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Title#15
Investigation into the functional failure of a propulsion propeller pitch-control actuator of MV Hebrides, operated by Caledonian MacBrayne. Pitch control was delivered as part of the propulsion system by RR Marine.

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Summary#60

The MV Hebrides ferry operated by Caledonian MacBrayne ran aground in Lochmaddy Marina in North Uist Sep 25, 2016 at 1105 a.m. LT while approaching the berth. It was reported that the grounding was caused by a technical failure of the port pitch control system. The pitch is set by a stepper motor which depends on a grub-screw for transfer of torque between the motor and the actuator via a three part coupling. The preliminary investigation carried out by the Marine Accident Investigation Board (MAIB) determined that the failure of the pitch control was caused by the grub-screw unscrewing from its intended position. In addition to the three parts of the coupling, the grub-screw and the motor shaft, the investigation also examined a new coupling sourced through the normal supply chain. The investigation came to the following conclusions:

- Both the event coupling and the new coupling deviated slightly from dimensional requirements with respect to outer diameter, length, body length (event only), position of grub-screw hole and grub-screw hole large diameter. None of these deviations were considered to be of significance for the development of the event
- The coupling that came loose had a concentricity of 0.016mm to 0.023mm between outer and inner diameter. The new coupling had concentricity of 0.002 to 0.009
- The event grub-screw, the new grub-screw and the motor shaft were dimensionally correct.
- Neither the event grub-screw nor the new grub-screw had any practical rundown torque.
- Both grub-screws were found to have hardened tips, ~100HV and 40HV harder than the mating shaft flat for the event and new grub-screw, respectively.
- The motor shaft, the event grub screw and the new grub screw were all austenitic stainless steels similar to S30400,S30430 and S30500 respectively. The material type or specifications were not known to this investigation.

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Engine types#24	**Engine marks/vehicle name**	**Vehicle number/build#28**		**Module**
N/A	N/A	N/A		N/A
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1 INTRODUCTION

The MV Hebrides ferry operated by Caledonian MacBrayne ran aground in Lochmaddy Marina in North Uist Sep 25, 2016 at 1105 a.m. LT while approaching the berth. It was reported that a technical failure of the port pitch control system, and then being unable to clutch out the port shaft, led to the vessel being unable to reduce speed sufficiently for the docking procedure. The bridge crew directed the vessel away from the ferry terminal linkspan and instead colliding with pontoons at Lochmaddy Marina and grounding. During the collision with the pontoons the starboard shaft and propellers became wrapped with mooring chains.

The pitch is set by an actuator which is controlled by torque provided by a stepper motor. The assembled arrangement is shown in **Figure 1**. The torque transfer from motor to actuator is via a three-part coupling, two coupling halves and a polymer “spider”, see drawing in **Figure 2**. The motor half of the coupling depends on a grub-screw for transfer of torque from the D-shaped motor shaft. The preliminary investigation carried out by the Marine Accident Investigation Board (MAIB) determined that the failure of the pitch control was caused by the grub-screw unscrewing from its intended position. This investigation was informed that the grub-screw is normally secured by two mechanisms; 1) use of a “locktite” type product and 2) application of a set torque value that ensures the set-screw deforms the D-shape shaft surface and thereby friction. The preliminary investigation found that a “locktite” type product had not been applied, and it was uncertain to what degree the grub-screw had been torqued up. It should be noted that following the grounding, the coupling was reassembled, the grub-screw torqued up and locktite applied to make the vessel operational and recover the situation.

The preliminary investigation also found that the motor coupling had been machined to fit the motor shaft.

The following activities were requested by MAIB to be carried out during the laboratory investigation:

- High magnification photography of the grub-screw, the coupling inner diameter and the motor shaft.
- Assess geometry of the motor coupling half. Of particular interest are inner diameter, inner diameter concentricity and the internal threads for the grub-screw.
- Assess geometry of grub-screw and motor shaft against drawing requirements. Of particular interest are the grub-screw threads.
- Clarify the design intent such as required torque and any run-down torque for the grub-screw.
- Measure run-down torque for grub-screw.
- Hardness measurements in grub-screw, D-shaft flat and motor shaft.
- Verify that the material of the grub-screw, the motor coupling and the motor shaft all have the correct microstructure and chemical composition.

A new coupling was sourced via the normal supply chain for comparison purposes.

Through-out the investigation the following naming convention is used for the two coupling halves; “motor coupling” attached to the motor shaft; “actuator coupling” attached to the actuator.

2 CONCLUSIONS

- The threads of the event grub-screw and the new grub screw were dimensionally within specification. It should be noted that the event grub-screw had a cone tip, while the new grub-screw had a cup tip
- Both the event coupling and the new coupling deviated slightly from dimensional requirements with respect to outer diameter, length, body length (event only), position of grub-screw hole and grub-screw hole large diameter. None of these deviations were considered to be of significance for the development of the event.
- The shaft dimensions were correct to the drawings from the sub-supplier of the motor.

- Both the event and new grub-screws were found to have a loose fit with no practical run-down torque. No specific run-down torque requirement has been identified, but the documentation from the end-supplier (Ref. 3) requests the grub-screw to be replaced if found to be a loose fit. The same documentation requires the torque to be firm hand-tight (1.5Nm). Use of the term “loose fit” in the documentation is considered undesirable.

- Both grub-screws were found to be harder at the cone/cup than the mating shaft surface. The difference was ~100HV for the cone and ~40HV for the cup. Neither the required hardness difference between the shaft and grub-screw tip, or the required grub-screw tip hardness were known to this investigation.

- The actual material specifications for the shaft and the grub-screw were not known to this investigation. Examination found all three to be austenitic stainless steels with varying degree of work hardening. Analysis of chemical compositions suggested the parts were made o steels similar to S30400 for the shaft, S30430 for the event grub-screw and S30500 for the new grub-screw.

- The debris removed from the motor-coupling bore had the form of fine particles (~5µm main dimension) and originated most likely from the grub-screw, the motor-coupling or the shaft. The debris did not contain any larger pieces of material.

- It seems certain that the smaller cone shaped imprints on the motor shaft flat were caused by the event grub-screw, both prior to the event and after the event when the coupling was re-assembled to recover the situation. The circular groove shapes must have been caused by the grub-screw used in the motor coupling that was replaced during the service visit in March 2016 (Ref. 2). The location of circular shapes within area C demonstrated that this earlier motor-coupling had been able to travel nearly 10mm away from the actuator coupling. It is assumed that no other coupling and grub-screw have been used in the assembly in addition to those described above.

3 INVESTIGATION

Visual examinations were done under white light at up to x40 magnification. Analysis of chemical composition was carried out in a scanning electron microscope (SEM) using semi-quantitative energy dispersive x-ray analysis (EDS). Examination of microstructure was carried out on polished cross-sections etched in micro ferric chloride.

3.1 Visual examination and dimensions.

Prior to any disassembly the pitch control assembly was x-rayed using computer tomography (CT-scan). The CT-scan showed the grub-screw engaged and in correct position, see **Figure 3**. The assembly was disassembled in the RR Air Safety Investigation (ASI) workshop, under the supervision of personnel from MAIB. Initially only the motor, connecting block and actuator were separated, **Figure 4**. The motor coupling was securely fastened to the motor shaft. Untightening of the grub-screw to remove the motor coupling from the shaft required some force before it came loose. This suggested locking compound had been used on reassembly of the coupling following the incident. The actuator half of the coupling which is secured in position with a key and keyway, did not come loose. To forcefully remove it from the shaft would require further disassembly of the actuator assembly. As this half of the coupling was not of prime interest it was decided to leave it on the shaft.

Motor coupling:

The motor coupling appeared to be in a good condition, though partly stained by a dark slightly greasy deposit. The surfaces of the outer-diameter and the coupling teeth had a good surface finish, while the inboard surface finish looked uneven which was confirmed with surface roughness measurements. The roughness was measured using a Taylor-Hobson Surtronic 3 in 28 different locations. The average Ra-value was 1.18μm, while maximum Ra-value was 2.66μm and min Ra-value was 0.47μm. A notable mark or score extended 360° around the bore at height with the grub-screw hole. See **Figure 5**. (The score was not included in the surface roughness measurements). The threads for the grub-screw were undamaged but with loosely adhering dark particulate material. The threads following cleaning can also be seen in **Figure 5** with possible remnants of locktite. The end-face opposite the coupling teeth had visually a rougher surface finish, see **Figure 6**. A piece of material was visible at the bore surface at the intersection with the grub-screw hole. The material was removed, cleaned in acetone and filtered before being analysed using EDS. Examination in the SEM revealed that the material consisted of numerous small particles (~5μm main dimension) but did not contain larger pieces of material torn off from the grub-screw as had been suspected initially. Viewed in the SEM using back-scattered detector, some of the particles (minority) stood out as heavier (visible as brighter) than the remainder. This normally suggests higher metal-content or containing heavier elements than the surrounding material. Analysis found the heavier particles to be steel with ~17wt% Chromium (Cr), ~8wt% Nickel (Ni) and several other elements in smaller concentrations. Analysis directly on the surface of metals, is unlikely to give an exact match with the parent alloy. The obtained chemical composition was a fairly good match with that obtained from analysis of the coupling itself and with the grub-screw. Hence, either of these are likely sources of the particles. The lighter particles were also Fe based but had Zn as the main alloying element (13wt%) with lower concentrations of Cr and Ni. No source for this material could be identified but the presence of Cr and Ni may suggest that these were agglomerates of material from different sources, including coupling and grub-screw. That these particles stood out as lighter despite containing Zn which is a heavier element, suggested that they also consisted of organic material such as carbon which can't be detected with the EDS detector used.

Grub-screw:

The grub-screw was of the conical shape and the cone was deformed by flattening. The resulting reduction in grub-screw length was estimated to be ~0.2mm, see **Figure 7**. The estimate is based on the assumption that the original grub-screw tip had the maximum allowable tip diameter of 1mm. The deformation also resulted in a step indicative of the degree of material displacement running 360° around the cone, marked with black arrows in **Figure 7** and **Figure 8**. The morphology of the end-face of the deformed cone suggested direction of movement across rather than circumferentially. The diameter of the conical end-face measured approximately 1.7mm (radius of ~0.85mm), see **Figure 8**. The threads appeared cut rather than rolled and were in a good condition. The thread pitch measured 0.7mm. See **Figure 9**. The outer diameter was measured to be 3.94mm. The length of the grub-screw measured to 7.89mm. After being initially unscrewed and breaking the applied locking medium, the grub-screw felt loose with no practical run-down torque.

Motor shaft:

The motor shaft measured 28.5mm long from the motor housing flange with a diameter of 9.52mm (30.1mm measured at the base of shaft). Towards the end-face it had a 20.2mm long and 7mm wide machined flat in a plane parallel to the tangential plane, resulting in a "D-shaped" cross-section. The "reduced diameter", at the machined flat, measured 8.43mm. These dimensions were within the drawing tolerances specified by the motor supplier (**Ref. 4**). The design intent for the grub-screw was to engage with the flat and thereby prevent the coupling from rotating on the shaft. Engagement with the grub-screw had left numerous deformation marks on the flat, see **Figure 10**. There were also marks on the shaft diameter, running in the circumferential direction, indicating engagement outside of the flat. The deformation marks on the flat could be divided into three groups. Within area A the marks were elongated shallow depressions with polished or fretted surfaces, with no distinct shape. Within areas marked B, the marks were formed by both depressions and raised material. The same surface morphology was present but the marks had distinct circular shapes. The circular marks could be further divided into smaller diameter circles forming cup shapes and larger diameter circles forming grooves. The circular marks are shown in **Figure 11** at higher magnification. The smaller cup-shaped marks had radii ranging from ~0.53mm to ~0.73mm. The larger groove-shaped marks all had a similar radius of ~1.26mm. The smaller cup-shaped marks were consistent with having formed by the imprint of a cone-shape. The larger groove-shaped marks were consistent with having formed by the imprint of a cup-shape. This is demonstrated in **Figure 12**. Circular groove shapes could also be seen within area C, but not as distinct as within area B. The radii of the circular shapes within area C were similar to the circular groove shapes within area B.

It should be noted that the deformed cone tip of the grub-screw had an approximate radius of ~0.85mm, see paragraph above. This is of a similar order to that of the conical shaped imprints within area B. The radius of the larger groove-shaped marks were similar to that of a conical shaped grub-screw (~1.16mm) that was supplied together with a new coupling in support of this investigation. See paragraph below "New coupling" (and **Figure 16**). This also suggested that two different grub-screws had been fitted to the shaft, see discussion.

