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Aircraft Engine Bearings and Splines

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Abstract

The purpose of this paper is to document the tribological issues related to bearings and splines in aircraft engines. The basic overview of each piece of hardware is presented to establish knowledge of basic configurations and uses in an aircraft engine. Key problems and issues related to operation of bearings and splines include wear, fatigue, lubrication, and heat dissipation.

Mechanical analyses of the failure mechanisms are described. Contact stress and bending stress issues are directly applicable to splines. Fatigue life, which is based on hertzian contact stresses are directly applicable to bearings. High strength materials coupled with low component weight is essential for successful aircraft engine sales; this lends to specific and expensive materials and manufacturing methods. History has lead to small improvements of geometry, materials, and manufacturing. However, the key issues noted above will always remain due to the strict design envelope, which is continually challenged.

1. Introduction

This document is a summary of applications, issues, and analyses relating to bearings and splines used in aircraft engines. Bearings are required in aircraft engines to allow free rotation of shafts, disks, and airfoils that compress air and extract power from a combustion cycle. Splines are required in aircraft engines to transmit torque between shafts that are lined along the length of the engine. Both bearings and splines require lubrication to minimize wear and extend field life. This lubrication must constantly be circulated to remain at an operational temperature. Failures of bearings or splines lead to engine shutdowns and possible catastrophic events in helicopters or airplanes.

An overview of splines and bearings is presented, in order to provide a foundation for understanding some of the basic problems facing the aircraft industry regarding these components. A basic mechanical analysis involving stress and fatigue is discussed below, leading into the material issues faced, and the problems associated with dealing with poor quality materials. The solutions and steps the industry is taking to standardize design and manufacturing are touched upon, in addition to open problems in the field.

2. Overview

Splines

A spline is a part of a shaft that contains a series of longitudinal, straight projections that fit into slots in a mating part to transfer rotation to or from the shaft. The longitudinal projections in aircraft engine applications represent a similar shape to that of involute spur gear teeth. These teeth are often shorter than standard gear teeth, and the backlash associated with the coupling is also much lower compared to a normal gearing application. A shaft with both internal and external splines is shown in Figure 1.

Bearings

Bearings are used to allow the transfer of both axial (thrust) and radial loads from a shaft to a structural housing. There are different types of bearings used in aircraft engines to accomplish the load support. There are always at least two supporting structures for each shaft. A simplified example is shown in Figure 2. Detailed dynamic analysis can be used to predict what the actual resulting loads of the shaft-bearing system are going to produce.

When dealing with thrust loads, a ball bearing is required. A typical ball bearing supports the radial loading and axial loading produced by the shaft. The load path is shown in a bearing cross section in Figure 3. This is a typical aircraft engine ball bearing. This is often referred to as an angular contact bearing. When dealing with pure radial loads, like the left side of Figure 1, a roller bearing is sufficient. A typical roller bearing cross section is found Figure 4. In main shaft engine bearings, ease of assembly is often a design parameter, requiring design techniques like the use of split inner ring bearings. This geometry results in a very effective method for lubricating the bearing, providing a convenient path for the lubricant to get directly adjacent to the contacting surfaces. A typical split inner ring (or gothic arch) ball bearing and a typical roller bearing is found in Figure 5.

Comment [a1]: any background information that will help orient the reader;
- a statement of the purpose of the topics reported on;
- a statement of the scope of the report, including any limitations of what it offers;
- a roadmap of what information is provided subsequently in the individual report sections.

In the subsequent sections the report should cover the following in detail, as applicable to your specific project:
- The key problems/issue related to this project;
- Mechanical analysis of the loading conditions for the interface;
- Materials issues;
- Solutions cited in the literature;
- Open problems in this field;

Other relevant topics as you see approporiate.

3. Key Problems / Issues related to Bearings and Splines

Operational life of aircraft engines, more specifically time-on-wing before overhaul, is a key deliverable in the industry. Bearings and splines are critical hardware in the engine that can determine the operational life of an entire engine. Issues that affect the operation of these parts are wear, fatigue, lubrication, and heat dissipation.

