—SHAFT DISPLACEMENT READINGS AT FIRST BULKHEAD INBOARD

The calculations on whirling speeds were confirmed by further readings from the ship (FIG.2). The main concerns at this time were:

(*a*) Damage to gearbox main wheel bearings. The measured deflections reflected along the shaft were of the same order as the oil film thicknesses.

(*b*) Damage to plummer bearings.

(*c*) Accelerated wear in the UW bearings adjacent to the IAB.

(*d*) Absorption of clearances and damage to the stern seal. (The stern seal was of a type which would suffer damage from shaft contact with the housing if the ST wore to 60% of its maximum allowance).

Two recommendations were made:

(*a*) The port shaft speed should be restricted to 100 r.p.m. in order to keep well clear of the whirling frequency.

(*b*) The port IAB pads should be renewed as soon as possible.

Early Repairs

Abortive attempts to dock at Sydney for repair were well reported in the national press and docking eventually took place in Singapore in January 1984. The magnitude of the preparations for this commercial docking, the support activities, and the ship's experiences are well covered elsewhere[2]. It is sufficient to record that the shaft work package, agreed after very careful consideration of the ship's weardown records, was:

(*a*) Replace both IAB and ST bearings.

(*b*) Replace both stern seals with a modified type which could accommodate the full weardown allowance of the ST bearings.

Examination of the UW bearings in dry dock revealed:

(*a*) Port IAB bottom pads worn down to the bearing housing (see FIG. 3).

(*b*) Port IAB shaft liner scored circumferentially at each end, outside the bearing surface, but in line with the bearing pad keep rings.

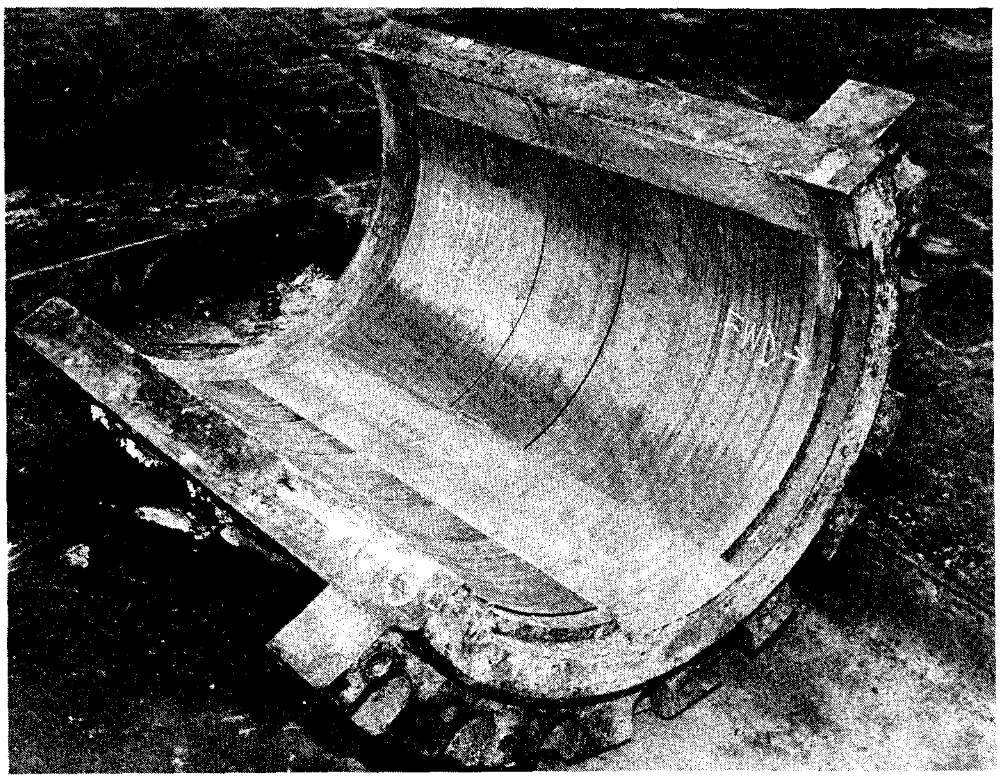


FIG. 3—WORN PORT INTERMEDIATE 'A' BRACKET BEARING (IAB)

(*c*) Cathodic chalk in all the bearings, though not on any of the shaft liners. (Samples were analysed by Portsmouth Dockyard Laboratory).

(*d*) No visual evidence of damage to the shaft liners in the port IAB. This latter point is particularly important in light of subsequent events.

(*e*) Shaft TIR at the IAB, with the IAB removed, of 0·027 inches. This was within allowable tolerances.

Bearing and seal replacement was carried out successfully in a thoroughly professional and competent manner under the 'eagle' eye of a Portsmouth Dockyard expert. The ship undocked and underwent sea trials during which the infamous 'knock' made its first unwelcome appearance. 'Knock' is an understatement. The character of the noise was more akin to a pile driver operating on the ship's hull in the vicinity of the IAB and was audible throughout the after end of the ship. There was no question of the ship proceeding without a full examination of the UW areas of the port shaft.

Regrettably this inspection revealed nothing of substance except for feeler gauge readings which could be interpreted as indicating a clearance under the shaft at the port IAB at certain shaft rotational positions. This indication was not rated highly because of the extreme difficulty of getting accurate feeler measurements in poor visibility and very awkward position. With hindsight this was probably the first real sign of the basic cause of the knock.

The second docking at Singapore confirmed that there was nothing visually amiss with the port IAB. The principle observations were:

(*a*) The Port IAB was in an 'as new' condition.

