Lifting fans for VTOL aircraft: Investigation into a quill-shaft failure in a 12 in. dia. gear-driven fan

Levy, G.G.; Rimmer, R.J.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/40004043
Laboratory Memorandum (National Research Council Canada. Division of Mechanical Engineering. Engine Laboratory); no. NRC-ENG-59, 1968-10

L.O. 16845A	NATIONAL RESEARCH COUNCIL	NO. NRC-ENG-59
FILE M2-17-13.T-6-11	DIVISION OF MECHANICAL ENGINEERING	PAGE 1 OF
PREPARED BY GGL & RJR	OTTAWA, CANADA	COPY NO. ~~18~~ 4
CHECKED BY EPC	LABORATORY MEMORANDUM	DATE October 1968
	SECTION ENGINE LABORATORY	

agb

SECURITY CLASSIFICATION OPEN

SUBJECT Lifting Fans for VTOL Aircraft: Investigation into a Quill-Shaft Failure in a 12 in. dia. Gear-Driven Fan

PREPARED BY G.G. Levy and R.J. Rimmer

ISSUED TO

Summary

The failure of a quill-shaft in a fan-in-wing model was investigated.

After examination of the available evidence it was concluded that the quill-shaft failure was caused by excessive wear on the inboard pinion bearing, resulting in mal-alignment and large bending stresses in the quill-shaft splines.

No design changes are considered necessary at this time.

List of Illustrations

Table of Contents

1.0 Introduction

During test running of a fan-in-wing model in the Propulsion Tunnel, a failure occurred in the fan drive line resulting in a turbine overspeed and automatic operation of the overspeed trip. Subsequently, it was found that the quill-shaft connecting the step-up gearbox to the fan hub bevel pinion had fractured.

Because a fairly extensive test programme was scheduled for this equipment, an investigation was initiated to discover the primary cause of failure.

2.0 Strip Examination

A preliminary examination of the fan hub parts showed that the quill-shaft had failed at the bevel pinion spline. The splined portion of the shaft was itself broken into 3 separate pieces, the largest piece also showed several circumferential cracks (Fig. 1).

The inboard bearing of the straddle mounted pinion assembly (Fig. 2) had failed, thus permitting the pinion to rock about its axis. The lower half of the outer race showed severe surface spalling; but, there were no signs of heat discolouration and no signs of lubrication breakdown.

The tips of 3 pinion teeth were chipped (Fig. 3) and there were damage marks on the housing adjacent to the pinion (Fig. 4).

At the turbine end of the drive, damage was confined to a ball bearing, the flexible shaft used for torque measurements, and 3 magnetic pick-ups. The flexible shaft was bent and contact had been made between the toothed-wheels, attached to each end of the shaft, and the pick-ups.

There were very light rub marks on the turbine casing; but the rotor itself appeared to be in good condition.

3.0 Operating Condition

A full description of the fan and drive is given in Reference 1.

At the time of failure the fan unit had run a total of 43½ hours, of which about 4½ hours had been run in the Engine Laboratory and the remainder in the Propulsion Tunnel at turbine speeds up to 17,800 RPM (13,650 RPM fan speed), and with tunnel air speeds varying from zero to about 120 ft/sec.

Steady state torque measurements taken just before failure indicated a turbine torque of 74.6 lb.ft., corresponding to an output of about 250 horsepower. The quill-shaft would have been transmitting slightly less than this because of losses in the drive train.

4.0 Discussion

The damage to the turbine end of the drive was probably the result of overspeeding following unloading of the turbine when the quill-shaft fractured. The amount of overspeed was not measured; but, with a turbine power of about 250 h.p., and an overspeed trip system delay time under static conditions of 0.22 seconds, the rotor may have reached a speed of 25,000 RPM. Under these conditions it is probable that the trunnion bearing failed (Fig. 5) thus causing an excursion of the torque shaft of a magnitude sufficient to damage the magnetic pick-ups and bend the shaft itself.

At the fan end of the drive line, the main features of interest were the broken pinion teeth, the failed inboard bearing and the 3 fractured sections of the quill-shaft spline.

Inboard Pinion Bearing

The inboard pinion bearing was recognized in the design as the most critical element in the drive line. Because of space limitations and high loading, this bearing had a design fatigue life of less than 7 hours. However, the bearing was not run at its design maximum speed and, in fact, spent about half of its running time at speeds and loads much below the maximum.