Actuator coupling:

The actuator coupling was not removed from the actuator shaft. Consequently, due to its position within a sleeve and flange surrounding the shaft, it could only be partially examined. The shaft, depicted in **Figure 4** and **Figure 13**, had a dark grey surface and was clearly older than the motor-coupling. The end-face and the prongs were damaged, visible as scores and cuts to the surfaces. Rather than being a result of operation, the damage appeared consistent with attempts to remove the coupling from the shaft.

Spider:

The spider was of a yellow colour and consisted of a hub with four equally spaced arms. It was marked ROTEX KTR GS9 on one face and PUR 3 on the other, see **Figure 14**. The end-faces and the arm surfaces facing the motor coupling prongs exhibited no evidence of damage. The arm surfaces facing the actuator coupling prongs exhibited some damage in the form of deformation. The observed damage was consistent with the poor condition of the actuator coupling prong surfaces.

New Coupling

A new coupling was received through the same supply route as the replacement coupling would have been supplied to MV Hebrides. The coupling consisted of two coupling halves, a grub-screw and a blue coloured spider. See **Figure 15**. One coupling half was supplied with a threaded grub screw hole. The other half was machined to take a key. The grub screw was fairly loose with no practical run-down torque.

The dimensional measurements of each component are summarised in **Table 1** below. Where the required attribute is not defined on the available drawing N/A is present in the requirement column.

Table 1. Measured dimensions, MV Hebrides motor coupling, new motor coupling, and motor shaft. Requirements are stated as nominal values (single value) or as minimum and maximum values.

	MV Hebrides [mm]	New coupling [mm]	Requirement [mm]
Coupling, outer diameter D	19.87	19.85	20.00
Coupling, inner diameter d	9.56	9.55	9.550 – 9.565
Coupling, bore surface roughness Ra [µm]	0.5 – 2.6[µm]	0.45 – 1.12[µm]	N/A
Coupling, total length	24.9	25.00	25.00
Coupling, concentricity outer D and inner d - (prong end) - (motor end)	0.023 0.016	0.009 0.002	N/A
Coupling, length without prongs	15.90	16.10	16.00
Coupling, grub-screw hole distance from end-face	10.20	9.80	10.00
Coupling, grub-screw hole thread large diameter D	4.09	4.12	4.000*
Coupling, grub-screw hole thread small diameter D_1	3.28	3.42	3.242 – 3.422*
Coupling, grub-screw hole thread pitch diameter D_2**	3.6***	3.7***	3.433 – 3.523*
Coupling, grub-screw hole thread pitch	0.7	0.7	0.7
Grub-screw, thread outer diameter d	3.94	3.87	3.838 – 3.978*
Grub-screw, thread inner diameter d_1	3.26	3.12	3.002 – 3.119*
Grub-screw, thread pitch diameter d_2**	3.44	3.44	3.433 – 3.523*
Grub-screw, thread pitch	0.7	0.7	0.7
Grub-screw, length	7.89	8.24	N/A
Motor shaft, diameter	9.52	---	9.512 – 9.525
Motor shaft, diameter, flat	8.45	---	8.3 – 8.5
Motor shaft length of flat	20.2	---	19.8 – 20.2
Motor shaft length	30.1	---	29.9 – 31.1

* Dimensional tolerances for the grub-screw and grub-screw hole threads based on the assumption that these are defined as 6g and 6G in accordance with ISO 4027 and ISO 4029.

** Diameter measured at half-pitch (P/2) height of threads.

*** Half pitch diameters were slightly large on both couplings. However, accurate measurements were made difficult by the limited resolution of the CT-scan.

3.2 Hardness, microstructure and chemical composition

Cross-sections were made of the motor shaft and both grub-screws (new and event coupling) to take hardness measurements, analyse chemical composition and assess microstructure. The cross-section of the shaft was made normal to the shaft axis, between the shaft end-face and the grub-screw marks. The cross-sections of the grub-screws were made in the plane of the screw axis.

Analyses of the chemical compositions were carried out on the cross-sections in the polished condition. The results are listed in **Table 2**. The specified alloys were not known to this investigation, but common alloys similar to the observed chemical compositions are suggested. Based on the observed chemical compositions and that the three components were non-magnetic, the materials were expected to be austenitic stainless steels.

Table 2. Chemical composition.

Element	Shaft	Event grub-screw	New grub-screw
Fe	69.6	66.2	64.3
Cr	18.5	17.8	19.2
Ni	7.8	10.8	11.8
Mn	3.4	1.0	2.8
Si	0.7	0.5	0.6
Cu	---	3.0	--
S	---	0.9	1.4
Similar alloy	UNS: S30400	UNS: S30430	UNS: S30500

Micrographs of the two grub-screws were produced by swab etch in micro-ferric chloride. The swab etch brought out clearly the macro-structural flow-lines resulting from the manufacturing, see **Figure 16**. The specific manufacturing process is not known for either grub-screw. However, based on the flow-lines the following can be inferred:

1) Event grub-screw: Cone and hexagonal socket were produced by upsetting of a straight work-piece. The threads, which were flat-bottomed, were then produced either by cutting or rolling. The flow lines following the thread profile are faint and could possibly have resulted from cutting. It should be noted that the specification, requires a minimum tread radius of 0.088mm. Upsetting of the cone and the socket will have caused notable work-hardening in the deformed areas.

2) New grub-screw: Cup was produced by machining. Hexagonal socket was produced by upsetting of a pre-drilled hole. The threads were produced by rolling and had a minimum radius in excess of the 0.088mm requirement. Due to the lack of significant deformation, a more uniform hardness would be expected.

A micrograph of the shaft cross-section was produced by electrolytic etch in aqua regia glycerol. The micrograph showed a fine grained austenitic structure with finely dispersed carbides and visible slip-bands, probably the result of prior forging/extrusion process. The micrograph can be seen in **Figure 17**.

Hardness was measured using Vickers micro-hardness (**Ref. 1**) and the results are listed in **Table 3** below. The position of the hardness measurements are shown in **Figure 18**.

Three sets of measurements were carried out on the shaft cross-section; core; traverse to outer diameter and a traverse to machined flat. The hardness measurements indicated a slight increase in hardness from the core (250 HV) towards the outer diameter (285 HV). Hardness near the machined flat surface measured (260 HV), consistent with the hardness–profile of the outer diameter traverse, indicating that the flat was machined after the hardness distribution from core to outer diameter had been achieved. The cross-section of the shaft showed a fine grained structure. No flow lines were witnessed. This was as expected as the cross-section was across the shaft axis and across the anticipated direction of forging or extrusion.

Three sets of measurements were carried out on the grub-screw from MV Hebrides; core; traverse from core towards flattened cone and a traverse towards the cone flank. The average core hardness was 262 HV. Two of the core indents were within the hexagon socket deformation area and showed distinctly higher values (core 1 and core 2). Excluding these two gave an average core hardness of 238HV. The cone traverse showed a marked increase from core levels to a maximum of 351HV within the flattened cone tip. This was expected as a consequence of deformation from use, resulting in work hardening. A second traverse towards the tip flank was made to verify whether the cone was hardened away from the deformation caused by contact with the shaft. The traverse, which extended into an area at the tip flank that appeared unaffected by the cone-tip deformation, exhibited an increase of hardness from the centre-line towards the cone flank with a maximum of 365HV. This exceeded the hardness measured within the flattened tip. This would suggest that the grub-screw had been hardened during manufacture.

Two sets of measurements were carried out on the new grub-screw, core and traverse from core to cup. The core hardness results were even with an average value of 288HV. The traverse did not exhibit an increase towards the cup and were in family with the core measurements. This was consistent with the limited deformation variation indicated by the flow-lines.

Table 3

	Shaft			MV Hebrides grub-screw			New grub-screw	
HV0.5	Core	Flat traverse	Diameter traverse	Core	Cone traverse	Tip flank traverse	Core	Cup traverse
Indent 1	243.7	259.6	285.5	335.7	350.7	365.2	280.0	299.6
Indent 2	253.0	258.8	282.1	307.9	350.5	346.1	294.7	302.4
Indent 3	248.0	248.7	273.3	276.9	292.5	320.4	286.6	274.8
Indent 4	256.7	250.7	261.2	238.2	238.3	N/A	286.3	289.8
Indent 5	247.9	241.0	258.7	224.6	223.8	N/A	293.6	N/A
Indent 6	N/A	244.4	247.6	224.6	N/A	N/A	N/A	N/A
Indent 7	N/A	245.9	248.6	223.0	N/A	N/A	N/A	N/A
Average	250		265	262			288	

4 DISCUSSION

- The darker grey surface of the actuator coupling when compared with the motor coupling and the damage to the prong-surfaces, were consistent with this coupling being older and attempted removal as reported in Service Report dated 23.03.2017, **Ref. 2**.

- It seems certain that the smaller cone shaped imprints on the motor shaft flat were caused by the event grub-screw, both prior to the event and after the event when the coupling was re-assembled to recover the situation. The circular groove shapes must have been caused by the grub-screw used in the motor coupling that was replaced during the service visit in March 2016 (**Ref. 2**). (It is assumed that no other coupling and grub-screw had been used in the assembly in addition the two described above). The location of circular shapes within area C demonstrated that this previous motor-coupling had been able to travel nearly 10mm away from the actuator coupling. Assuming that the previous coupling had the same geometry as the event coupling with prong length of ~9mm, the coupling will have been close to disengagement. This investigation has not received information that the coupling had previously disengaged.

- Both the event coupling and the new coupling deviated slightly from dimensional requirements with respect to outer diameter, length, body length (event only), position of grub-screw hole and grub-screw hole large diameter. None of these deviations were considered to be of significance for the development of the event. The half-pitch diameters were also slightly larger than maximum tolerance. However, accurate measurements of these were made difficult by the limited resolution of the CT-scan. Based on comparison, the event coupling and the new coupling are very similar, but with the event coupling having a higher value for concentricity. The grub-screws were both within specification with respect to main thread dimensions. It should be noted that the event grub-screw had a cone tip, while the new grub-screw had a cup tip. Also, the event grub-screw threads where flat-bottomed without a minimum radius of 0.088mm as specified. This is not considered to have had any impact on the event.

- The documentation from the end-supplier (**Ref. 3**) requests the grub-screw to be replaced if found to be a loose fit. This requirement is in addition to the use of locktite. Use of the term "loose fit" is undesirable as it is open to interpretation. However, both the event and the new grub-screw were found to be a loose fit within tolerance, meaning they could be moved radially and axially with fully engaged threads and no thread locking.

- The cone/cup tips of both grub-screws were found to be harder than the mating flat surface of the shaft. The difference was in the range of ~100HV for the event grub-screw and ~40HV for the new grub-screw. Though this investigation has been informed that the grub-screw was required to be harder than the shaft (**Ref. 3**), the specific requirement is not known. Hence it can't be concluded whether the grub-screws were conforming with respect to hardness.

- Possible alloy matches for the motor shaft and the two grub-screws were suggested based on chemical composition analysis and the material being non-magnetic. However, it was not known to this investigation what alloys were specified.

- In addition to the difference in shape (cone vs. cup), the alloy composition, the macro-structural flow lines and the manufacturing of threads, differed for the two grub-screws examined. It is not clear from the received documentation whether this is permissible for the coupling design.

5 REFERENCES

Ref. 1. ITSB5477 Issue 2, Vickers Micro Hardness Testing of Shaft and Screw Cross-Sections. Author [redacted], Issued 10th February 2017.

Ref. 2. KPRS-A8BK3Z. RR Service Report, MV Hebrides, Author: [redacted], Issued: 23.03.2016.

Ref. 3. Rolls-Royce. DMN000238972. Service procedure for Propeller pitch control actuator coupling, revision A, issued 03.11.2016.

Ref. 4. HY200 3424 Hybrid Stepping Motors, supplier specification.