Lubrication and heat dissipation are closely related issues. Lubrication is always needed for these types of surface contacts to minimize wear and maximize life. The high temperature of aircraft engines leads to overheating of the lubrication until it begins to change properties, losing its viscosity until it is eventually burnt onto the surfaces of metal. Continual circulation of lubrication dissipates heat from these surfaces to allow for consistent and effective lubrication. Methods of lubrication include capillary action and spray from nozzles. Capillary action can be seen in bearings when lubrication is fed through the inner or outer race of the bearing directly to the surfaces in contact. Capillary action is also seen in splines with radial holes that allow lubrication to enter at the point of surface contact. Nozzles spray lubricant to specific locations in a design so that all contact surfaces receive appropriate amounts of lubricant. Often lubrication sprayed in one area is expected to travel to another area via centrifugal force or capillary action.

Wear occurs on typical contact surfaces, such as mating spline gear teeth and a bearing's rolling element to race. Wear is also an issue on surfaces with no intended relative motion, such as bearings press fit on shafts or into housings. Two key elements to wear are lubrication and coefficient of friction (surface roughness) that are both discussed in this paper.

Fatigue ultimately determines the operational life of aircraft engine hardware. Incorrect calculations and predictions of this failure may lead to in-flight engine shutdowns or catastrophic failures. Fatigue failure modes are different for splines and bearings. Splines typically experience failure due to shearing of teeth. Bearings that are sufficiently lubricated and isolated from contaminants experience failure due to contact stresses. Fatigue on either piece of hardware can be initiated by hard particle contamination. Hard particles originate from insufficient cleaning methods on parts assembled into oil-wetted areas of the engine.

4. Mechanical Analysis: Bearings and Splines

Splines [5],[8]

Two main failure mechanisms for spline teeth are bending stress at the root fillet of the tooth and contact stress at the point of load from adjacent teeth.

The basic analysis of spline teeth begins by transmitting the shaft torque, T, to a tangential load, W_t, defined as,

$$W_t = \frac{2T}{P_d} \tag{1}$$

where P_d is the gear pitch diameter. See schematic in Figure 6. The total load on the tooth, R, is then defined as,

$$R = \frac{W_t}{\cos(\theta)} \tag{2}$$

where θ is the pressure angle commonly set to 30 degrees.

The first failure mechanism, shown in Figure 7, of bending stress in a tooth is defined as,

$$\sigma = \frac{W_t P_d}{FJ} \tag{3}$$

where F is the face width of the tooth and J is a geometric factor that combines:

- Tooth geometry in the root fillet area
- Stress concentration in the root fillet
- Load sharing between teeth
- The position of highest load with adjacent teeth.

The second failure mechanism, shown in Figure 8, of compressive stress is based on Hertzian contact and is defined as,

$$\sigma = C_p \sqrt{\frac{W_t}{P_d F I}} \tag{4}$$

where C_p is the elastic coefficient based on material properties of the mating teeth and I is a geometry factor based on radii of curvature at the contact point and the load sharing between adjacent teeth.

Bearings

There are many different parameters that affect the predicted fatigue life of a bearing. These parameters include, but are not limited to, the internal radial clearance between the races and the rolling elements (see Figure 9), bearing geometry, reaction loads, speeds, and the oil film layer. The life for a bearing is almost always given in terms of an L_{10} life. This is either the expected amount of time or number of revolutions that would result when 10% of a group of bearings will begin to experience fatigue failure. There are many standards set by the FAA or other governing aircraft regulatory entities that specify a requirement for bearing life. Since there is a probability of failure associated with this type of engine part, these components are carefully monitored, and replaced as needed.

A generic equation for calculating the L_{10} bearing life is defined as follows,

$$L_{10} = \frac{16700}{N}\left(\frac{C}{P}\right)^K \tag{5}$$

where N is the rotational speed (rpm), C is a basic load rating (geometry dependent), P is the loading, and K is a constant. The variable K is typically 3 for ball bearings and 10/3 for roller bearings. [1] The effect of geometry and load has more of an impact to the fatigue life compared to the rotational speed. Loading from rotational speed needs to be taken into account due to the centrifugal force of the balls exerted on the outer race as the speeds increase. Since the governing equation for centrifugal force due to a point mass is as follows,

$$F_{centrifugal} = mr\omega^2 \tag{6}$$

the loading can increase dramatically as typical engine speeds are in the thousands of revolutions per minute and the rolling elements can be over an inch in diameter.