(*b*) A discoloured arc, about 80° width, over the whole length of the port IAB shaft liner, but no discernible wear.

(*c*) Bell-mouthed wear of both MAB bearings, port particularly, to the extent that the shaft was being supported on about 70% of its normal length

(*d*) Unusual TIR readings measured at the bulkhead, with the IAB bearing in place.

Of the above the TIR readings were the most significant pieces of evidence and are plotted in full in FIG. 4. They showed quite clearly that the shaft locus at the IAB, faithfully mirrored at the bulkhead, had a distinct discontinuity, best discribed as a 'step' over which the shaft appeared to 'fall' once per revolution. This was a positive indication that one of the causes/effects had not been eradicated, and, more importantly, one which could not be explained by any of the visual evidence.

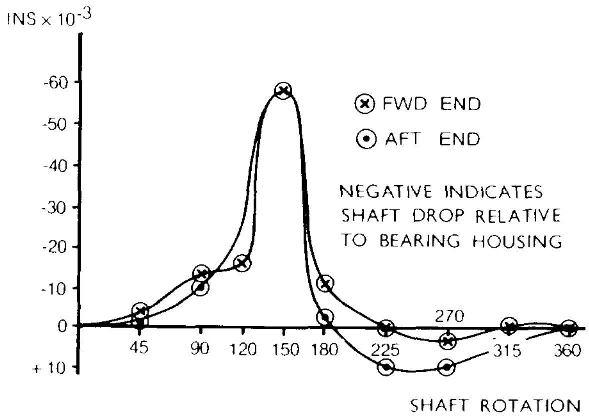


FIG. 4—TIR AT PORT IAB: SHAFT ROTATED WITH NEW BEARING IN PLACE

Attention turned then to the MAB. The effect of the bell-mouthed wear was to increase the effective overhang of the shaft aft of the MAB. It is known that this has a fundamental effect on the whirling frequency of the shaft and is included in the calculations in reference 1. It was also known that the shaft was not dead centre in the IAB housing, tending to the starboard side by 0.020 inches, and that relatively small movements of the effective MAB bearing centre would have some influence on the IAB reaction.

From these facts a theory was developed as follows:

(*a*) Statically, the loading system induced by the worn MAB, the natural throw of the shaft, and the position of the shaft in the IAB, would allow the shaft to 'climb' the inboard side of the IAB and drop as the shaft continued to rotate, thus causing the unusual TIR readings and the knock.

(*b*) Dynamically the same mechanisms were at work aided by the lowering of whirl speed arising from the increased overhang.

TABLE I—*Design Afloat Bearing Reaction (in lb.) calculated by YARD*

	Bearings							
	1 (*MAB*)	*2* (*IAB*)	*3* (*ST*)	*4*	*5*	*6*	*7*	*8*
Port	61 700	6400	32 900	32 200	15 500	32 600		
Starboard	61 900	4 900	36 100	29 900	27 000	31 700	15 300	32 700

During the second docking in Singapore the port MAB was renewed. Initial indications during basin trials were promising but full sea trials soon revealed that the knock had not been eradicated though its character had changed slightly. However, new information was gained. The knock could no longer be heard when:

(*a*) The ship went astern.

(*b*) Port rudder was applied.

(*c*) The shaft speed was less than 35 r.p.m. ahead.

This was clear evidence that there was a direct connection between the hydrodynamic behaviour of the propellor/rudder system and the shaft.

Propeller Offset Thrust. It is well known that propeller thrust is neither uniform nor acts through the centreline of the propeller disc. Wake variations cause a sinusoidal variation in thrust, at blade rate, whose amplitude increases with speed. The point of application of the resultant thrust can only be estimated, as can the amplitude of the oscillation. Measurements in some applications [3] have shown variations up to 80 per cent. of average full power steady thrust.

It was already known from analysis of the original design that the IAB had a low bearing reaction (see TABLE I), and that it was likely statically to unload at a weardown only marginally above the maximum allowable value. Offset propeller thrust will cause a bending moment in the shaft which would influence the load on the IAB with magnitude and direction dependent upon shaft speed and direction of rotation of the propeller. It would also be influenced by the rudder position since the ship design is such that application of port rudder partially obscures the port propeller disc.

Although the docking measurements showed no gross alignment errors in the UW shafting it was now possible to postulate a situation where the IAB was marginally loaded at low speeds thus allowing the bearing to load and unload under the influence of the natural throw. This theory assumes some hull distortion on undocking which alters the UW shaft alignment to reduce the IAB loading to this marginal state. When the ship then went astern or applied port rudder the loading changes induced by offset propeller thrust shaft bending moment could explain the apparent disappearance of the knock.

Early Conclusions

Some progress had been made towards identifying the causes of *Invincible*'s malaise but the fundamental illness remained obscure. The following were thought to be important influences:

(*a*) Cathodic chalk.

(*b*) The low IAB reaction.

(*c*) Shaft alignment.

(*d*) Shaft dynamics and their interactions with hull and propeller hydrodynamics.

This list is not exhaustive and there were other possible contributory factors of lesser probability, the most favourable being the 'flat' liner theory. This, simply, supposed that there was a flat on the IAB shaft liner formed when the IAB pads wore out in October 1983, and the shaft was allowed to bottom on the bearing housing. This theory could explain the continuing knock but was unsupported by any practical visual or dimensional evidence of the sort of discontinuity which could be imagined to cause the knock.

