E-ISSN: 2707-4552
P-ISSN: 2707-4544
IJMTME 2020; 1(1): 15-19
Received: 06-11-2019
Accepted: 10-12-2019

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Reliability prediction of deep groove ball bearings of rotary actuator

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Abstract
Success of a vehicle depends to a great extent upon the performance of actuator, which is one of the critical elements. Fuel control valves are used in engines to control the fuel to oxidizer mixture ratio. The valve is actuated through a rotary electro-mechanical actuator. The rotary actuator consists of DC motor as its prime mover, planetary gear box for torque multiplication and a sensor for feedback. Planetary gear train is used, to have a gear box of compact size and minimum inertia. In order to reduce the frictional losses and increase the actuator life, all gears of the planetary gear train are supported on deep groove ball bearings. For the development of electro-mechanical actuators, the key areas include electronics, failure detection and monitoring techniques, and reliability. In this work, reliability prediction of deep groove ball bearings is carried out, by applying appropriate failure rate models. The reliability of bearings is predicted to provide the measure of component performance to meet the system requirements.

Keywords: actuator, deep groove ball bearing, failure rate, reliability

Introduction

Success of vehicle depends to a great extent upon the performance of actuator, which is one of the critical elements. Actuators are used for actuate the fuel control valves used in the liquid engines in order to regulate the flow to oxidizer mixture ratio. Actuators of electro mechanical or electro hydraulic in nature are used for this purpose. Electro mechanical actuators are preferred over the electro hydraulic system for the reasons like simple configuration and less number of components, reduced efforts in system development and test, reduced system weight, no life restricting elements.

For the development of electro mechanical actuation system, the key areas include power electronics, motor technology, thermal design, failure monitoring and detection techniques, and reliability. Reliability is one of the key challenges posed during the development phase. It is one of the critical parameters while designing actuators, which have to be built-in during the design phase itself.

Reliability prediction is an important task carried out in the early stages of product development. Predicting the reliability of actuators will aid to capture the weak links in the system and failure modes in the design. Also it provides an awareness of potential equipment degradation during the equipment life cycle. As a result of performing a reliability prediction, design of equipment can be improved; development testing time can be optimized [1].

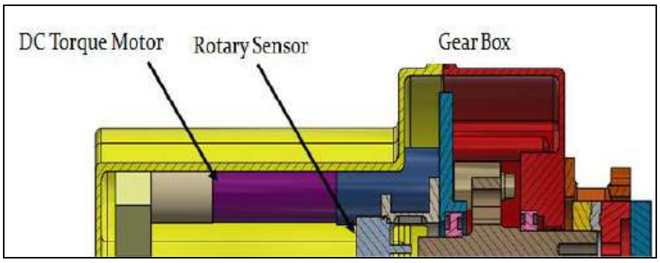

Fig 1: Section view of a rotary actuator

Electro mechanical actuator assembly consists of components like, a DC motor as prime mover, Sensor for feedback, spur gears, deep groove ball bearings etc. The present work is limited to predicting the reliability of deep groove ball bearings from the actuator assembly.

Appropriate models were applied to predict the failure rate of bearings. To estimate the failure rate of bearings, dynamic load rating, operating speed, operating temperature and service conditions are considered.

Literature review

Predicting the reliability of mechanical components apart from the electronics components have gained much importance in the design phase especially in the aerospace and defence sector. Limited number of work has happened in predicting the reliability of mechanical components.

A. Related work

Laurence J. Bement, *et al*. [3] in their study discussed a new methodology for predicting the mechanical functional reliability of pyrotechnic devices. In current method, for predicting the reliability of a particular device requires thousands of successful tests of very similar components and no performance measurements are made in go, no-go testing. The new approach begins with measuring, understanding and controlling the mechanical performance variables within a device. Application of this approach, provide considerable cost savings and better understanding of the component. Small-sample statistics of the data collected is used to predict functional reliability. X. He, *et al*. [2] in their paper presents an application of the method of coefficient of variation to the characteristic analysis of statistical distributions of failure rates and structural reliability. It also mentions that the Coefficient of variation can be used in both reliability based design of mechanical components and evaluation of product. The concept of coefficient of variation simplifies the calculation of statistical parameters. This application also states, by determining the simplified relation between coefficient of variation and statistical parameters, the characteristics of statistical distributions by means of coefficient of variation can be analyzed.

In the related literatures, the authors discussed mainly about the reliability prediction of structural elements. The application of coefficient of variation for establishing failure rates are also discussed. For the present work, failure rate of bearings are predicted by considering the operational factors.