Contact stress on the races is the most common form of failure. The hertzian contact stress will induce a fatigue failure beneath the surface of the bearing race. This causes a portion of the material to break away from the parent body, further creating high contact stresses on the balls, which could lead to part function failure.

5. Material Issues

Splines

The materials for splines used in aircraft engine applications are typically dependent on the material of the shaft that is transmitting torque. Weight, cost, fatigue capability, and ultimate strength are all factors in deciding shaft material. The spline area of the shaft is often hardened (through carburization or nitriding) to increase the load carrying capability and reduce wear. [7] Material inclusions are detrimental to performance, resulting in increased stress concentrations, especially in the spline roots. Aircraft engine drive shafts are typically made from forgings or from large bar stock. Splines are also used in transmitting torque on gear shafts within the engine. A common gear material is AISI 9310. These gears are often much smaller than the main engine drive shafts, so they are often made from bar stock.

A homogeneous material, including material hardness, is important to the spline manufacturing processes. Non-uniform material properties can often cause undesirable deflections in the part, including out-of-roundness or runout. The type of process used to form the splines also affects the material properties. An example of this would be that rolled splines produce a stronger spline due to cold working, compared to a cut spline. [7]

When splines are used to transmit the torque from one shaft to another, the two shafts are often made of different materials. This needs to be taken into account in the design to ensure that the growth of one shaft more than another during varying temperature conditions does not adversely impact the function. This could cause increased stress conditions, which would result in a reduced fatigue life.

Bearings

Typically, in bearing design, the material selection for the rolling elements is based on operating conditions. Harder materials are desirable for high load, low speed applications. Aircraft engine bearings typically have high speeds and relatively low loads, therefore softer materials are typically selected. Common bearing materials are bronze, copper-lead, tin bronze, manganese bronze, aluminum bronze, and steel. [6] Bearings are typically manufactured from either forgings, bar stock, or wire. Bearing cages are typically made of standard AISI 4340 steel with silver plating. The silver plating is used on the cages to reduce the coefficient of friction between the rolling elements and the bearing cages in addition to preventing corrosion.

The reduction of material inclusions is essential for performance. Foreign inclusions can be incredibly detrimental to the rolling element fatigue life. An example of a non-metallic inclusion is sulfide developing in alloys. Hard, metallic inclusions are considered more detrimental than a sulfide-type inclusion. [4]

6. Solutions Cited in Literature

Splines

The spline manufacturing process is determined based on the basic part configuration, the tooth geometry and the production rate needed. Splines configurations are grouped in four different types as shown in **Error! Reference source not found.**. The tooth form also is taken into account when determining the cutting tool. Splines can be classified as involute splines, straight sided or serrations as shown in Figure 11.

Some manufacturing processes are rolling, milling, broaching, hobbing, shaping, shaving and grinding. In the aviation industry, rolling and grinding are the most common. One type of roller uses hydraulic cylinders, timer racks, and gears while the other common roller uses hydraulic pistons motors. Splines are ground when accuracy and durability of the power transmission are critical.

For some applications the spline is tapered, usually 0.54 degrees, to reduce up to 15% the maximum principle stress of the shaft. This can also be interpreted as increasing the maximum spline fatigue load capability by 15% [9]. However, the industry has reached a plateau since the technology used for this components are relatively mature and new theories have not been defined. Longer life and lower weight are key solutions still waiting to be found. In the aviation industry, component testing at various conditions is the most common approach to determine areas of improvement that could eventually overcome the current capabilities.

Bearings

Bearings are evaluated on the basis of how much load they can carry, at what speeds they can carry this load, and how long they will serve under the specified conditions. Friction, start-up torques or forces, ability to withstand impact or harsh environments, rigidity, size, cost, and complexity also are important design considerations.