It was very clear from the conclusions outlined above that a very wide-ranging and thorough practical investigation and engineering analysis were necessary. At the very least this would require the removal of the port propeller and the after two lengths of port shafting, accompanied by an exhaustive series of measurements. To have the greatest chance of success this scale of operation could only be realistically performed in a Royal Dockyard. The ship had already virtually completed her deployment in the Far East so the order to proceed to the U.K. caused little disruption to the operational programme.

Until this time the technical supportive work was still being performed by the Sea Systems Controllerate and C.-in-C. Fleet, both in the U.K. and during the docking periods and sea trials in the Far East. Measurements and readings to date had been taken by ship's staff with the instrumentation available on board: clock gauges, feelers, pokers, etc. They were extremely comprehensive and invaluable in the early analysis but more sophisticated techniques would be necessary if a real solution were to be produced. Resources for this nature of work are beyond both ship's staff and MOD, and, equally importantly, the level of involvement was already being detrimental to other areas of work. Vickers Shipbuilding and Engineering, Ltd. (VSEL) and YARD were therefore called in to assist—VSEL as the original designers, YARD to provide the measurement and instrumentation expertise, and to help with the analysis.

Investigation

Invincible was scheduled for DED in June 1984. A comprehensive work package to investigate, analyse, and rectify the shafting defect was urgently required as this would almost certainly form the critical path of the DED. It is often the case with machinery defects whose origin is obscure that a solution has to be generated before the true cause has been established in order to define a repair strategy. *Invincible*'s shafting problems were no exception and the eventual repair was to a certain degree constrained by the programme required by the Dockyard in order to meet operational dates.

The outline work package was fairly readily specified:

(*a*) Measure all bearing reactions on both shafts.

(*b*) Remove, inspect, and if necessary renew, both MAB, IAB bearings.

(*c*) Remove both after lengths of port shafting. Inspect for damage and trueness. Check both propellers for pitch and balance.

(*d*) As far as possible check port shaft alignment.

(*e*) Reassemble, with alignment of UW shafting adjusted to a degree to be defined following analysis of results of measurements and trials.

Each stage of the dismantling of the shafting system was to be accompanied by a standard package of feeler gauge readings, pokers, and runouts (TIR) inboard and outboard. The precise detail of the measurements would depend upon the results of sea trials and the ongoing analysis during the investigative phases.

The first step in the investigation was to obtain the maximum amount of information before the ship docked. Two phases were essential:

(*a*) Complete measurement and definition of the port shaft behaviour afloat under as many dynamic conditions as possible.

(*b*) Determination of the shaft alignment afloat.

Dynamic Measurements

The objectives of the dynamic measurements were to:

(*a*) Quantify and define the shaft movement under all conditions.

(*b*) Characterize the Knock and pin-point its origin, particularly in relation to the shaft rotational position.

To achieve these objectives YARD devised an instrumentation package comprising non-contact displacement transducers mounted at several positions inboard on the port shaft to measure the horizontal and vertical shaft movement, together with triaxial accelerometers on the 'A' bracket palm plates. An electronic shaft marker was fitted and the whole package was connected to a U/V recorder. This instrumentation was fitted in Gibraltar during the ship's return passage and trials conducted between Gibraltar and the U.K. in March 1984, with as many conditions of speed, rudder angle, and direction of rotation as possible. A limited number of tests was also carried out on the starboard shaft for comparison and completeness.

Shaft Alignment

Invincible's original shaft alignment had been performed by VSEL on the building slip. It is a straightforward line of sight alignment between the MAB and a datum mark on the engine room forward bulkhead. Gearboxes are set in relation to this line to achieve a specified gap and offset between the two halves of the gearbox output coupling, and MAB and ST are slope bored to the shaft elastic line (FIG. 5). It is assumed that the bearing reactions

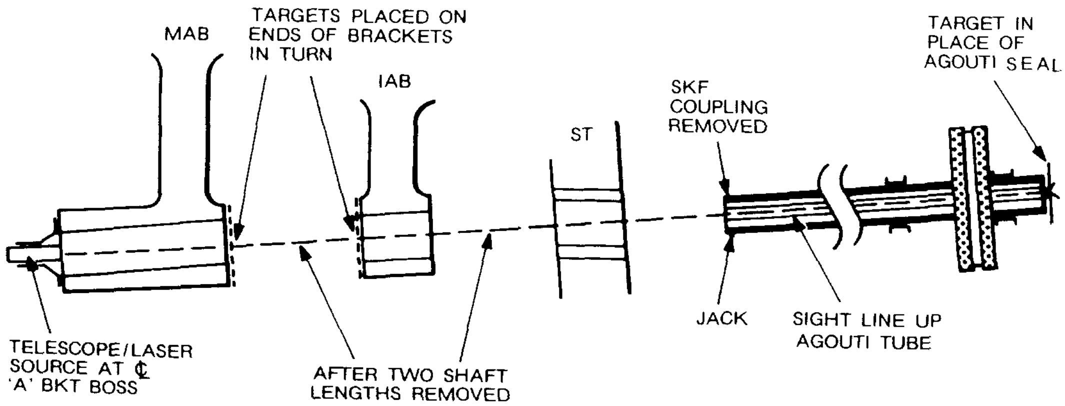


FIG. 5—METHOD USED FOR SHAFT ALIGNMENT CHECKING

of the outboard bearings are then as per design. Inboard bearing reactions were measured during CSTs, following the hull vibrational problems, and found to be satisfactory.