A similar assembly had previously run a total of 80 hours under identical conditions without failure.

Quill-Shaft

Wear marks on the pinion splines suggested that the unusual failure of splined portion of the quill-shaft occurred in stages and was caused by a failure mode other than torsional. The shaft was made from 4340 steel and was dimensioned to give a shear stress of 50,000 P.S.I. at design conditions after through-hardening to Rockwell C32-C36.

The shaft, which passed across the fan flow annulus, was closely faired to represent a stator blade slightly thicker than the others. There were no signs of contact between the shaft and fairing that may have indicated vibration or whirling problems.

Bevel Pinion

The bevel pinion teeth showed no abnormal wear patterns, but the location of damage marks on the housing indicated very clearly that contact had been made either with the toe of the pinion teeth or with a piece of broken tooth. In the former case it would be reasonable to postulate that the bearing had failed, thus permitting the necessary movement of the pinion towards the housing, and that the teeth were intact until the moment of impact. In the latter case, a fatigue failure of the teeth may be implied, resulting in the momentary trapping of a piece of tooth between pinion and housing, followed by bearing failure triggered by shock loading.

In order to resolve this point, the parts in question were submitted to the Physical Metallurgy Division of the Mines Branch with a request that they examine the pinion teeth and the quill-shaft for evidence of fatigue and to offer an opinion as to the primary cause of failure.

Their conclusions (see Appendix) supported the view that the inboard pinion bearing failed first and that the damage to the pinion teeth and the quill-shaft occurred subsequently.

Although it was not specifically noted in the report, it may be inferred that there was no evidence of fatigue on the pinion teeth.

5.0 Conclusions

1. The sequence of failure appears to be that the inboard pinion bearing failed first thus permitting the assembly to tilt. The resulting mal-alignment was responsible for the quill-shaft failure and for the tooth damage.

2. The Mines Branch report noted that the bearing failure occurred either because of the normal loads or because the preload was lost. Preload was applied to the outer race by a Belleville washer. The washer was still intact after stripping and there was no evidence that the preload had changed prior to failure. It must therefore be concluded that the bearing failed because of normal loading.

3. The average fatigue life of a bearing is approximately 5 times the design fatigue life (Ref. 2). However, small changes in loading have a pronounced effect on the life expectancy. This factor, in conjunction with the normal scatter in results, probably accounts for the difference in life experienced between the two bearing sets used so far in the 12 in. fan.

4. The measured hardness of the quill-shaft, 39-40 RC, is appreciably outside the range of 32-36 RC called for on the manufacturing drawing. The reason for the difference is currently under investigation.

5. No design changes are contemplated at this time, since the main problem is associated with the restricted space available in the 6 in. dia. fan hub. The running time between precautionary bearing changes might perhaps be reduced to the neighbourhood of 40 hours.

6.0 References

1. Lifting Fans for VTOL Aircraft: Mechanical Development of a Gear-Driven Model Fan Installed in a Wing.
By - G.G. Levy, R.J. Rimmer, T.W. Hopson
Laboratory Memorandum NRC-ENG-54
April 1967.