6 IMAGES

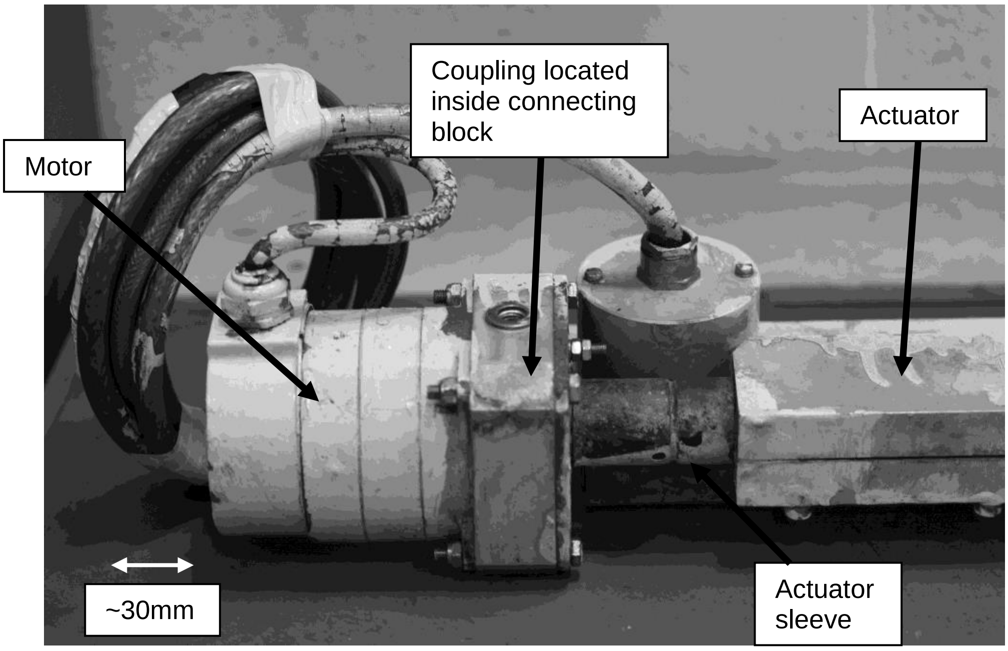


Figure 1. The image shows the pitch control assembly with the motor to the left and the actuator to the right. The coupling with the grub-screw is located inside the block at the centre of the assembly.

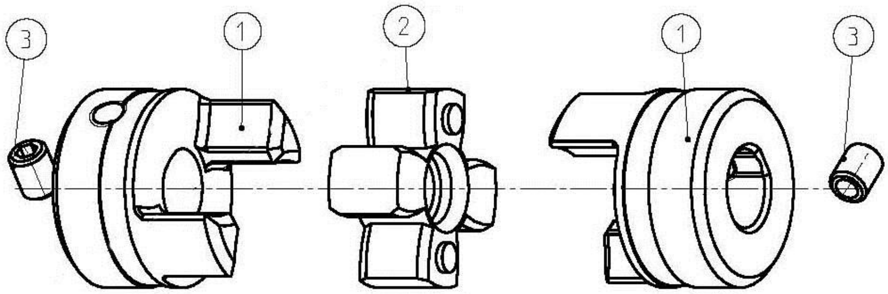


Figure 2. The transfer of torque from the motor to the actuator is via a three part coupling. The three parts of the coupling are the two coupling halves (no.1) and a polymer "spider" (no.2). The prongs of the polymer spider located between the two halves prevents metal to metal contact. The motor coupling half is secured to the motor D-shaft by a grub-screw (no.3). The sketch above shows a slightly different coupling. The actual coupling investigated had straight sided cylindrical outer diameters and was supplied with key and keyway for the actuator half rather than a grub-screw.

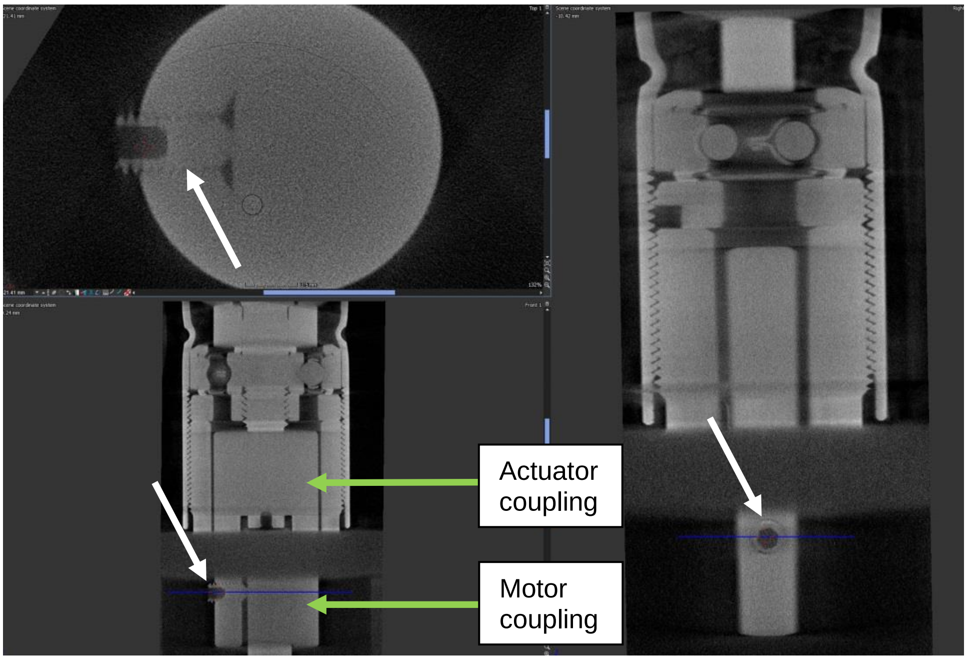


Figure 3. Prior to disassembly of the pitch control assembly, the coupling was imaged by computer tomography. Upper left image: Section through the coupling, grub-screw and shaft in a plane normal to the shaft axis. The location of this section is marked by the blue lines in the lower left image and the right hand image. Lower left image: Section in a plane defined by the shaft axis and the grub-screw axis. Right hand image: Section in a plane parallel to the shaft axis and normal to the grub-screw axis, intersecting the grub-screw in the hexagonal socket. The large threaded portion and the ball bearing visible in the latter two images are part of the actuator sleeve. The grey band going across both these images is due to the actuator flange thickness preventing x-ray penetration. All three images above show the grub-screw (white arrows) engaged and in the correct position.

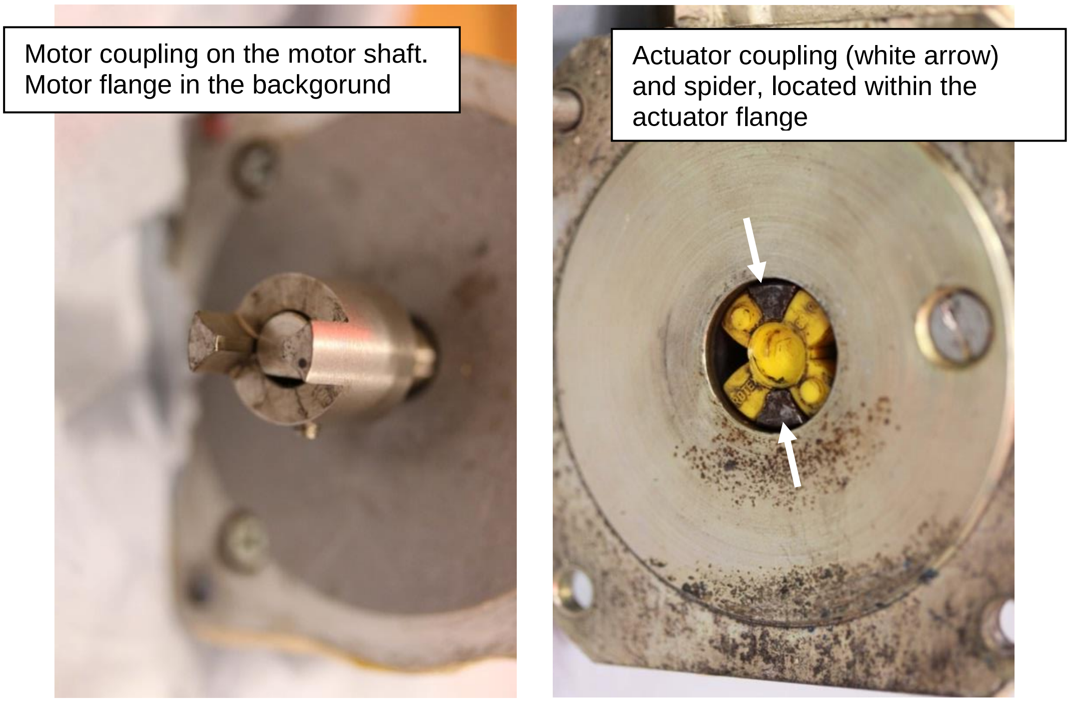
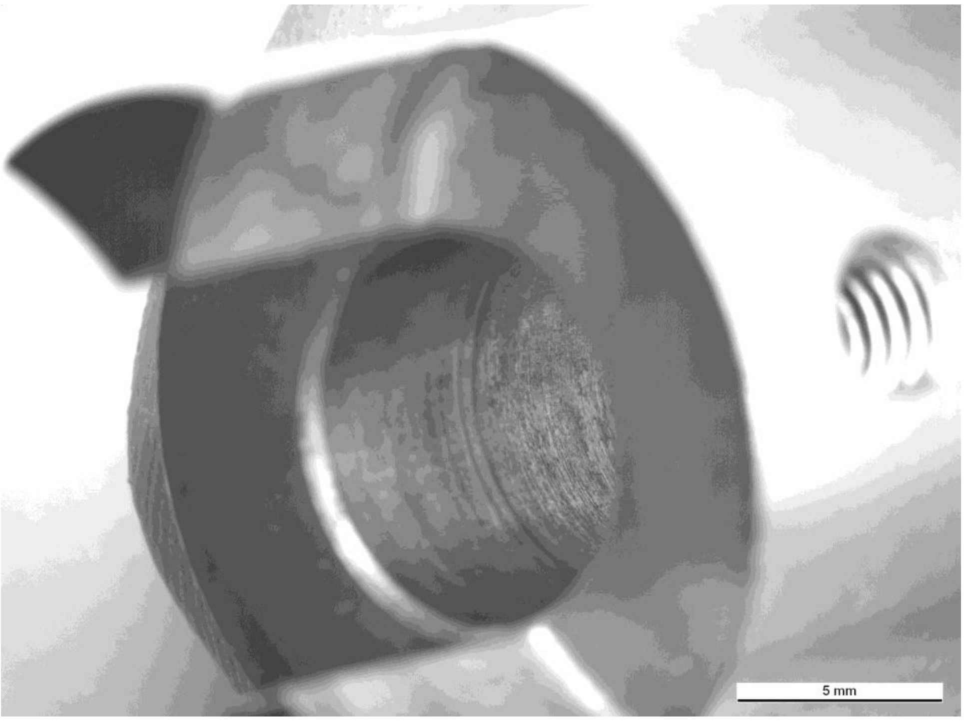


Figure 4. The images show the motor coupling and the actuator coupling with the spider, following disassembly. For scale, the outer diameter of the coupling is ~20mm.



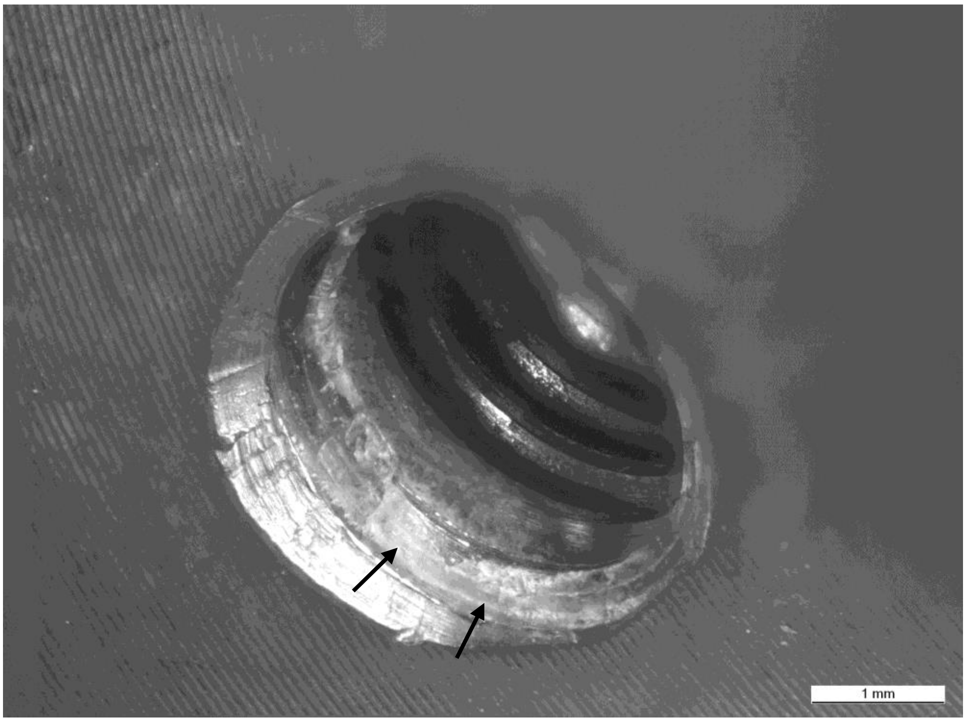


Figure 5. The upper image shows the relatively rough surface of the motor coupling bore and the 360° circumferential score. The lower image shows the threads for the grub-screw which were found to be in a good condition. The two black arrows indicate the presence of a locktite type material. Both images were taken after cleaning.