Over the years, engineers estimated the life of both ball bearings and roller bearings with the aid of ANSI/AFBMA standards for ball bearings (1950) and roller bearings (1953), which were updated in 1978 and 1990, plus ASME bearing life factors (1971).

Recently, the Society of Tribologist and Lubrication Engineers (STLE) developed new life factors that reflect improvements in bearing components such as steel manufacturing and lubrication, which have taken place over the last 50 years. These improvements increased bearing life substantially. The new life factors, which make it possible to predict bearing life much more accurately, are described in the book STLE Life Factors for Rolling Bearings [6].

Some of the common manufacturing processes are forging, compressive residual stress, and controlled-hardness. Forging produces a fiber orientation in the race material that makes the races less sensitive to variations in steel quality. Bearings with forged races can have dynamic capacities up to twice as high as bearings with races cut from tubing [6].

Compressive residual stress reduces maximum shearing stress and increases fatigue life. For bearings with light to medium loads, residual compressive stress can increase life. But for bearings with heavy loads, the effect is significant.

Controlled-hardness bearings have rolling elements and races matched for hardness. Generally, the rolling elements are 1 to 2 R_c harder than the races. Since fatigue life is related to hardness, the matching process can result in order-of-magnitude improvements in fatigue life [6].

The use of ceramic balls in ball bearings has been a highly specialized area. In high speed, high temperature applications the higher cost of the ceramic ball bearings has become desirable. The inertial loads are reduced due to the lower centrifugal forces being exerted on the races from the lower density ceramic balls. There is also a large reduction in lubricant required for ceramic balls [4].

7. Open Problems in the Field

Key problems and issues related to this hardware have not changed in recent history. Wear, fatigue, lubrication, and heat dissipation continue to be open issues in this field. Aircraft engines are being designed to output more thrust or shaft horsepower with lower fuel consumption rates and at a lower cost. In efforts to achieve these goals, design changes and high-level business decisions create challenges for bearing and spline designs.

New materials and cooling designs in the combustor and turbine of an engine increase overall operational temperatures, making heat dissipation on splines and bearings increasingly difficult. Higher temperature oil is not an easy solution because these types of oils are not available in all locations of the world where engines are operated.

A selling point of aircraft engines is weight-to-power ratios. Business pressure to reduce weight requires accurate wear and fatigue assessments that will not compromise safety. Business pressures to reduce cost of manufacturing can affect the surface finish and leads to trade-offs with friction and heat generation. Cost reductions can also lead to improper handling and cleaning, increasing risks of particle contamination.

Contamination is a specific issue found in aircraft fleets across the world. Contamination in the oil system can create rapid failure in a bearing or spline. Screens in the oil system reduce probability and electrical chip detectors are used notify the cockpit if anything is found.

These problems will continue to be open items in the field of aircraft engine splines and bearings as long as the design envelope is challenged.

8. Conclusion

The basic needs of splines to transmit torque and bearings to withstand radial and thrust loads are achieved through a long history of methods and practices. These practices address key tribological issues that are related to wear, fatigue, lubrication, and heat dissipation. Materials are continually developed to reduce inclusions, increasing part reliability. Manufacturing processes and cleanliness are important for successful operation that meets intended life requirements.

These critical components in aircraft engines will continue to see business pressures to improve. This pressure forces engineers to challenge the design space and create next generation splines and bearings.

References

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Figure 1: External (Male) & Internal (Female) Splines on a Shaft [2]

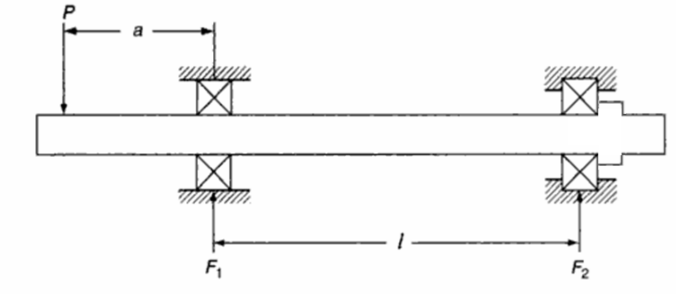

Figure 2: Simplified Shaft-Bearing System

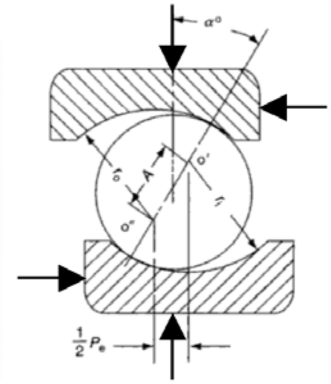

Figure 3: Typical Ball Bearing Load Path (Thrust and Radial Loads)