The difficulty, then, in rechecking the shaft alignment in service is that the original conditions cannot be reproduced without major and prohibitive dismantling of machinery, and with the ship in dry dock. In *Invincible*'s case it was essential to be able to measure the afloat alignment, since the problems occurred afloat, or at least to devise a means of relating dry docked readings to those afloat. The latter was chosen as the only practicable method and comprised the following major activities:

(*a*) Measurement of inboard bearing reactions afloat.

(*b*) Fitting of strain gauges to the shaft inboard.

(*c*) Establishment of a datum for the shaft alignment afloat.

(*d*) Comprehensive measurements of feelers, pokers, and runouts.

This (*d*) gives no real indication of the shaft alignment but it does show the shaft position within bearings and any changes which occur between the dry docked condition and afloat. This is a very time-consuming process and was achieved by a combination of ship's staff divers removing all the rope guards and fairing plates from the IAB and MAB, plus the UW shaft coupling cover—no mean feat in the relatively short time available in Gibraltar. The actual readings were taken by the Plymouth clearance diving (CD) team when the ship arrived back in Portsmouth in March 1984.

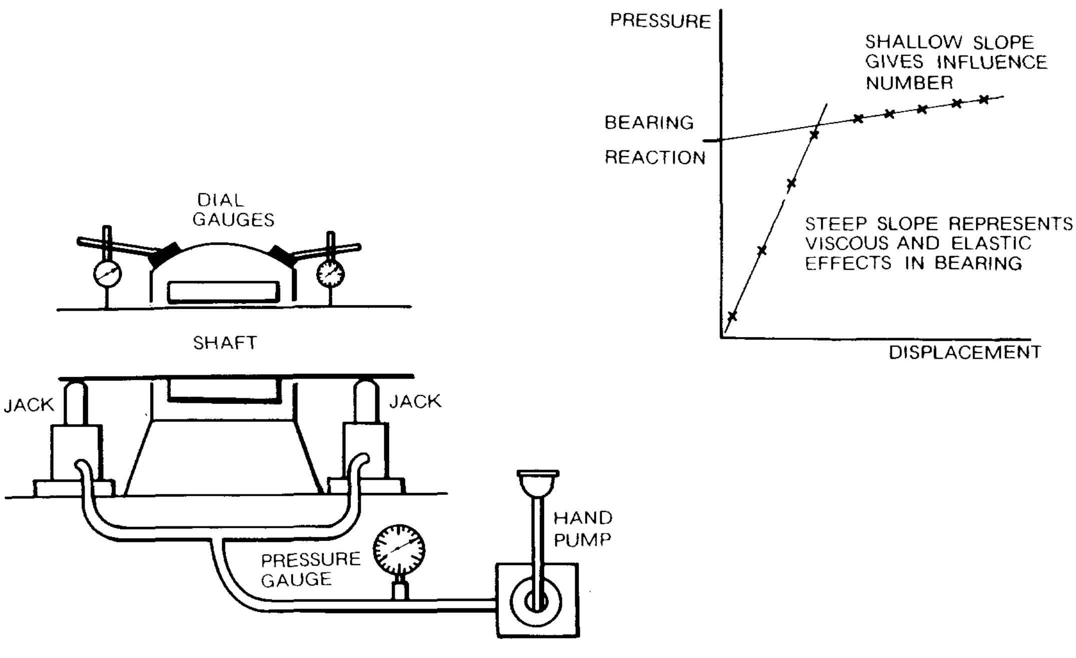


FIG. 6—MEASUREMENT OF BEARING REACTION

Values of bearing reactions were probably the most crucial clues to any significant changes to shaft alignment since build. Obviously the UW bearing reactions could not be measured afloat but any gross changes in the UW alignment would show up in the plummer bearing reactions. Comparison could then be made with the complete set of reaction measurements to be taken in dry dock to attempt to predict the real loads on the MAB and IAB afloat. Afloat measurements of the plummer bearings were taken in Portsmouth by the Dockyard with VSEL supplying the method, the gear, and on-site advice. The method used is shown in FIG. 6 and the readings taken in TABLE II. They showed no significant departures from the design. The fitting of strain gauges, as in (*b*) above, was an alternative method of achieving a similar result.

TABLE II—*Measured Bearing Reactions, before and after re-alignment*

	MAB	*IAB*	*ST*	*Plummer*
Design docked	73 100	11 500	36 100	32 200
Measured docked	68 100	8 300	37 700	30 500
Derived afloat*		300		
Realigned docked	74 270	19 600	29 800	
Predicted afloat	62 870	14 500	26 280	
Equivalent bearing pressures	62 psi (67)**	40 psi (10)**	42 psi (62)**	

* This figure was an attempt to take account of all the measured changes in alignment between afloat and docked.