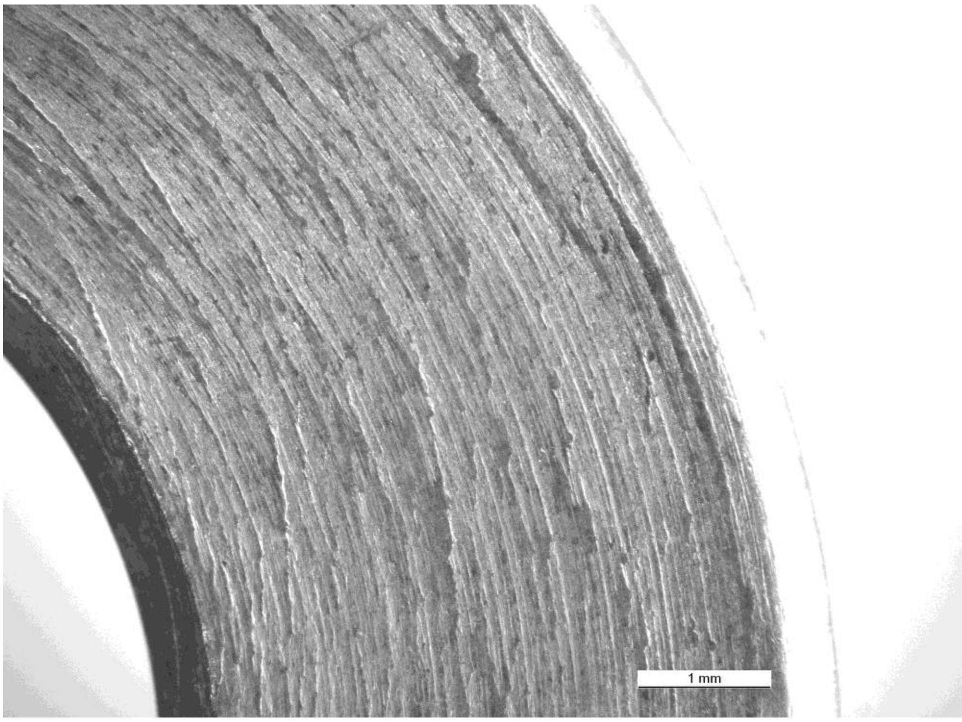


Figure 6. Visually, the motor coupling end-face (opposite to the prongs) had a rougher surface.

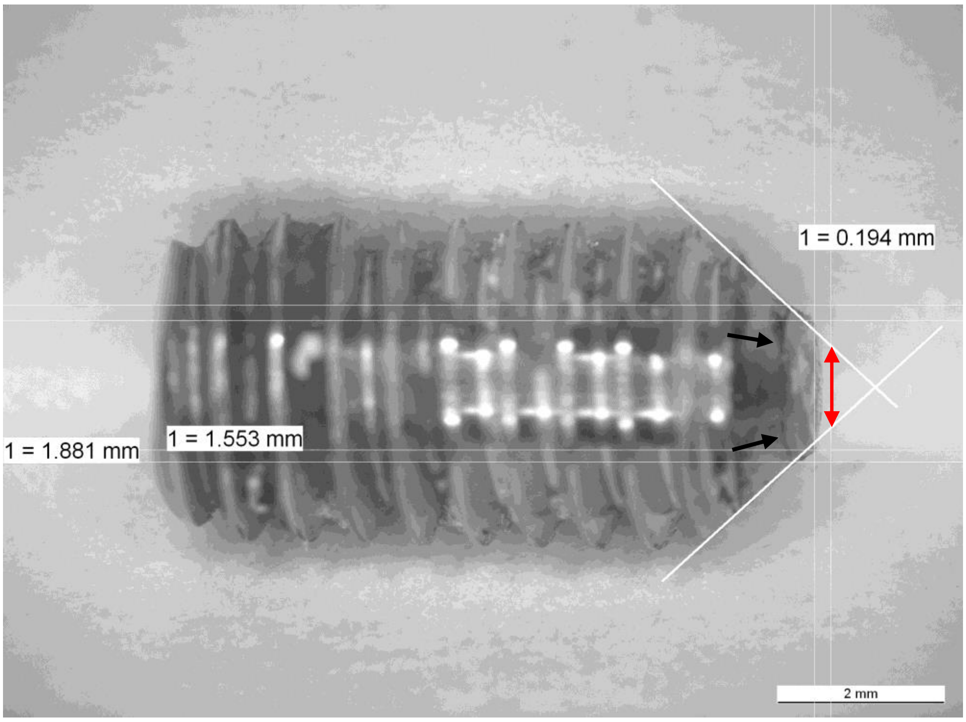
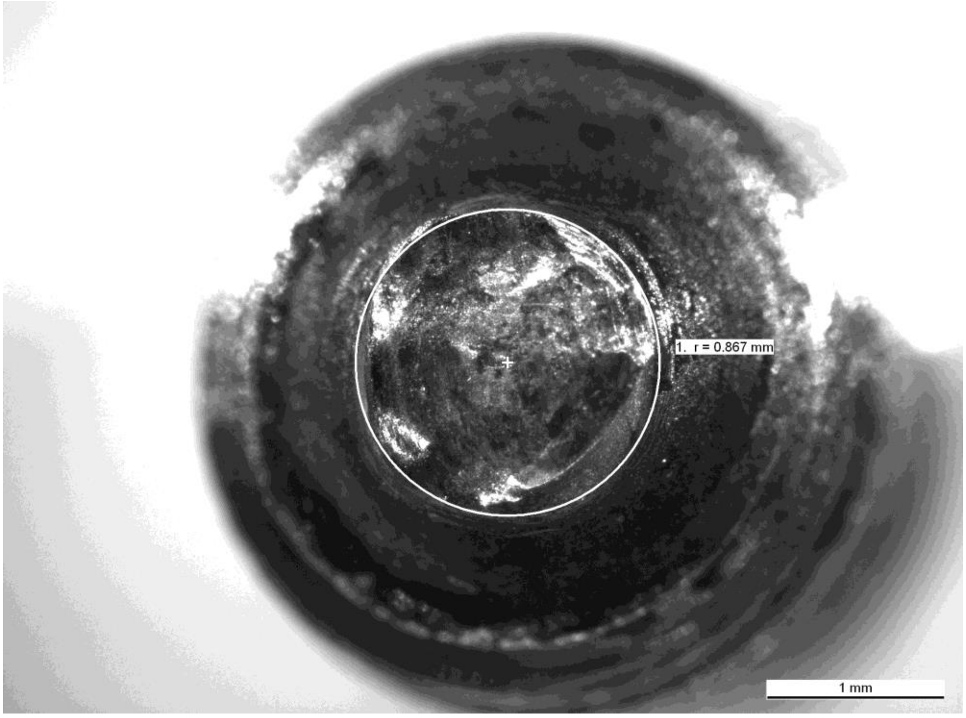


Figure 7. The cone shape of the grub-screw had been deformed, resulting in an estimated ~0.2mm shortening of the length. This is based on an original tip diameter of 1mm (maximum allowable indicated with red arrow). A possible crack ran 360° around the cone adjacent to the deformed end-face, marked with black arrows. In the photograph the centre-line of the grub-screw is out of focus. This is due to the need for keeping the projected profile in focus to enable measurements to be taken.



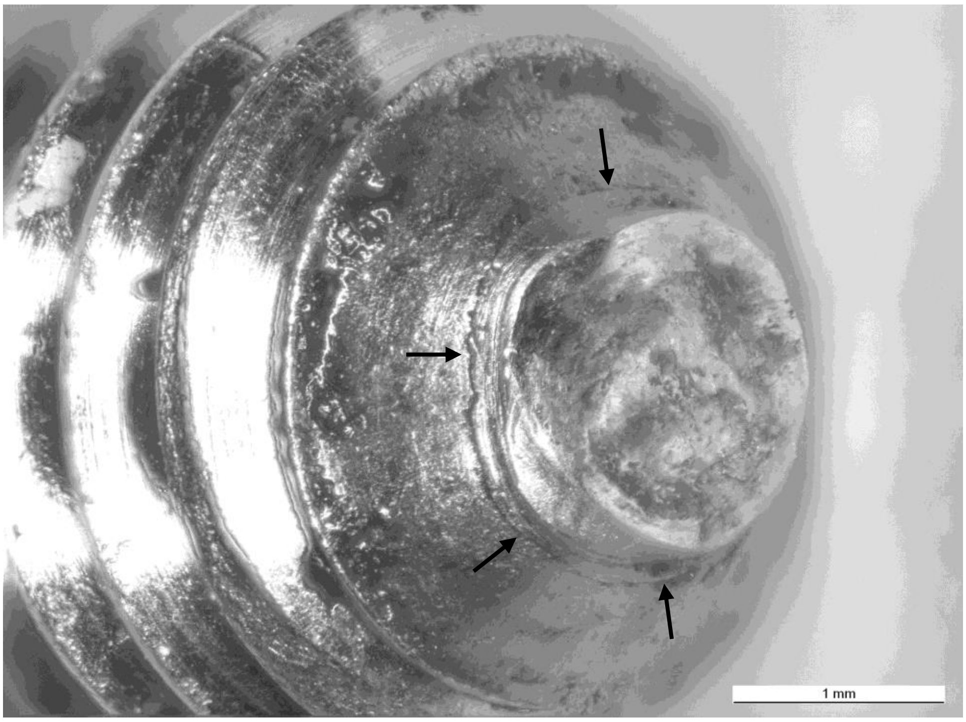


Figure 8. The deformed cone end-face had the approximate shape of a circle with a diameter of ~1.73mm. The deformed tip did not have a perfect circular shape and the drawn in circle of r=0.867mm is for illustration rather than an accurate measurement. Hence within the text of the investigations the diameter of the deformed tip is stated to be ~1.7mm. The possible crack running 360° around the cone is marked with black arrows in the lower image.

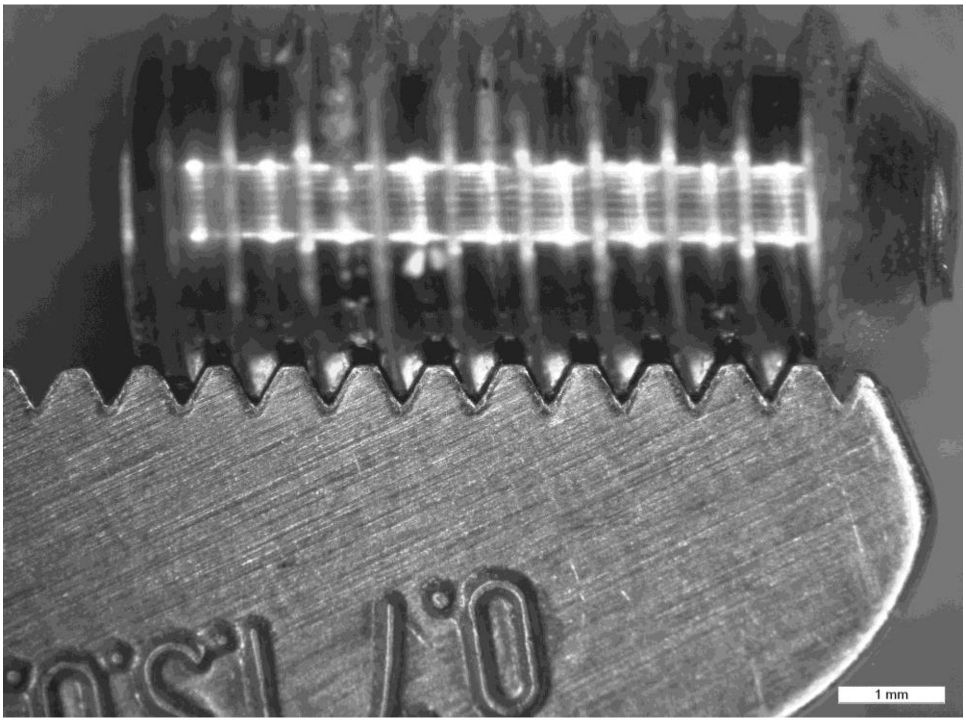


Figure 9. The threads were in a good condition and had pitch that fitted with the 0.7 gauge.