Figure 4: Typical Roller Bearing Load Path (Radial Loads Only)

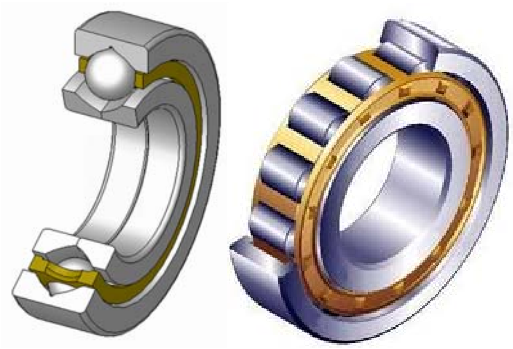

Figure 5:Typical Aircraft Engine Bearing Geometry. Split Inner Ring Ball Bearing (left) and Roller Bearing (right)

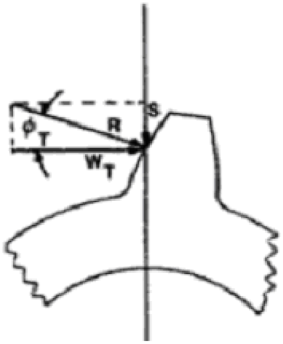

Figure 6: Spline tooth loading [5]

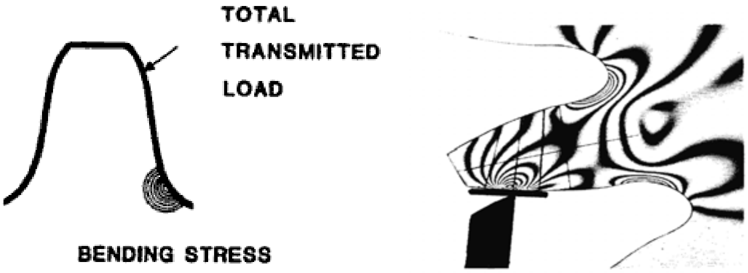

Figure 7: Bending Stress Contours on Spline Teeth [5],[8]

Figure 8: Contact Stress Contours on Spline Teeth [5],[8]

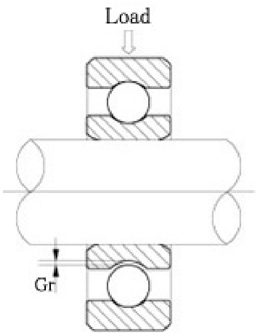

Figure 9: Internal Radial Clearance in Bearings (Gr)

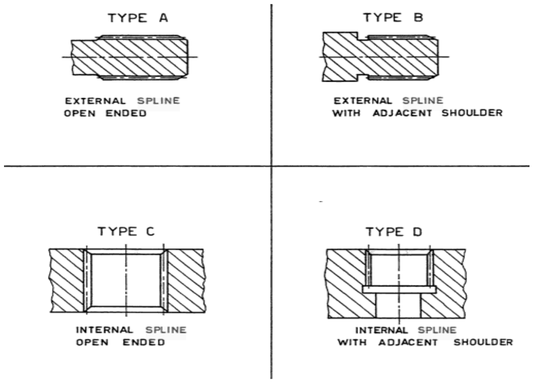

Figure 10: Spline classification based on part configuration [3]

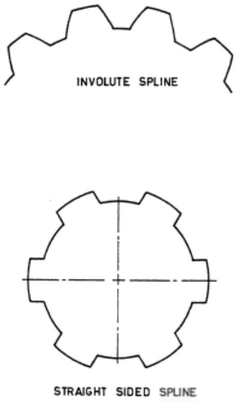

Figure 11: Tooth Forms [3]