2. Engineering Catalogue G-3
The Barden Corporation, Danbury, Connecticut.

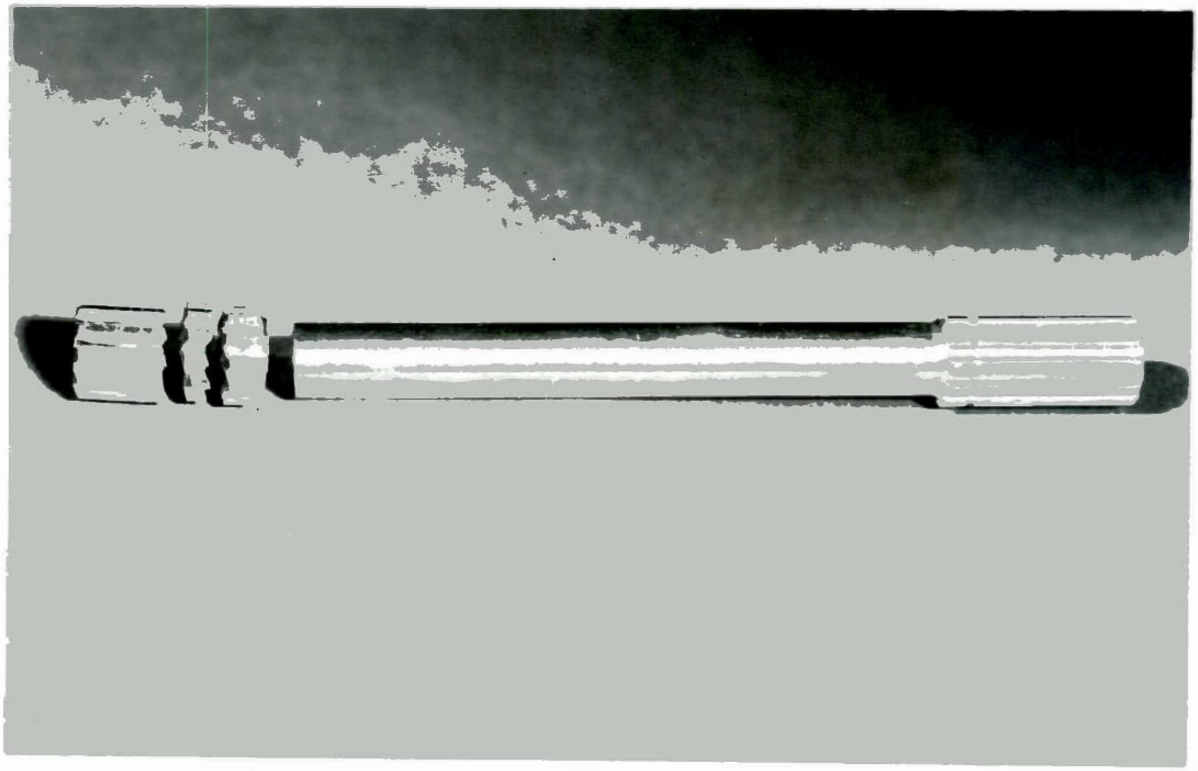

FIG. I QUILL SHAFT

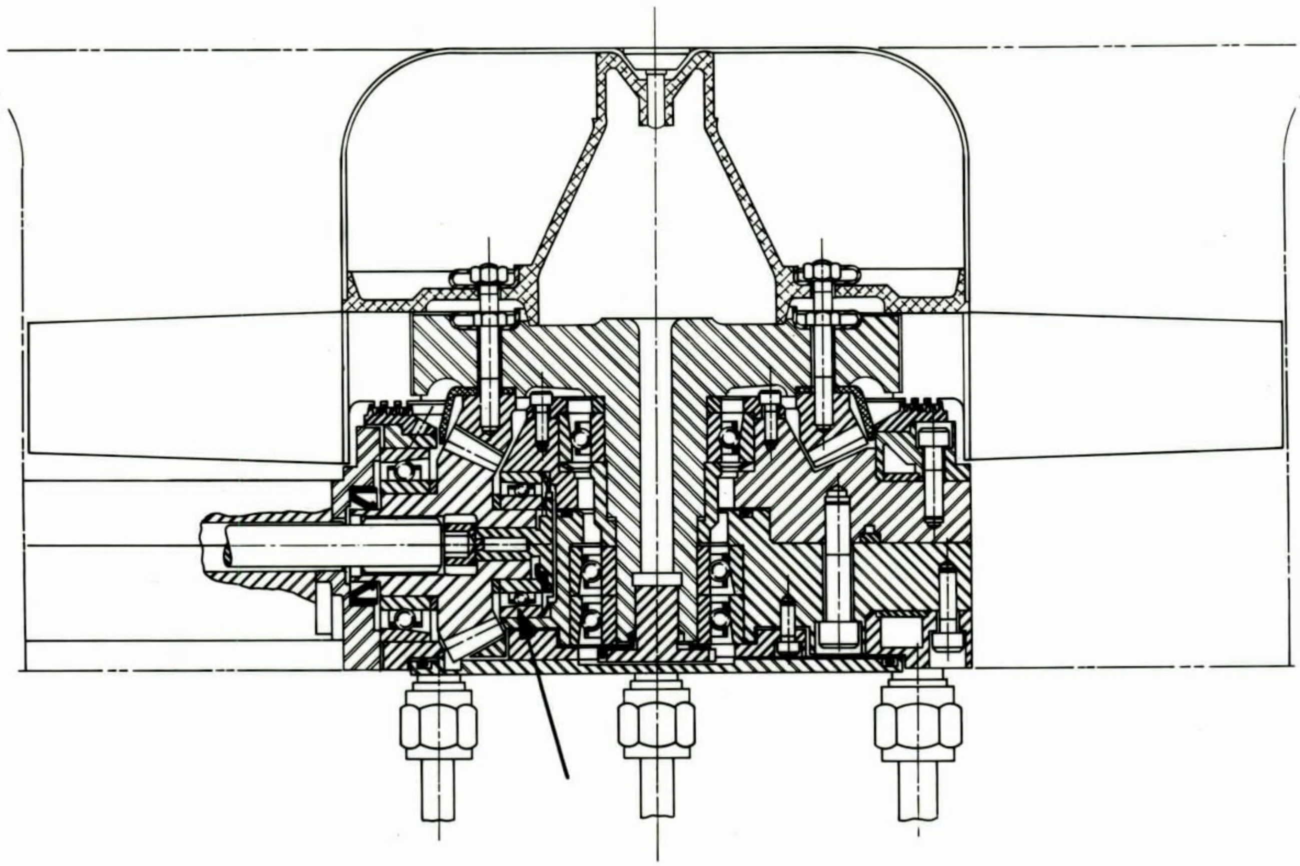

FIG. 2 SECTION THROUGH FAN HUB

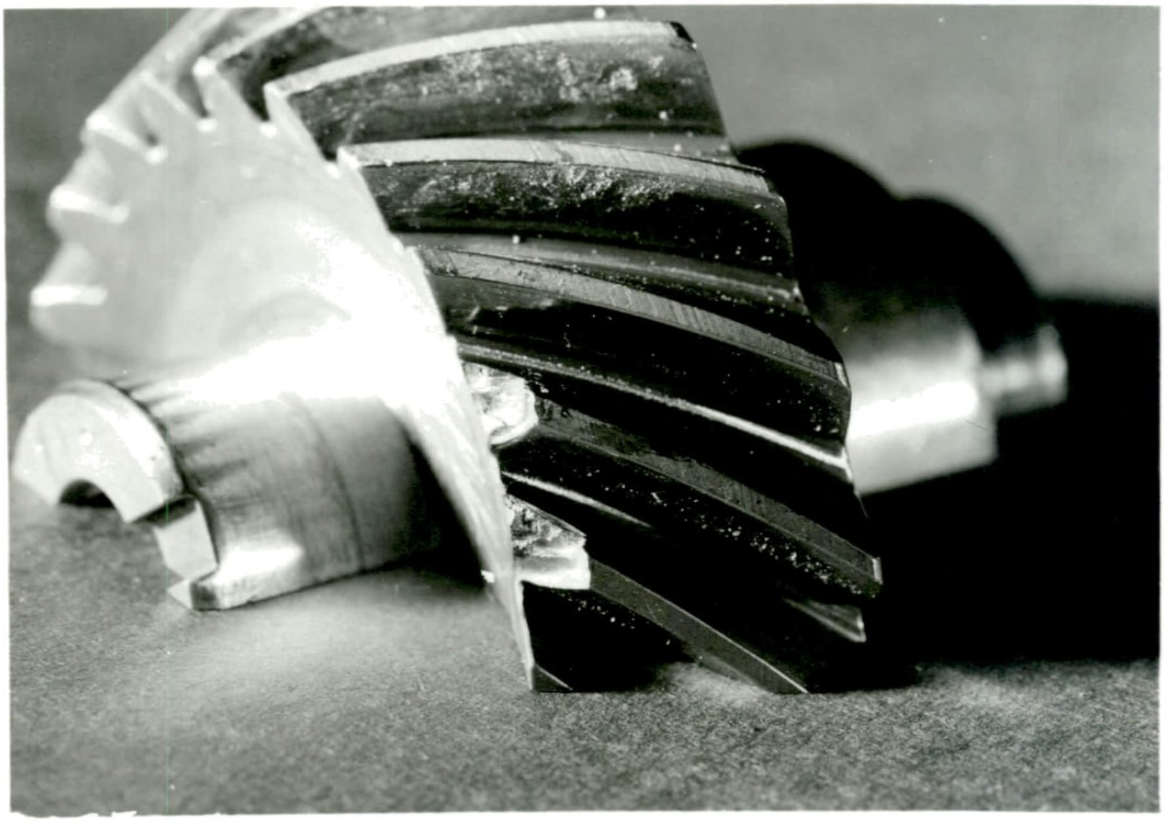

FIG. 3 CHIPPED PINION TEETH

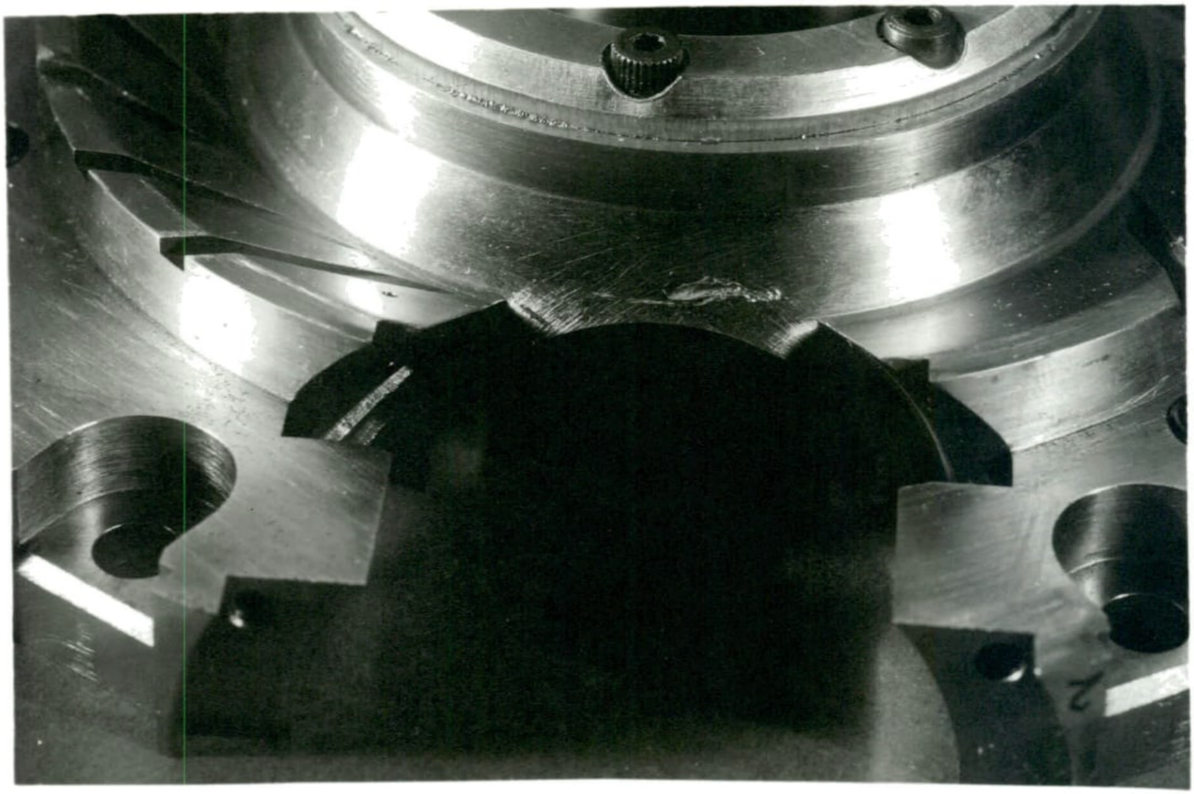

FIG. 4 DAMAGE MARKS ON HOUSING

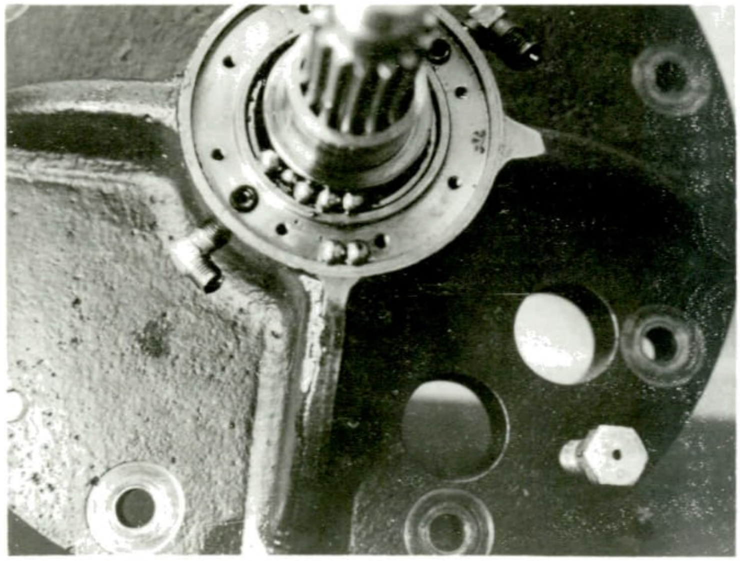

FIG. 5 TRUNNION BEARING

APPENDIX

CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES

MINES BRANCH

OTTAWA

PHYSICAL METALLURGY DIVISION

TEST REPORT PM-68-22

FAILURE OF MODEL FAN DRIVE

by

E. G. Eeles

Engineering Physics Section

September 16, 1968

PHYSICAL METALLURGY DIVISION

TEST REPORT PM-68-22

To: National Research Council,
Ottawa 2, Ontario
Attention: Mr. E. P. Cockshutt, Head, Engine Laboratory

Re: Failure of Model Fan Drive

- -