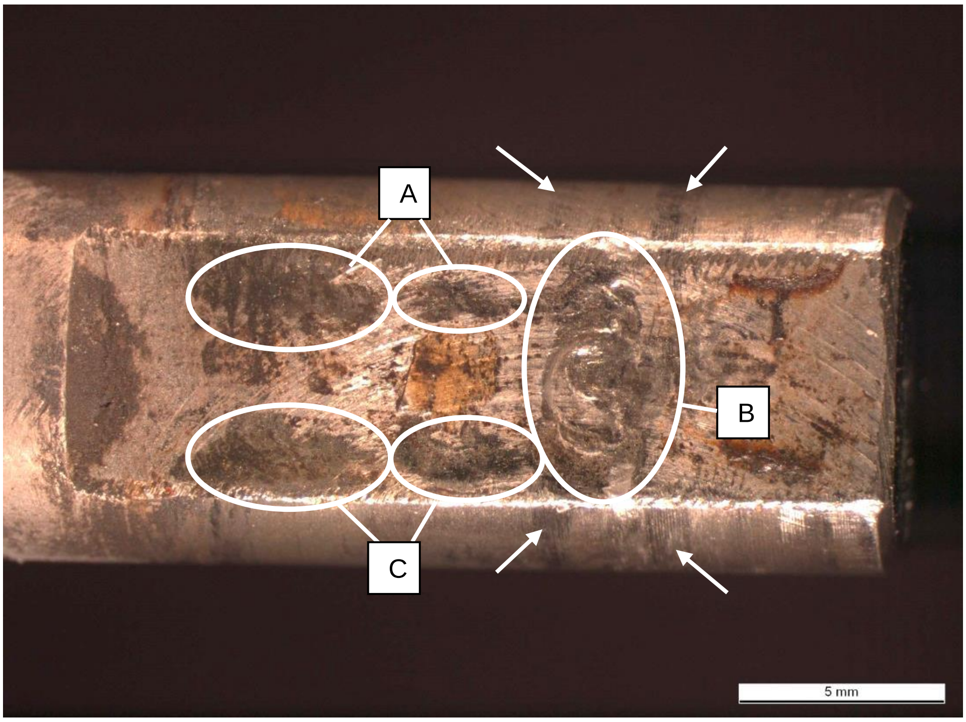
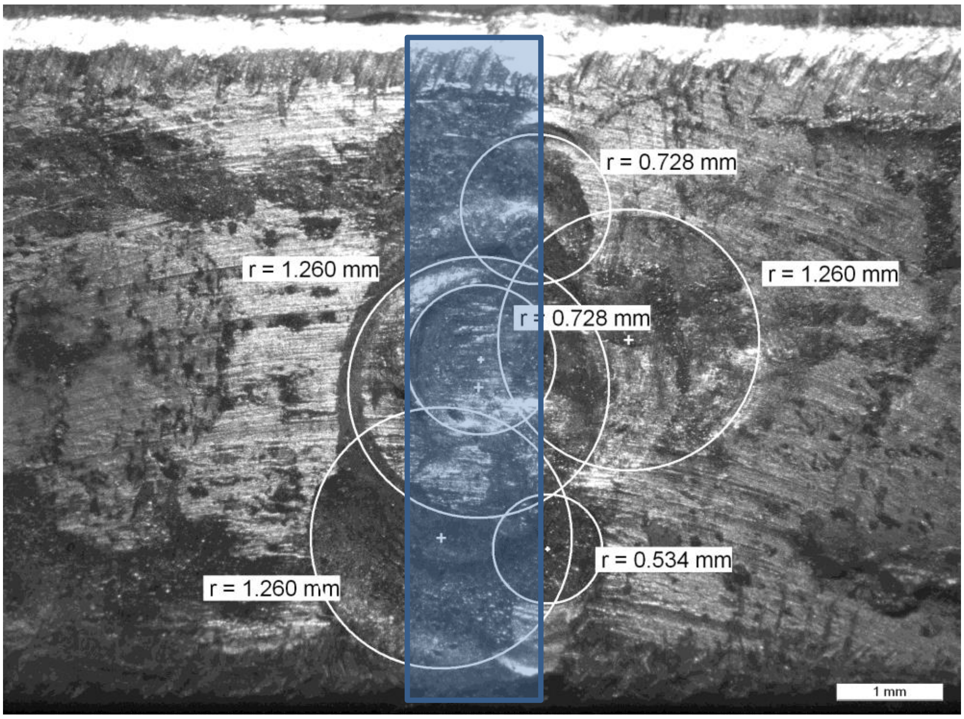


Figure 10. Engagement with the grub-screw had left numerous damage-marks on the motor-shaft flat in several distinct areas (encircled). The marks were visible as fretted/polished deformation. Areas marked A were predominantly fretted/polished deformation with no clear shape. Within area B the marks had taken on a circular shape. Also within area C the marks had a circular shape, but less distinct than in area B. See Figure 11. There was also evidence suggesting engagement with the grub-screw outside of the flat, on the shaft diameter (white arrows).



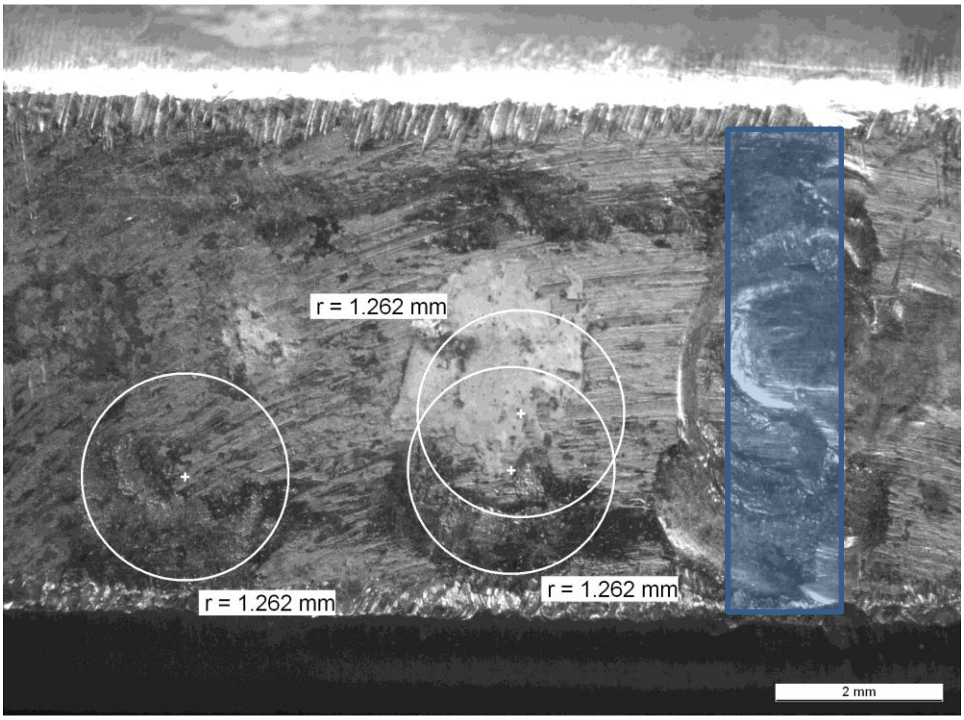


Figure 11. The images show circles fitted to the semi-circular shaped marks within areas marked B and C. The marks in areas marked C were less distinct than those in area B. The radius values are best estimates and should only be considered accurate to +/- 0.1mm. The shaded bands indicate the intended axial location for the grub-screw, 6.8mm to 7.8mm away from the shaft end-face. The band is drawn across the full width of the flat, though the intention is for the grub-screw to be centred.

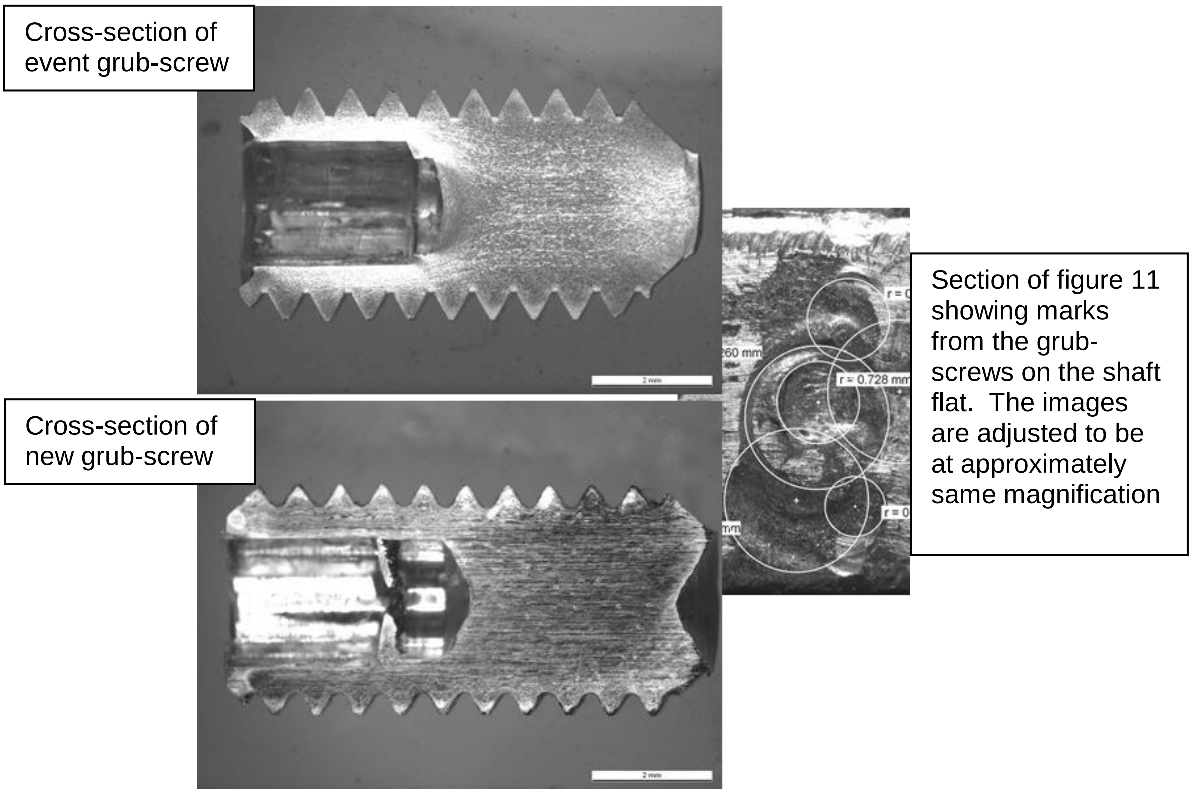


Figure 12. The images, which are at same magnification, illustrate how the small imprints fit with the cone and the larger fit with the cup.

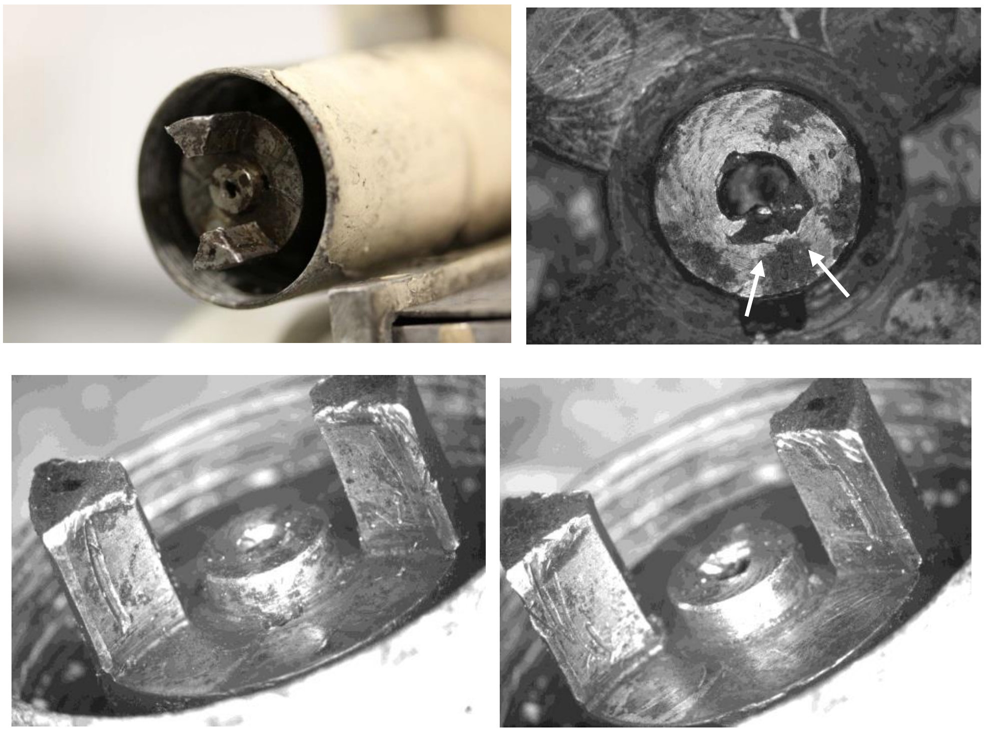


Figure 13. Top left: actuator coupling pictured as located within in sleeve. Top right: damage to actuator shaft end-face (white arrow). Bottom left and right: damage to the load-carrying prong surfaces (rotated 180°). For scale, the outer diameter of the coupling is ~20mm.