** Figures in brackets are pre-realignment estimated bearing pressures. All figures are for unworn bearings.

The establishing of a datum, (*c*) above, gave rise to considerable debate. From the changes in bearing reaction and the strain gauge measurements described above there would not be a unique solution for the change in the outboard alignment. Several possibilities could give the same changes because of the influence changes in any one bearing position have on the reactions of those adjacent. It was necessary therefore to attempt to provide a datum for the shaft line to relate to that to be measured in dry dock. Obviously there exists no means of sighting along the whole shaft while the ship is afloat. Neither was it possible, without enormous effort and wholescale disruption of compartments, to sight through the ship low enough down to be certain of the relation of the line to the shaft. Two obvious positions existed in *Invincible*—the flight deck and the hangar. Datum sights were set

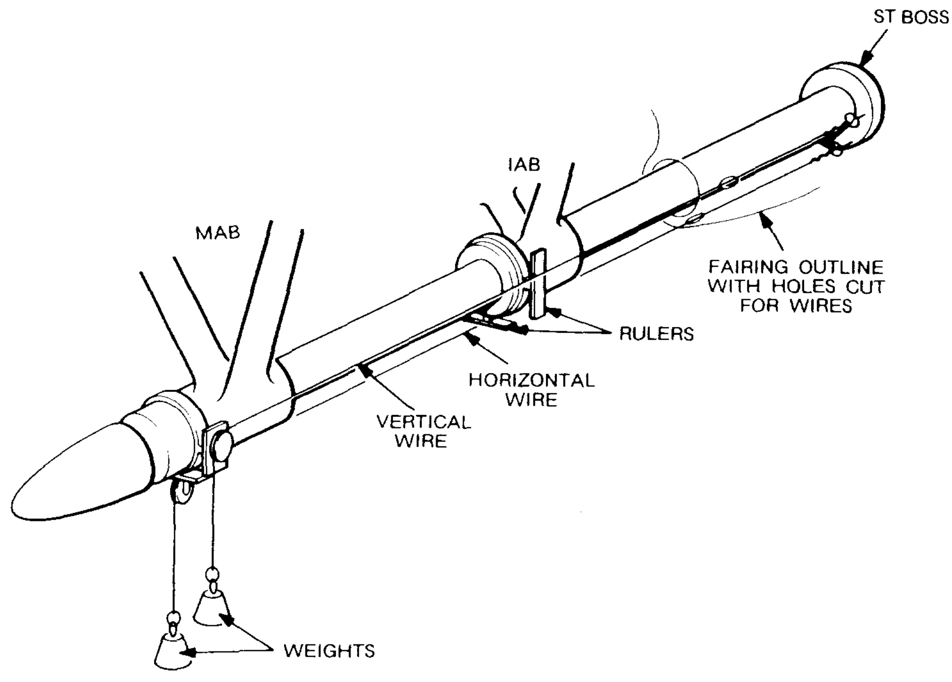


FIG. 7—UNDERWATER ALIGNMENT WIRE

up therefore on the flight deck on three lines, centreline, port, and starboard, for telescope alignments to be taken, together with a subsidiary line in the hangar. By this means it was hoped to be able to relate the hull movement on docking to the shaft line movement. It was recognized that this would be difficult and at best very empirical and so the 'engineer's' solution was added to the package. This comprised simply of a wire stretched between the ST after boss and the MAB, tensioned with weights hanging on the end. A suitable rule was fixed to the IAB, across which the wire ran, thus enabling the change in position of the IAB relative to the ST and MAB to be determined. In the event two wires were fixed to each underwater shaft line, one to measure the horizontal displacement, the other the vertical. This gear was designed at Bath, turned into a practical proposition by Devonport FMG, and fitted by Plymouth CD Team in a mammoth feat of diving lasting almost 36 hours immediately prior to the ship docking down. FIG. 7 illustrates the apparatus.

A further, very simple, additional measurement was added during the docking. This comprised a clock gauge fitted at the first bulkhead inboard, bearing on the shaft which gave extremely valuable corroborative information on the shaft movement during the docking process.

Results

Sea Trials, Gibraltar–U.K., March 1984

(*a*) *Port Shaft*

(*i*) The knock quite positively emanated from the port IAB and registered as a clear once per revolution impact followed by 'bounces' at 10Hz. Although the knock disppeared audibly when the ship went astern or put on port rudder, the accelerometers still registered about 70% of the audible reading.

(*ii*) The knock occurred when the previously observed discoloured patch on the IAB liner was at the bottom of the IAB.

(*iii*) The knock was accompanied by an upward movement of the shaft at 239 bulkhead.

(*iv*) Maximum runouts at the bulkhead were 0·027 inches vertical, 0·039 inches horizontal. (Maximum trial speed was 80 r.p.m.).

(*b*) *Starboard Shaft*

(*i*) No unusual knock or other noise under any of the trial conditions.

(*ii*) Runouts at the bulkhead of 0·037 inches horizontal and 0·017 inches vertical.

Alignment Readings

(*a*) *Pokers*. Poker gauge readings were generally satisfactory and consistent within expected limits both afloat and in dry dock. There were some anomalies associated with shaft rotation.

(*b*) *Feelers*. all were satisfactory and normal except for the starboard IAB which, afloat, seemed to indicate a small clearance under the shaft at the forward end. Both MAB showed evidence of 'bell-mouthed' wear.

(*c*) *Flight Deck telescope measurements*. There was general indication of increased 'sag' of the stern on docking, thus confirming earlier assumptions. This suggested a possible drop of 2 mm at the IAB on docking but precise interpretation was difficult because of a reported scatter of up to ±2 mm on the measurements.

(*d*) *UW Wire.* Remarkable consistency was achieved in the use of this apparatus by at least four different divers. it showed a maximum possible interpretation of a 1 mm rise at the port IAB, and 0·75 mm on the starboard.

(*e*) *Bearing Reactions.* The plummer bearing reactions were consistent with the readings at (*c*) above, i.e. an increase in value on docking at the after plummer to reflect a drop in the outboard shafting. Both IAB were significantly lower than the design intention, whilst MAB and ST were within the experimental accuracy of the method used (see TABLE III). The clock gauge placed at the bulkhead confirmed the drop in the shaft suggested by the flight deck optical measurements. Strain gauge readings proved impossible to relate to the outboard shafting but confirmed the trend of the plummer bearing reaction measurements.