On August 8, 1968, a request was received from the National Research Council (their reference M2-17-13.T-6-11) to study the failure of the drive for a model fan assembly. The most significant failure was in the quill shaft which drove a bevel gear assembly. Discussions with officers of the National Research Council revealed that the shaft specifications called for SAE 4340 grade steel, heat treated to 32-36 Rc.

The shaft had failed at the driving end in the splines within the bevel gear, see Figure 1.

Figure 1. Failed Assembly.

The bevel gear is carried by two angular contact bearings, the inboard one of which had failed. It was stated that this failed bearing was running at a design load approximately 20% less than the maximum load rated by the manufacturer.

Optical Examination

A visual examination of the parts, Figure 1, showed an unusual failure, with the splined section of the driving end of the quill shaft having separated into three pieces. It is logical to assume that the initial failure of the quill shaft was to separate that portion farthest inside the gear, followed by subsequent separation of another piece with eventual fracture of the shaft at the end of the splined portion.

A more detailed examination of the largest, inboard, portion of the spline (see Figure 2) showed the additional presence of several circumferential cracks. Cracks running in this direction will only be caused either by torsional stress or by some longitudinal tensile stress. As the fit of this portion of the spline into the bevel gear was still adequately tight and no appreciable spline wear is evident, it is very unlikely that sufficiently high torsional stresses were developed. The conclusion, therefore, must be that the failures were due to the action of the longitudinal tensile stresses.

Figure 2. Quill Shaft Spline Tip.

The presence of such longitudinal tensile stresses would have been caused by misalignment of the gear with respect to the quill shaft. The obvious source of this misalignment is the failure of the inboard bearing, allowing the gear to tilt on the splined end of the quill shaft due to the separating forces of the meshed gears. This tilting action is equivalent to a bending moment across the length of the splines and results in alternating tensile stresses at the surface of the male splines. Compensatory loads of opposite sign will be induced in the female splines, but due to the increased section, the stresses would have been lower. Therefore, there is a much lower probability of cracking in the bevel gear splines.

To study the female splines more adequately, the bevel gear unit was cut through the centre to expose the splines. The wear pattern on these splines was in accordance with the progressive failure of the quill shaft splines, becoming much more pronounced as the driven area became less, see Figure 3. In addition, the profile of the wear pattern was in accordance with the hypothesis of tilting of the bevel gear with respect to the quill shaft. Magnaflux examinations, both before and after cutting the gear, did not show any cracks either in the spline or anywhere else in the unit.