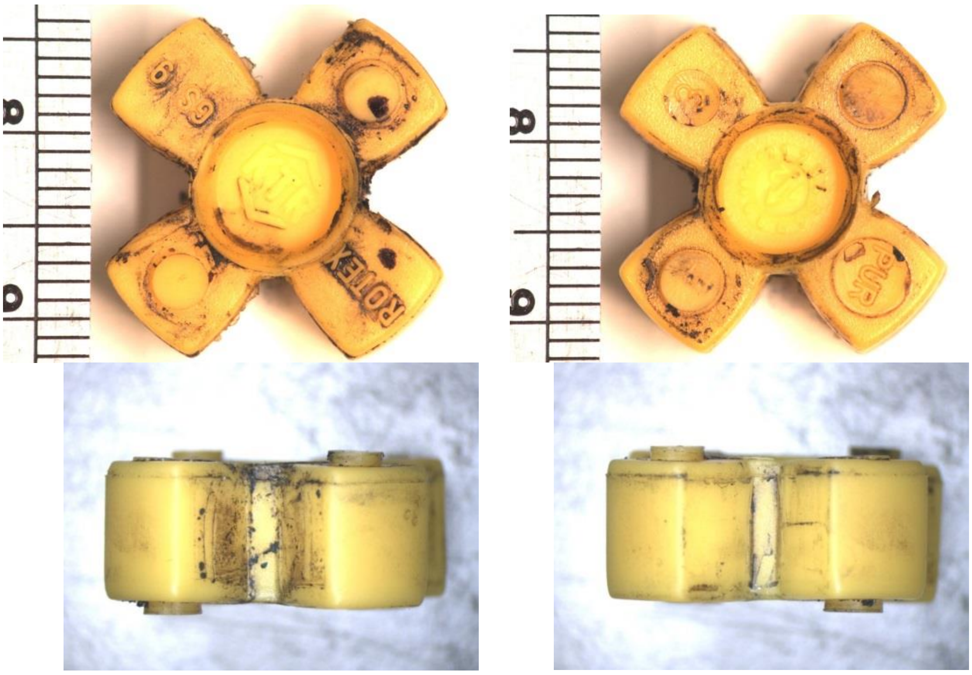


Figure 14. The two upper images show spider end-faces with marking. The lower left image shows damaged prong loaded faces, that had contacted the actuator coupling. The lower right image shows undamaged prong loaded faces, that had contacted the motor coupling.

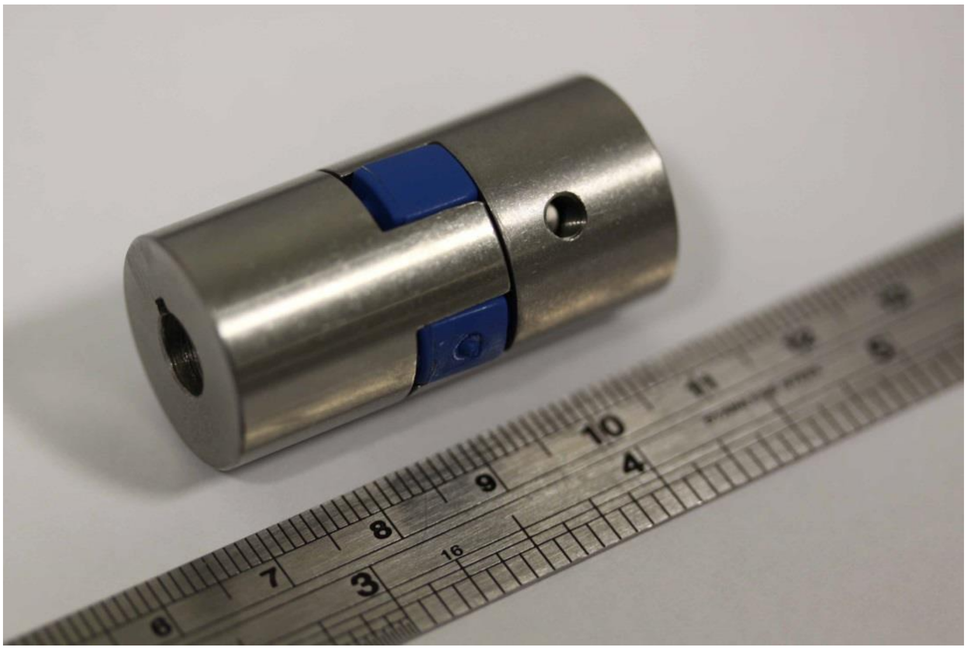
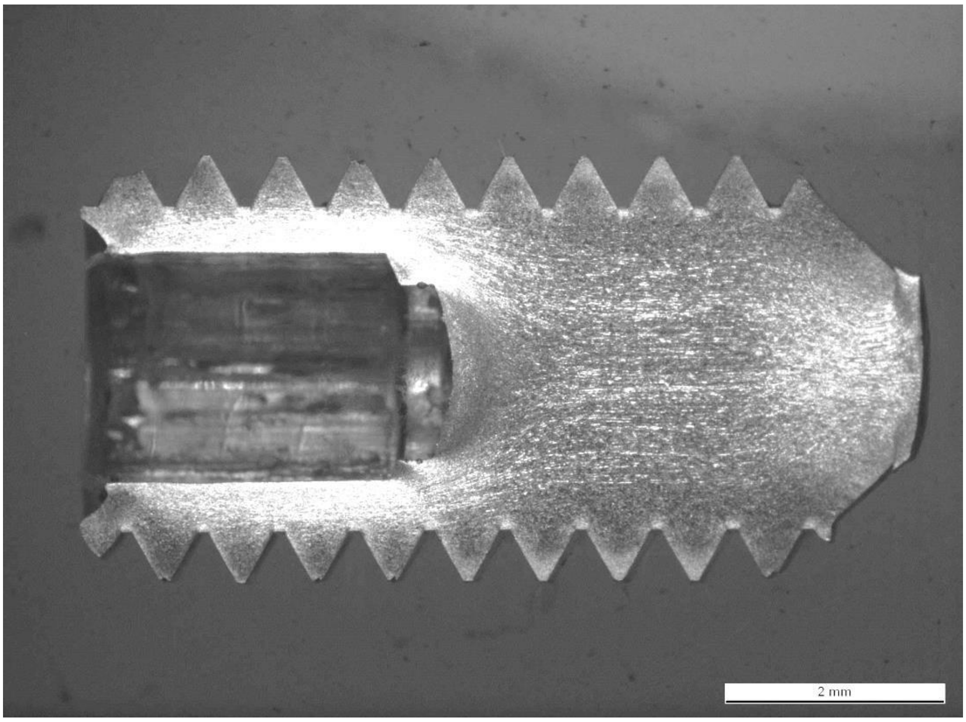


Figure 15. A new coupling was received through the same supply route as the replacement coupling would have been supplied to MV Hebrides. Motor coupling to the right with grub-screw hole and actuator coupling to the left with key-slot.



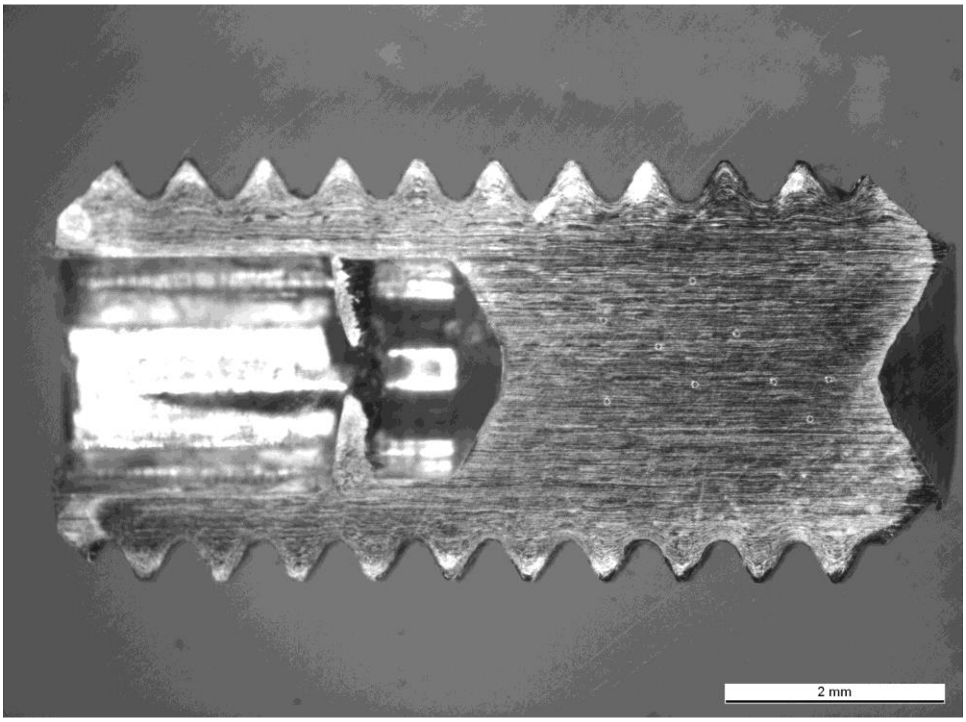


Figure 16. The two images show the macro-structure of the event grub-screw (upper) and the new grub-screw (lower). The difference in flow lines resulting from the manufacture of the grub-screws is evident.

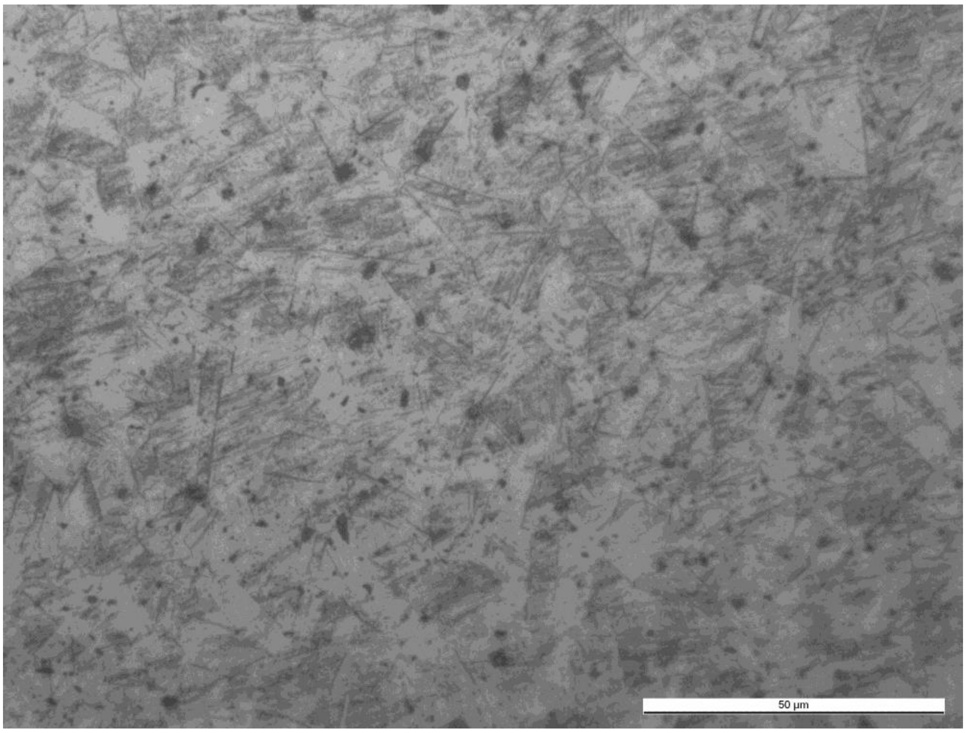


Figure 17. The shaft exhibited a fine grained austenitic structure with finely dispersed carbides and visible slip-bands.