TABLE III—*Measured Afloat Plummer Bearing Reactions* (*in lb.*)

	Bearings	
	4	*5*
Port		
Design	32 200	
Measured CSTs	32 618	
1984 jacking	28 654	
1984 strain gauge	30 052	
Starboard		
Design	29 900	27 000
Measured CSTs	30 514	31 639
1984 jacking	28 829	30 576

Visual/Dimensional

(*a*) *Port IAB Liner.* A 'flat' of maximum depth 0·070 inches, 70°/80° arc length existed on the liner at a position which coincided with the discoloured area previously reported, and in such a position that it would be at the bottom of the IAB when the knock occurred. It ran the full length of the bearing surface of the liner and had a bright strip at each extremity of the arc.

(*b*) *MAB.* As predicted by the feelers, both MAB were worn to a bell-mouthed shape.

(*c*) *General Liner Appearance.* In taking the feelers and runout readings in dry dock the shaft was turned many times by turning gear. The result was that the ST and MAB liners were polished bright whilst both IAB were left dirty except for the bright strips reported in (*a*) above.

(*d*) *Optical Alignment.* Two methods of alignment checking were attempted, by laser and telescope. Both were applied when the two after lengths of the port shaft had been removed, and used the after end of the MAB barrel as the after datum. The forward datum was a target on the forward end of the shaft in way of the Agouti seal, with the sighting line being up the Agouti tube (FIG. 5). Adjustment was made to allow for the difference in position between the original sighting mark on the bulkhead and the Agouti seal centre line. Laser techniques were insufficiently accurate and the telescope and sight method showed that:

(*i*) The MAB and ST were slope bored in the correct sense. (The design calls for the MAB to be bored at an angle of 0·5 milliradians to the line of sight, aft end low; and the ST at an angle of 0·3 milliradians, aft end high (see FIG. 5).)

(*ii*) The IAB and ST appeared to be 1 to 1·5 mm below the original-line of sight.

Analysis

From the glut of data now available the following important conclusions were possible:

(*a*) Both IAB reactions were significantly less than the designed intention, to the extent that the weardown to unload these bearings afloat would be less than the maximum allowable weardown. When this point was reached no further wear would be recorded by poker gauges since the shaft would be statically unsupported.

(*b*) The IAB liner had suffered damage, not obvious to the naked eye, but measurable and generally consistent with a worn-out bearing and metal-to-metal contact between bearing journal and housing.

(*c*) Although the IAB reactions were less than designed they were probably within 'build tolerances' and there was no evidence of significant deficiencies or deteriorations in the shaft alignment. All alignment measurements indicated a reassuring consistency.

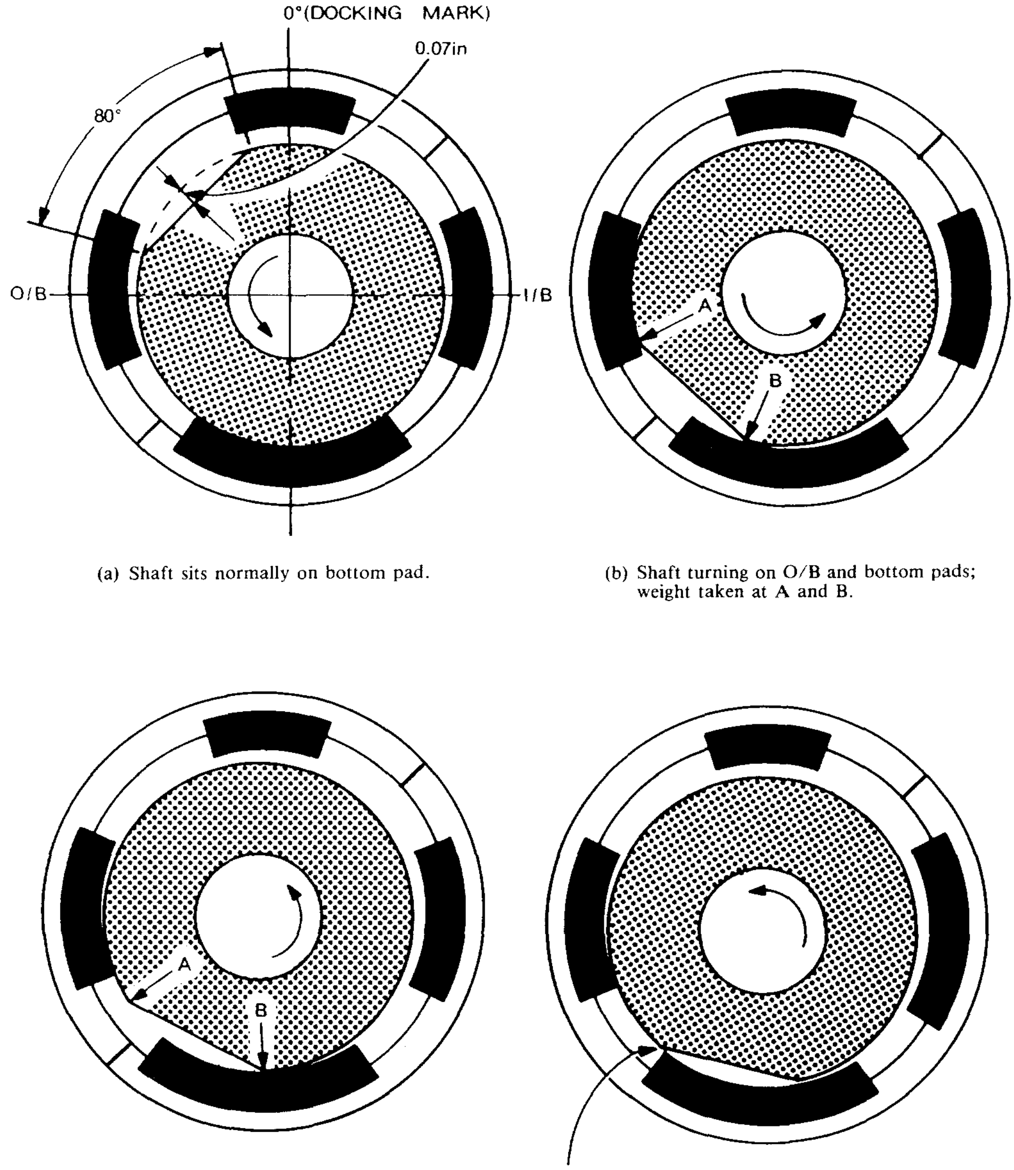
A further important point which emerged from discussions with ARE, Haslar, was the estimated point of application of the propeller thrust in the *Invincible* propellers. This was above and inboard of the propeller disc centre line in a sense which would cause a bending moment in the shaft to increase the IAB load under ahead thrust. Conversely, astern thrust would tend to unload the IAB, and application of port rudder could be shown to influence the thrust in such a way as to reduce the bending moment.