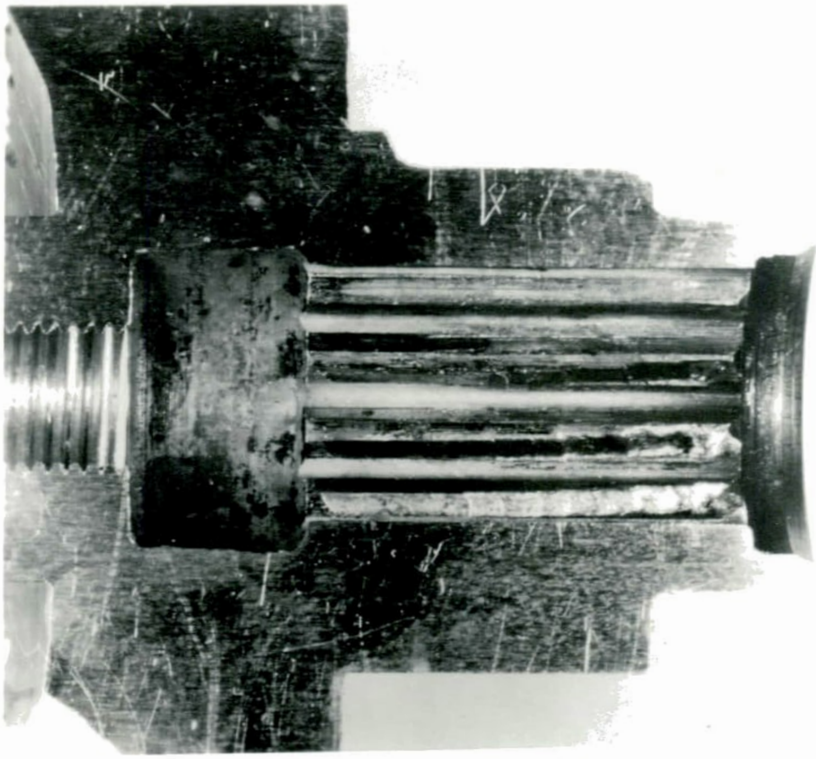

Figure 3. Bevel Gear Splines.

There is considerable evidence to support the hypothesis that tilting of the bevel gear was the cause of failure of the quill shaft. The outer race of the inboard bearing is stationary and it showed an uneven breakdown of the bearing surface. Figure 4 shows this race after fracturing into four pieces.

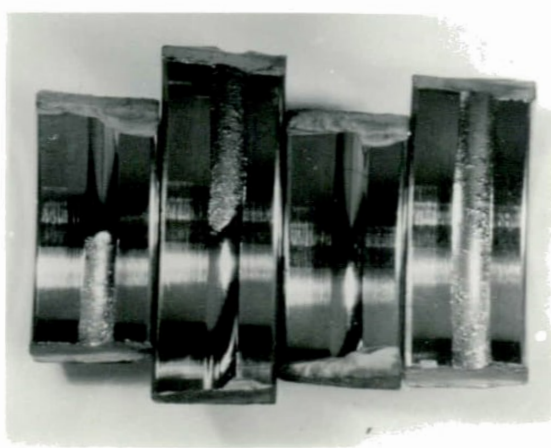

Figure 4. Inboard Bearing Outer Race.

The failure of the surface over only a part of the race is strongly suggestive of excessive force in one direction. In normal operation the loading of this bearing will be largely unidirectional due to the separating thrust of the gears. The conclusion is, therefore, that either the bearing failed due to these normal loads or that there was a loss of the preload applied to maintain correct alignment of this and the outboard bearing.

Metallurgical Examination

A section was taken from the quill shaft near the point of final separation. The structure was tempered martensite with an average hardness of ~~44 Rc.~~ 39-40 RC.

The measured hardness, ~~44~~ 39-40 Rc, is consistent with the microstructure observed and, for 4340 grade steel, corresponds to a tempering temperature of less than 800°F. This temperature falls within the embrittlement range for this steel and, in most cases, it is recommended that this range be avoided. While this factor is not considered in any way to be responsible for the failure of the quill shaft, it is recommended that either lower or higher hardness values be used. In view of the application, higher hardnesses may be preferable.

Summary

It is considered that the primary cause of failure of this assembly was the failure of the inboard bearing. This allowed misalignment to develop, creating excessive bending stresses in the driving spline of the quill shaft.

It is recommended that steps be taken either to increase the capacity of this bearing or to redesign the assembly to reduce the bearing loads.

E. G. Eeles,
Engineering Physics Section

EGE/gm