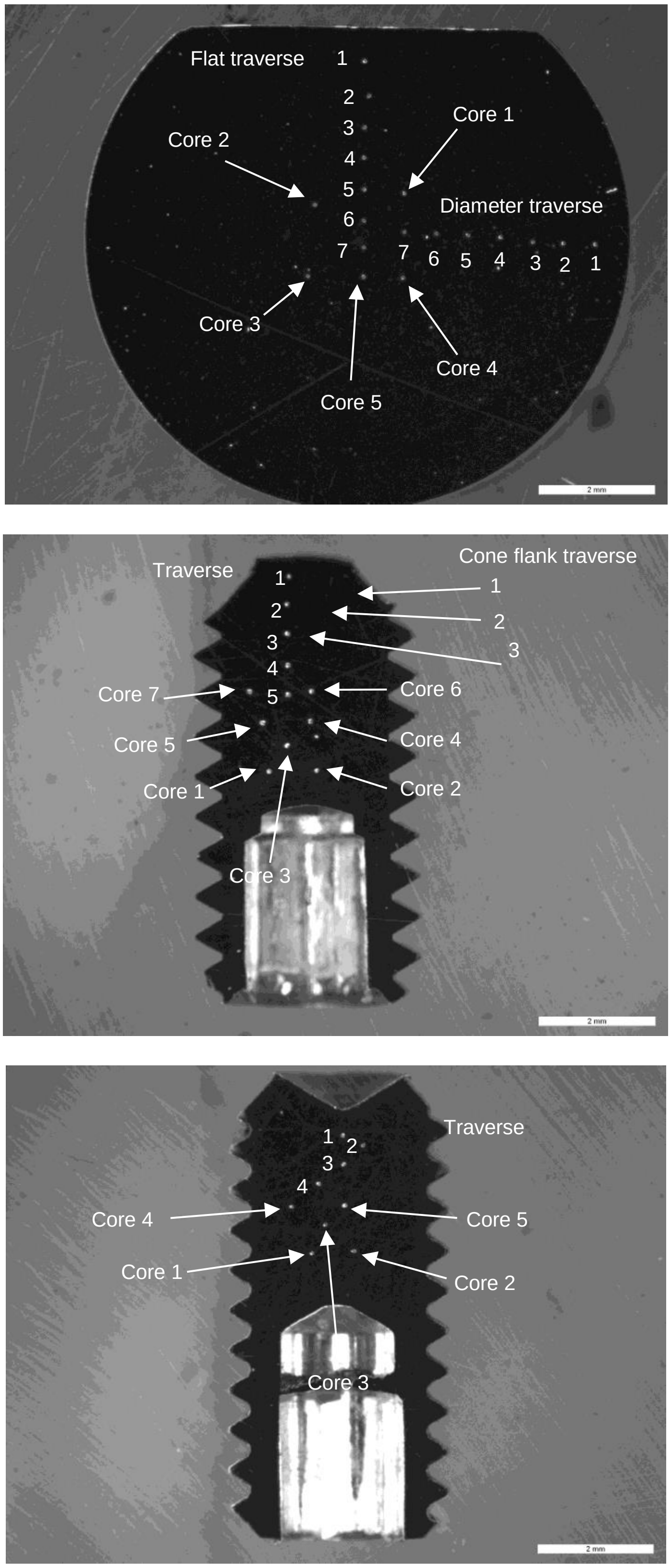


Figure 18. The images show the positon of the individual hardness indents, upper image is the motor shaft, followed by event grub-screw and new grub-screw.

Rolls-Royce Service Letter dated 2 May 2015

Rolls-Royce

Propulsion – Marine Services

Service letter

RECOMMENDED ACTION

UPGRADE FOR CONTROL SYSTEMS AVAILABLE

Applies to:

All vessels with controllable pitch propellers and the remote control systems **Helicon-MP, Helicon-CT w/CPP, HeliconX or with Helicon-X3 delivered prior to September 2009**

Background:

The Helicon range of propeller and thruster control systems was first launched to the market in 1984. A large number of improvements have subsequently been implemented both to the Helicon system hardware and to the system software since this original release.

In 2002 Pitch Deviation Alarm functionality was incorporated into Helicon-X, providing alarm indication in the event of detecting deviation between commanded pitch and actual pitch. In 2005 Helicon-X3 was first released. In 2009 Automatic Clutch-Out functionality on pitch deviation was added as a standard feature in Helicon-X3 for propellers incorporating stepper motor with linear actuator drives.

In parallel with incorporating this increased functionality in new deliveries, a number of upgrade solutions have been developed for both Pitch Deviation Alarm and Automatic Clutch-Out features. These enable equivalent functionality to be incorporated in systems delivered prior to the functionality being incorporated as standard. On older vessels they similarly act to mitigate the consequences of scenarios that can result in uncontrolled pitch application.

Recommended action:

For the remote control systems Helicon-MP, Helicon-CT w/CPP, HeliconX and the first releases of Helicon-X3 delivered prior to September 2009, it is recommended to implement the software upgrades set out above. An alternative option is to perform a full Remote Control upgrade to the current version of Helicon-X3.

It is anticipated that the upgrade would take 1 – 2 days and would require access to your vessel.

Contact information:

To receive more information about the available software upgrades or an offer for a remote control upgrade please contact Rolls-Royce Marine through the contact information in the footer of this letter.

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Template id.: DMN300005271
Rev.: A
Approved date: 05.04.2013
Approved by: [redacted]

Job description - Actuator Inspection

Scana
SCANA MAR-EL AS

SCANA CREATES PROGRESS

Job description

Actuator inspection

MAC-series pitch actuator

Efficient sailing
- Safe harbouring!

Ownership

Liabilities

Scana Mar-El AS strains to ensure that all information in this document are correct and precise, but disclaims liability for any errors or omissions.

Warning

The equipment to which this manual applies must only be used for the purpose for which it was designed. Improper use or maintenance may cause damage to the equipment and/or injury to personnel. The user must be familiar with the contents of the appropriate manuals before attempting to operate or work on the equipment.

Scana disclaims any responsibility for damage or injury caused by improper installation, use or maintenance of the equipment.

Improvements

To assist us in making improvements to the product and to this manual, we welcome comments and constructive criticism. Please send all such in writing to:

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Att: Product improvement
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Norway

E-mail: mar-el@scana.no
Telephone: +47 35 07 58 00
Telefax: +47 35 07 58 01
Web: www.mar-el.no / www.scana.no

Revision history

Rev.	*Description*	*Initials*	*Date*
-		[redacted]	28.09.2015
A	Added appendix with exploded view pictures, and references to this in the text	[redacted]	26.11.2015

[redacted]

Table of Contents:

1 Introduction

The MAC-series of pitch actuators from Scana Mar-El consists of a step motor controlled ball screw with an attached feedback unit. Several variations exist depending on strength, stroke length and feedback solution, but the basic design is the same.

The expected length of life will vary greatly with the environment the actuator is used in. Replacing the actuator solely according to running hours is therefore not a good solution. A properly conducted inspection can identify wear and tear before it becomes a problem. When the status is known, a qualified decision can be made about how to proceed. A properly maintained actuator may last a long time with a few key parts renewed, while a condition which is left to develop into a fault may lead to loss of control over the actuator.

2 Scope

This description is valid for the following actuators:

MAC	**-**	**xx**	**y**		**D**	**nnnnn**

xx = Stroke length (10 = 100mm / 15 = 150mm / 30 = 300 mm)

y = Motor type (2 / 4 / 6 / 7)

n = Potentiometer (D20492 = single / D20493 = double / D21020 = triple)

3 Inspection

The following checks are to be used to verify that the actuator contains parts of correct type and in good condition, so that the actuator is fit for use for another period. It is expected that the person doing the inspection is able to identify damaged or worn parts. Some of the routines can and should be performed by ships engineers. Tests that involves dismantling the actuator should be performed by qualified personnel.

In the appendix you will find exploded views with numbered parts. The inspection routines refer to these pictures for easier understanding of the texts.

The actuator should be inspected regularly. The interval can be adjusted if inspections show the interval to be too short or too long for a given vessel.
As a general rule we suggest yearly intervals.

In the same general way, the lifespan of the actuator is suggested to be 15.000 hours. This value can be greatly extended by identifying and replacing worn parts.

3.1 Cleaning

Keeping the actuator clean and free from oil and dirt is an important step to avoid problems. Normally it will be sufficient to just wipe off dirt with a clean rag. Avoid using high pressure water jets. Do not use powerful cleaning agents, as these may damage the belt in the feedback assembly (see Feedback assembly).

3.2 Installation

It is vitally important that the ball screw can operate freely without lateral movement. The actuator bracket will absorb movement along one axis by rotating on two bolts. This is intended to follow the curvilinear motion of a pitch “arm”. The ball screw **must not** be forced to bend sideways. Sideways tension on the ball screw while it is moving in or out will damage the bearings.

- Move actuator from full ahead to full astern and verify that the ball screw piston is not being bent sideways.

3.3 Feedback assembly

The linear motion of the actuator is measured by a potentiometer. The movement of the ball screw is transferred through a belt and pulley arrangement to the potentiometer.

- Remove the protective cover **(11)** (two bolts)
- Inspect belt **(6)** for cracks and/or deformation
- Verify that the rod **(7)** is securely fastened both to the belt and to the rod carrier **(10)** at the tip of the ball screw piston.
- The rod shall move freely without binding in the nylon-sleeve.
- Check belt tension by pushing a finger at the middle of the belt. Should flex abt. 5mm. (If the belt is too slack the feedback will be imprecise, if it is too tight it may damage the pot.meter shaft)
- Check that the toothed pulley **(8)** is securely fastened to pot.meter shaft with two set screws
- Move the ball screw piston out and in, verify that both pulleys are turning smoothly (look for signs of corrosion on pulley bearings and bolts)
- Reinstall protective cover

3.4 Feedback potentiometer

The feedback potentiometer is located under a cover and is fixed in place by two clamps.

- Power off the control system or disconnect the actuator.
- Remove the cover **(12)** over the feedback pot.meter by removing two bolts. You may also have to loosen the cable gland to lift the cover far enough to inspect the pot.meter.
- Check that the pot.meter is securely fastened by the two clamps **(5)** (also verify that clamps and/or screws do not touch the solder connections coming out of the pot.meter)
- Visually inspect solder connections for corrosion, loose connections or other obvious problems

Measure the pot.meter for problems. Perform tests for each track of the pot.meter.

- Check that there are no connection to chassis/metal
- Check total track resistance (end-to-end of the pot.meter). Should be approximately 1kΩ for each potentiometer deck. Measure between wire 2 and 4 for deck one, between wire 6 and 8 for deck two and between wire 10 and 12 for deck 3 (number of decks depends on actuator model). This value should not vary when moving the actuator piston.
- Move actuator piston slowly in and out while measuring resistance between wiper and end-points. Measure first between wire 1 and 2, and then 1 and 4 for deck 1. Repeat with 5 & 6 and 5 & 8 for deck two. Deck three is wire 9 &10 and 9 & 12. The resistance-change should be smooth with no sudden jumps. *Note that this test may be difficult to perform with a purely digital multimeter. Use a good digital meter with "bar-graph" function or an analog meter.*
- Reinstall cover

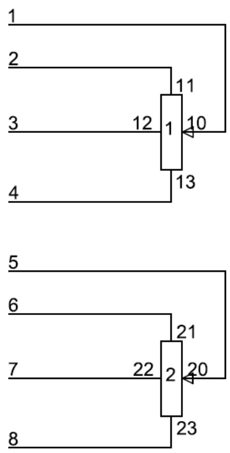


Fig. 1 Two-deck potentiometer

3.5 Step motor

The step motor is at the rear end of the actuator **(1)**. Some variants will have the electrical connections under a lid at the back of the motor, others have a connection box on top of the actuator with internal wiring down to the step motor. There are four wires coming out of the actuator. Two for each coil. Wire 1 and 2 is for coil 1, while wire 3 and 4 is for coil 2.

- Check that connection box is undamaged, and clean inside.
- Check and if necessary tighten screws in terminals. Also tighten screws in unused terminals (if any)
- Measure resistance of each coil in the stepmotor. The resistance will vary with type of connection (serial or parallel), but should be the same value for both coils. Normal values for parallel connection is approximately 1Ω. For serial connection the value is approximately 4Ω.
- Check that there is no connection between the two coils
- Check that there is no connection between a coil and chassis

3.6 Ball screw

The ball screw **(5)** transforms the rotation of the step motor to linear motion. It is a sealed unit, filled with grease, with no serviceable parts.