This feature had been taken into account in the original design. The design IAB loading was deliberately low in the static case in order to avoid the likelihood of it overloading at full power in the fully dynamic case. The performance of *Invincible*'s MAB, with bell-mouthed wear and a combination of new and partially worn pads, clearly demonstrated that loading above the normally accepted limits does not necessarily wear out UW bearings.

A mechanism could now be postulated to explain the sequence of events that had befallen *Invincible*. Measurement of the bearing reactions in dry dock suggested that the IAB loads could fall as low 3000 lb. afloat. At this level the bearing wear need only be 2·5–3 mm ahead of its adjacent bearings to cause static unloading of the bearing. (This calculation is done by simply using the influence numbers of *Invincible*'s shafting. For the IAB a movement of 1 mm causes a change of loading of approximately 1140 lb.). When this point is reached there is little chance of cathodic chalk deposits being rubbed off under the normal turning action whilst alongside. When the ship arrived in Portsmouth in July 1983 the reported weardown was of this order on the port shaft but not the starboard. The figures from the ship's records were port 3·7 mm and starboard 2·79 mm. (These figures are actual clearances and not weardowns). This fatal combination of a long period in port, with a critical level of weardown, had not occurred before in the ship's history.

Cathodic chalk is at its worst, i.e. hardest, when allowed to grow undisturbed for a number of weeks. It has been shown in laboratory experiments that cathodic chalk will grow inside the annular space of an UW bearing[4], and tests on two Type 42s have shown that the right conditions exist in H.M. ships' 'A' bracket bearings to allow the growth. Analysis of the deposits taken from the bearing housings of *Invincible* in Singapore were positively identified by CDL Portsmouth as cathodic chalk. The likelihood is, therefore, that *Invincible* left Portsmouth in October 1983 with a hard coating on her port IAB with little prospect of getting rid of it at sea. Accelerated wear took place, accompanied by the onset of whirl (at 120–130 r.p.m.) once the weardown had reached the point where the shaft was no longer supported on the bearing under the action of offset thrust bending moment. At this point the weardown would continue, but could no longer be measured by the poker gauges since the shaft would always come to rest in its natural elastic line, clear of the bearing. Poker gauges will only measure weardown as long as the shaft remains in contact with the bearing.

Once the bearing material was completely worn away the shaft would make contact with the bearing housing under high thrust and cause damage to the liner and housing. Precisely why the liner should be worn over an arc of only 80° is not fully understood though it is thought to be caused by the natural throw of the shaft. At one stage it was believed to be associated with propeller blades being out of pitch but this theory was not borne out by measurements. A large scale model of the 'flat' liner was manufactured by the author and served to demonstrate how a flat of the kind measured could cause a knock (see FIG. 8).



(a) Shaft sits normally on bottom pad.

(b) Shaft turning on O/B and bottom pads; weight taken at A and B.

(c) Trailing edge clear of O/B pad; load on O/B pad now distributed.

(d) THE KNOCK and position of maximum downward displacement of shaft. Trailing edge of flat strikes leading edge of bottom pad. Shaft bounces against inboard pad.

FIG. 8—THE 'KNOCK'

The Remedy

The remedy had to satisfy four requirements:

(*a*) The IAB had to be rendered insensitive to unloading through normal weardown.

(*b*) The bearing load on the IAB would have to be increased to a level at which cathodic chalk would be rubbed off during normal shaft turning operations in harbour.

(*c*) The IAB shaft liner would have to be restored to circularity.

(*d*) It had to be achieved within the constraints of the Dockyard programme.

(*a*) and (*b*) above were 'mutually inclusive' and could be achieved by increasing the bearing load. This in turn could be achieved by lifting the bearing. The question was by how much much, and the answer was effectively dictated by the degree to which the elastic line of the shaft would be altered in the ST and MAB. Both MAB were to be renewed, including reboring, as were both IAB. The ST, however, were not due for replacement. Any work which could not be contained within this programme would put the completion date out.

