DETERMINATION OF TURBOPROP REDUCTION GEARBOX SYSTEM FATIGUE-LIFE AND RELIABILITY FROM COMPUTER GENERATED TESTS

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ABSTRACT

Two computational models for the fatigue life and reliability of a turboprop gearbox are compared with each other and with field data. The two models are (1) Monte Carlo simulation of randomly selected lives of individual bearings and gears comprising a gearbox and (2) life analysis of the bearings and gears in the gearbox using the two-parameter Weibull distribution and the Lundberg-Palmgren life theory. These results were compared with field life results from 75 gearbox failures. Field data for the gearbox resulted in an $L_{10}$ life of 2100 hours and a Weibull slope of 1.3. The Lundberg-Palmgren method resulted in a calculated $L_{10}$ life of 1735 hours and a Weibull slope of 1.17. For the life estimation produced by the Monte Carlo method, the median $L_{10}$ life approached 1775 hours and the Weibull slope approached a value of 1.21. There is reasonably good engineering correlation between the life results obtained from the field data and those predicted from the Lundberg-Palmgren analysis and the Monte Carlo simulation.

Keywords: Probabilistic life, Contact fatigue life, Weibull analysis, Monte Carlo simulation, Gearbox life

INTRODUCTION

Bearing and gear fatigue life is a major factor in the evaluation of gearbox life. The fatigue life model proposed by Lundberg and Palmgren (ref. 1) is the commonly accepted theory for predicting rolling-element bearing life and is used in handbook life equations. Mathematical models have been developed for surface fatigue life of spur and helical gears (ref. 2). These life models are based on a modified Lundberg-Palmgren theory due to the similarity in fatigue failures between bearings and gears.

Another method for determining the life of a system comprising multiple components is by Monte Carlo simulation (ref. 3). Vlcek, et al. (ref. 4) determined the life of rolling-element bearings using this method and the two-parameter Weibull distribution (ref. 5). They correlated their results with laboratory and field bearing life data (ref. 4).

A reliability model for planetary gear trains has been developed (ref. 6). This model is based on the individual reliabilities of the gearbox’s bearings and gears. The reliability of the gearbox system is treated as a strict series probability combination of the reliabilities of the same gearbox components. Each bearing and gear reliability is calculated and the results are statistically combined to produce a system reliability and life for the total gearbox. Due to the different component Weibull slopes, a linear curve fit is performed in this model to determine the system Weibull slope and $L_{10}$ life.

In order to provide a methodology for calculating life and reliability for typical reduction gearboxes for present day and future turboprop aircraft, this work’s objectives were to determine and compare system fatigue lives based on: (1) the two-parameter Weibull distribution and the Lundberg-Palmgren life theory for both bearings and gears comprising the system using strict-series system reliability; (2) Monte Carlo simulation of randomly selected lives of individual bearings and gears comprising the system; and (3) comparing both methods to field generated lives and failure distributions of 75 turboprop gear boxes.

RESULTS AND DISCUSSION

A commercial gearbox, consisting of two stages with a single-mesh spur reduction followed by a five-planet planetary gearbox comprising eleven rolling-element bearings and nine spur gears (ref. 7), was used for this analysis. The life and reliability of the gearbox was evaluated using a Monte Carlo simulation of the lives and reliabilities of its main power train bearings and gears and an analytical system model which uses the same component lives and reliabilities.

The lives of a 2800 kW (3750 HP) rated turboprop gearbox was determined from field data using Weibull analysis
(Ref. 7). These data gave a gearbox \( L_{10} \) life of 2100 hrs. and a Weibull slope of 1.3. Applying the Palmgren-Langer-Miner linear-damage rule to the gearbox loading yielded an input torque of 1266 N-m (11205 lb-in) at 1380 RPM resulting in 1833 kW (2457 HP). This life is represented by a hollow circle in Fig. 1.

Using the Lundberg-Palmgren analysis for the bearings and gears for these same input values produced estimates of 1735 hours for the \( L_{10} \) life of the gearbox and 1.17 for the Weibull slope for the life distribution of the gearbox. This result is represented as the straight dashed line shown in Fig. 1. The Weibull slopes of the gears were assumed to be 2.5 and the bearings 1.1.

The estimates of the 90% confidence limits for the gearbox \( L_{10} \) life for a Weibull slope of 1.2, using the method of L. Johnson (Ref. 8), are shown by the solid curves of Fig. 1.

Eight thousand (8000) virtual gearbox systems were randomly assembled and virtual life tested by Monte Carlo number generation comprising 400,000 gearbox tests. Figure 1 shows the \( L_{10} \) life estimation produced by the Monte Carlo method. In this graph, the squares represent the minimum \( L_{10} \) life among the groups of gearboxes, the triangles the median \( L_{10} \) life and the diamonds represent the maximum \( L_{10} \) life. For the large number of gearboxes treated, the minimum and maximum values follow but exceed the 90% confidence limit values given by the methods of Johnson (ref. 8) for a Weibull slope of 1.2. The median \( L_{10} \) life approaches 1775 hours in this plot. In a similar plot for the Weibull slope, it approached a value of 1.21.

Both methods calculated the life of the gearbox according to a strict series probability model. The Monte Carlo method did this by taking the life of the gearbox as the life of the shortest lived component in each case. The program analysis did this by calculating the reliability of the gearbox as the product of the reliabilities of the components in the gearbox. This required a curve fit approximation in the program to determine the gearbox system Weibull distribution with its \( L_{10} \) life and Weibull slope. The similarities of the results for the two methods validate the curve fitting assumptions for combinations of bearing and gearing contact stress fatigue lives in the analytical model.

**SUMMARY**

Two models for the fatigue life and reliability of a turboprop gearbox are compared. The two models are a Monte Carlo model and an analytical system-life model which uses a strict-series system reliability. The system fatigue lives are based on the fatigue lives of the bearings and gears in the gearbox using the two-parameter Weibull distribution and the Lundberg-Palmgren life theory. The results were compared with field life results from 75 gearbox failures. These results were obtained:

1. Field data for the gearbox resulted in an \( L_{10} \) life of 2100 hrs. and a Weibull slope of 1.3. The Lundberg-Palmgren method resulted in a calculated \( L_{10} \) life of 1735 hrs. and a Weibull slope of 1.17.

2. For the life estimation produced by the Monte Carlo method, the median \( L_{10} \) life approached 1775 hrs. and the Weibull slope approached a value of 1.21.

3. There is good engineering correlation between the life results obtained from the field and those predicted from the Lundberg-Palmgren analysis and the Monte Carlo simulation.

4. For the Monte Carlo simulation, the minimum and maximum values follow but exceed the 90% confidence limit values as determined by the methods of Johnson (ref. 8) for a Weibull slope of 1.2.

**REFERENCES**