- Visually inspect for damage. Look for scoring of piston, dents in chassis or signs of grease leaking out.
- Rotate the piston by turning the rod end bearing **(9)**. The piston will move smoothly in and out (because the stepmotor locks the input shaft).
- Move piston in and out by pulling/pushing on the rod. It should move smoothly and with some resistance.
- Keep moving piston in or out while applying force sideways. Check for tendencies to lock. The ball screw is sensitive to bending forces and will easily be damaged if allowed to work with sideway forces. See also Installation

3.7 Rod end bearing

The rod end bearing **(9)** transfers the force to the servo arm. If there is slack in the connection this will influence directly on the pitch position. If the rod end bearing should loosen and fall off this will cause loss of the pitch control.

- Check for freeplay/slack
- Check that it is solidly screwed onto the ball screw piston (LockTite), both end bearing, and nut towards the rod carrier **(10)** should be tight without slack.
- Verify that the rod carrier **(10)** spins easily when rotating the ball screw piston
- The bearing inside the rod carrier should be locked firmly in place with no room for movement.

3.8 U-bracket bearings

The bracket **(2)** takes up the force/weight of the actuator and also works as a bearing for movement in one direction. The bearings **(11)** contains rubber gaskets to keep vibrations from reaching the pot.meter or the rest of the actuator.

- Check that all bolts are tight
- Check that the rubber gaskets are not worn out.

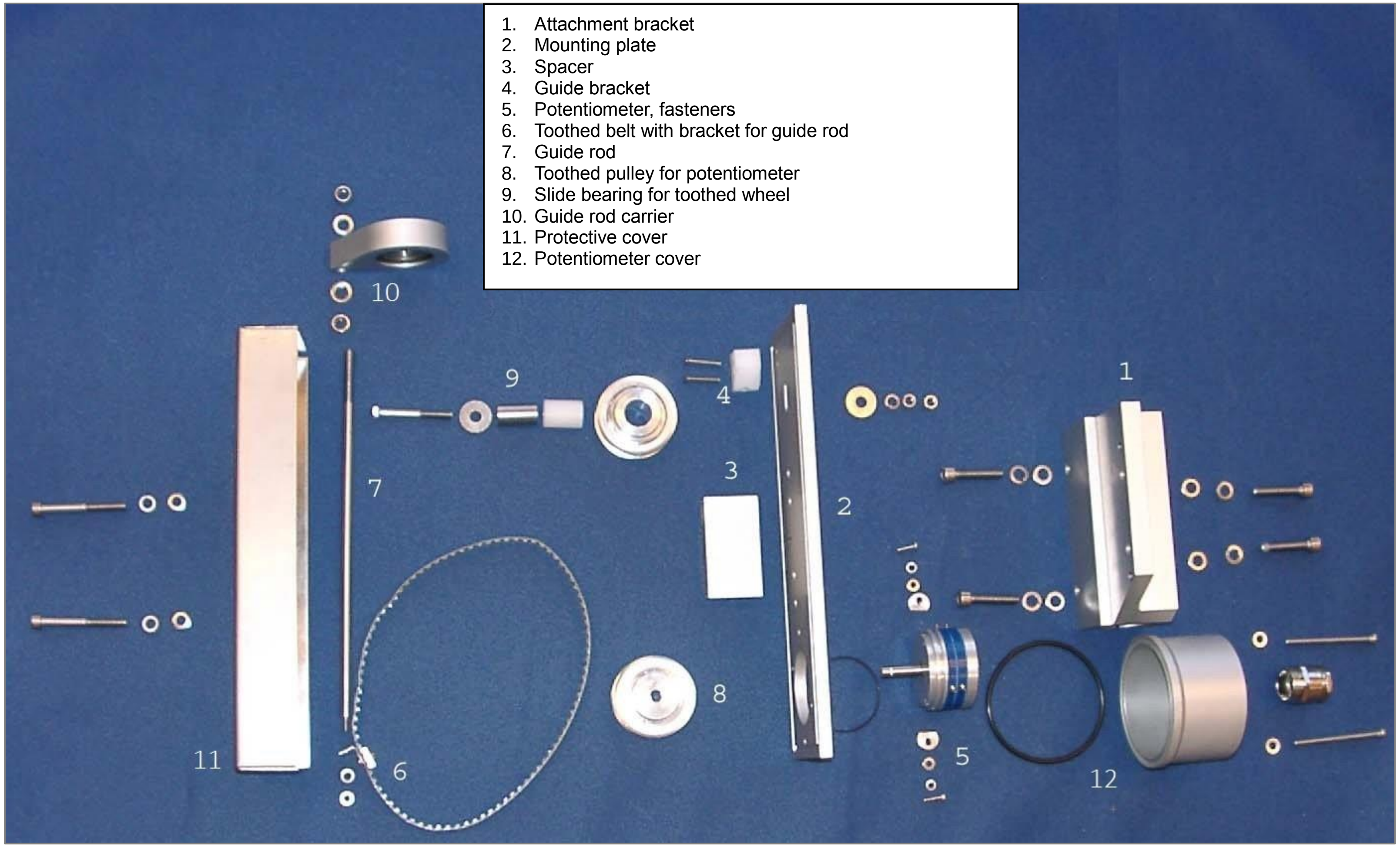
3.9 Rotex coupling

<u>*Caution:*</u>
This procedure requires dismantling the actuator and should only be performed by competent personnel

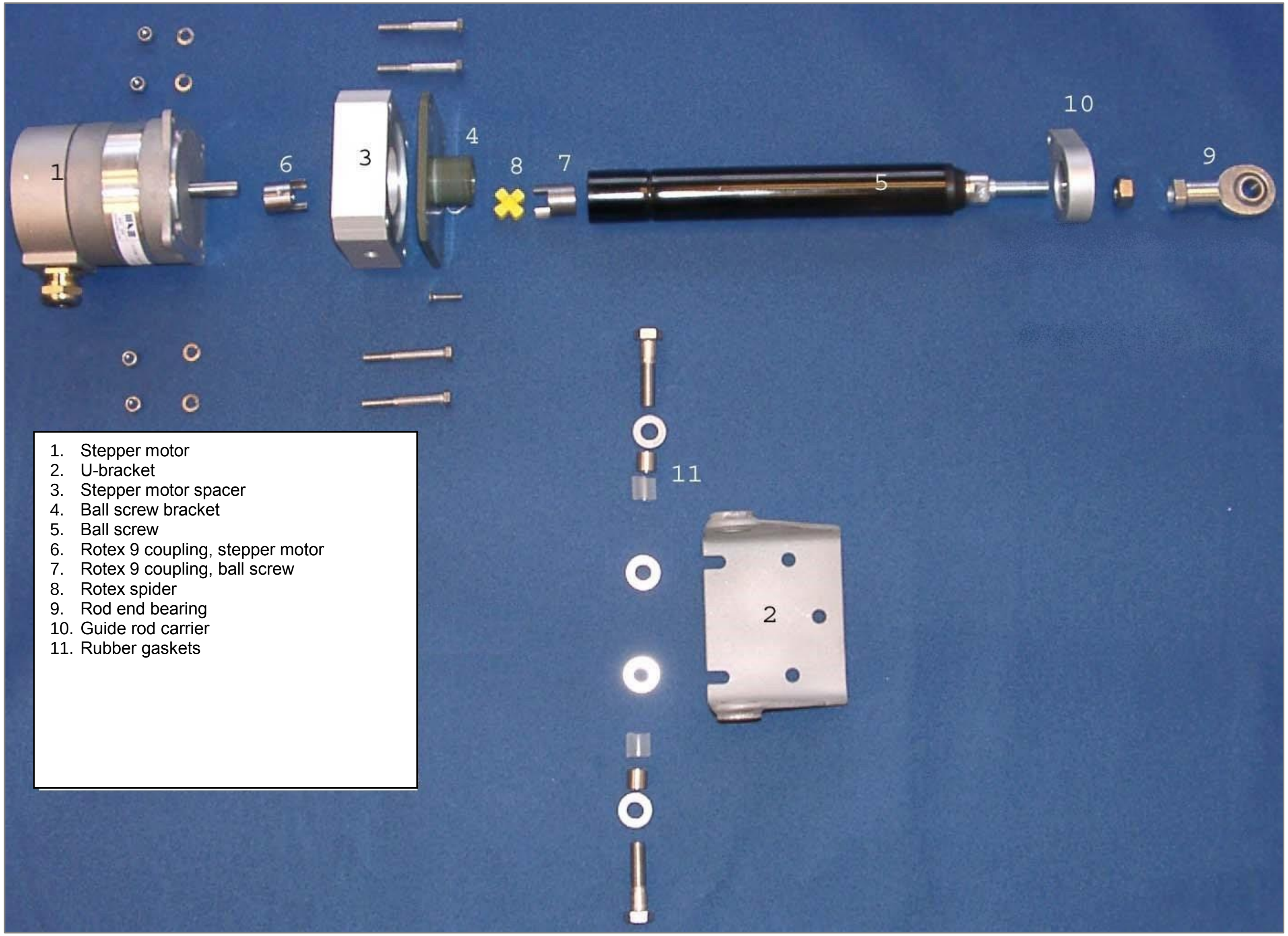
The connection between the step motor and the ball screw is made by a Rotex coupling (6,7,8). This can only be inspected by opening the actuator. The actuator should be removed to a clean and tidy place before dismantling starts.

- Remove the four bolts holding the step motor together with the ball screw assembly. The actuator will split into three parts. The step motor, the mid-section with the u-bracket and the ball screw with the feedback assembly.
  As long as the feedback assembly is not removed, the actuator can be put back together without disturbing the pitch feedback settings.
- Look for obviously worn or damaged parts
- Check that the Rotex coupling is connected to the step motor with a securely fastened set screw (LockTite). The set screw shall be on the flattened part of the shaft. The shaft shall protrude approximately 1-2mm through the coupling.
- Check that the rubber spider **(8)** of the Rotex does not have cracks or is otherwise deformed.
- Check that the Rotex coupling **(7)** is connected to the ball screw with a key. This should be a snug fit and normally this part of the Rotex should stay in place and be difficult to remove. If it falls out it is most likely worn out. In this case both the ball screw and the Rotex must be checked to see if one or both parts must be replaced.
- When fitting the step motor back on, make sure that the two halves of the Rotex coupling meshes completely (the part with the set screw **(6)** can be pushed too far onto the step motor shaft, and then the Rotex may slip when applying force)

Appendix A1: Feedback assembly with potentiometer



Appendix A2: Ball screw with step motor and U-bracket



Job description - Actuator Inspection

Scenario No.14	CRITICAL EQUIPMENT FAILURE (Main Engine, Steering Gear, Electrical Power)			Page 1 of 1
RESPONSIBILITIES: ***Master: In overall command. C/E: i/c E/R operations. Remainder of Officers and crew to form into emergency parties as directed on the muster list***				
	Module IV		***Module V***	***Module VI***
Action to be taken by others	Action to be taken by Officer of the Watch	Action to be taken by Master	Reporting Procedures	Supporting Documentation
INITIAL ACTIONS →	▪ Call the Master → ▪ Ensure C/E and/or duty engineer advised ▪ Ensure alarm has been acknowledged in E/R ▪ Display appropriate Collision Regulations lights and shapes ▪ Prepare to man emergency steering until all way is off the ship or main steering is operational	▪ Prepare for anchoring if in shallow water ▪ Establish communications with the Engine Room to determine nature of failure ▪ Ascertain whether there are any injured crew members ▪ Advise traffic in the area of the nature of the critical equipment failure →	OOW/Master to broadcast **Safety** or **Urgency Message** on VHF Ch.16	
SUBSEQUENT RESPONSE ↓ ▪ Where there has been an electrical failure/blackout, ensure all applicable systems ready for power on. ▪ Check stability of applicable systems after start-up. ▪ Establish cause of failure and if necessary enter further safeguards ▪ Cancel Urgency message. ▪ Advise Company Duty Manager ▪ Arrange for replacement parts that have been used from ship's spares ▪ If appropriate, update planned maintenance system →		▪ Assess situation based on updated sit-reps to determine if any consequences of equipment failure → ▪ Monitor progress of repairs ▪ Prepare to evacuate passengers and/or crew should there be a risk to their safety → ▪ Prepare to ask for immediate assistance should the situation deteriorate and there is a risk to life →	OOW/Master to broadcast updated **Urgency Message** on VHF Ch.16 OOW/Master to broadcast updated **Distress Message** on VHF Ch.16	▪ Navigation charts ▪ Tide tables ▪ Weather forecasts ▪ General Arrangement plan ▪ Cargo information ▪ Company reports