For once all the 'gods' smiled at once! 8 mm turned out to be the optimum figure from several considerations. It provided a suitable increase in loading, just over 9000 lb., estimated, and also proved to be the maximum which could:

(*a*) Be achieved by a combination of 'banding' the bearing housing and offset boring the bearing. These were limited by the amount of material in the housing and the bearing pads respectively.

(*b*) Be allowed without the need to rebore the slope of the ST.

(*c*) Be accommodated at the MAB without the new MAB slope encroaching on the normal total weardown allowance.

This figure of lift was therefore selected and was split between 'banding' (0·250 inches) and the remainder (0·070 inches) by offset boring the IAB (see Fig. 9). A new after intermediate shaft was fitted.

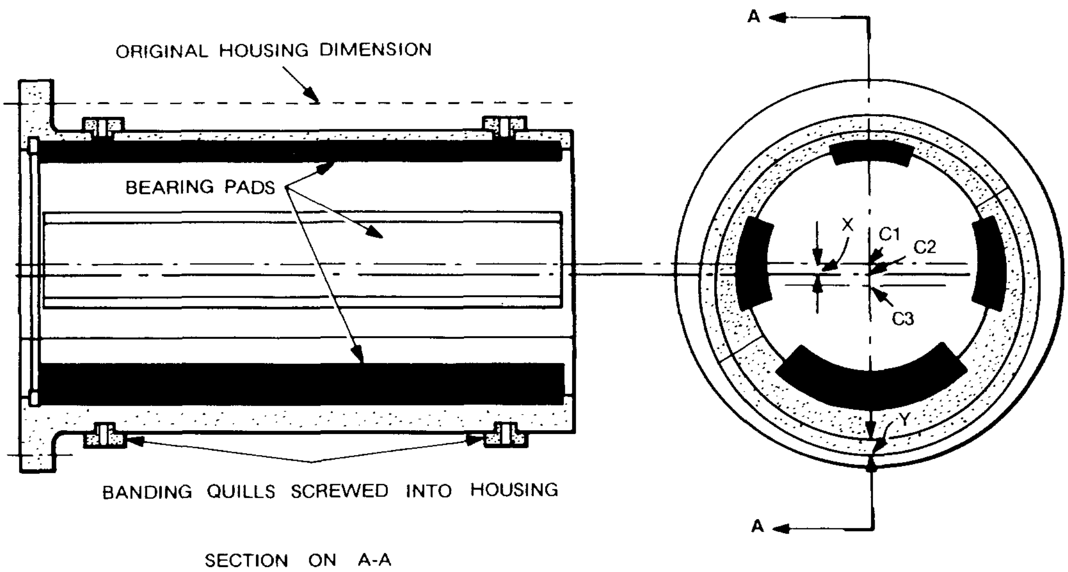


Fig.9—Banding arrangements at IAB

C_1 = bearing pad bore centre
C_2 = housing bore centre
C_3 = new bearing outside diameter and banding centre
Y + X = total bearing lift

All runouts, clearances, and bearing reaction measurements were repeated during the reassembly and the only surprise was the amount by which the IAB reactions increased (see TABLE II). Adjacent bearing loads were satisfactory and subsequent analysis has provided an explanation for the figures. During the intitial bearing reaction measurements the MAB were in their worn state, whilst the second set of readings was taken with new bearings. Analysis has shown that the point of application of the MAB bearing reaction has a significant effect on the adjacent bearings, and this had not been taken into account when calculating the lift to be applied.

In order to establish the bearing loads afloat a scheme was devised to strain gauge the 'A' bracket arms and lead the cables through a watertight gland in the ship's hull to recording instrumentation. By this means it was hoped to be able to examine the influence of propeller thrust on the IAB reaction and in the longer term monitor the change in bearing reaction as the IAB wore down. In practice calibration showed that the gauges could not distinguish between horizontal and vertically applied loads. Hence, there would be great difficulty in separating the influence of hydrodynamic effects and changes in the bearing normal loads.

After all the repairs were complete there was no further evidence of unusual runouts. All that remained was to test the dynamic performance of the shafting.

Sea Trials

Post DED sea trials were an unqualified success for the port shafting. There was no evidence of the knock and all other aspects of performance of the shaft were satisfactory. The ship did full power, with considerably less hull vibration than at any time since CSTs. The latter was totally unexpected and is still under investigation.

The 'A' bracket strain gauge system functioned correctly and it was possible to identifying blade rate variations in strain. It was also possible to observe the increase in strain gauge readings as power increased, or when rudder was applied. However, the system was so sensitive that even passing waves caused a variation in strain! Precise quantitative analysis proved impossible on board and subsequent attempts have had little success. However, the system remains installed and available for the future, should that become useful.

Conclusions

Final proof of the success of the repair will be a long-term matter of carefully monitoring bearing wear rates, but initial prognosis is good. Measurement of the bearing reactions of the other ships of the class has shown an identical load distribution to *Invincible* and so the same remedy will be applied during their forthcoming docking periods.

In the meantime the *Invincible* story has given new impetus to a wide range of bearing development initiatives including further research into the factors influencing the formation of cathodic chalk, bearing material selection, and bearing design. A full size bearing test rig is in course of procurement and will be installed at RAE (Pyestock) with the object of developing a new concept of underwater bearing.

Most of the influences which conspired to cause *Invincible*'s difficulties are present to differing degrees in all R.N. warships but as far as is known no other surface warship has the single most important factor, a very lightly loaded UW bearing. Submarine shaft alignment and bearing problems are another story.

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