Methodology

The methodology for predicting the reliability of deep groove ball bearings of rotary actuator is outlined in the following sections.

A. Selection of ball bearings

Ball bearings are used to reduce the frictional losses and increase the actuator life. All the gears of the planetary gear train are supported on ball bearings. Deep groove ball bearings are selected since the predominant load is radial.

Ball bearing is selected based on its static and dynamic load carrying capacity. Static load capacity of the bearing is the load at which permanent deformation of the ball and race equals 0.01% the ball diameter. This permanent deformation is caused by excessive load. The dynamic load capacity of the bearing is the load that will provide a life of one million revolutions. The dynamic load is an important factor in assessing bearing life.

The tolerance class of bearings used is ABEC7. ABEC stands for Annular Bearing Engineering Committee, which is an industry accepted standard for the tolerances of ball bearing. Five tolerance classes are there like 1,3,5,7,9. The higher the number provides better precision, efficiency and greater speed capability [4].

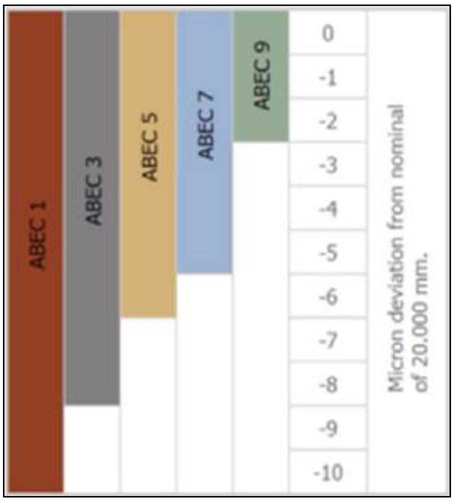

Fig 2: ABEC Class (Image Source: https://en.wikipedia.org/wiki/ABEC_scale) [4]

B. Types of bearings and its location in actuator

Ball bearings of different sizes are used at different locations of the actuators. In the input side for supporting the motor shaft, for supporting the planetary gears, bearings are provided on the gear carrier and in the output side of the actuator. The details of the bearings used in different locations in the actuator are provided in Fig. 3.

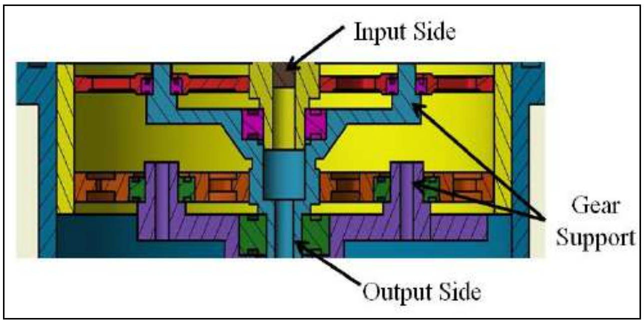

Fig 3: Locations of bearings

The details of the bearings used in different locations, its dimensions and its dynamic load capacity are provided in Table I.

Table 1: Bearing dimensions and load capacity

S. N	Bearing Location	Bearing Size (mm)	Dynamic Load (N)
1	Input Side	15x24x5	1610
2	Gear Box-Type 1	10x26x8	3950
3	Gear Box-Type 2	10x19x5	1510
4	Gear Box-Type 3	10x19x5	1510
5	Gear Box-Type 4	12x24x6	2410
6	Output Side	15x32x9	5600

C. Failure rate prediction of ball bearings

Failure rate of mechanical components like bearings are not generally mentioned by a constant failure rate distribution because of operating modes, environment conditions, loading, degradation, wear, fatigue etc. Bearings are one among few components that are designed for a finite life [1]. Establishing base failure rate for a bearing is extremely difficult based on the performance data. Some bearings are assigned a L_{10} life, which is the number of revolutions at a known load that 90% of identical bearings will complete before failure.

Factors like operating environment, velocity, lubrication properties, misalignment, type of loading, temperature and contamination levels are also considered while predicting bearing life to correlate the L_{10} life. Various multiplying factors along with L_{10} life are applied to determine the failure rate for the intended operating environment.

The models used for predicting the bearing failure rate is from the Handbook of Reliability Prediction Procedures for Mechanical Equipment developed by Naval Surface Warfare Center. The handbook uses a series of models for different types of mechanical components to predict failure rates considering wear, fatigue, stress, flow rate, aging etc.

D. Failure rate model of ball bearings

The failure rate of ball bearings is predicted based on the model as per the Handbook of Reliability Prediction Procedures for Mechanical Equipment [1].

- Bearing life with reliability of 90%, millions of revolutions (L_{10}), is given by

$$L_{10} = (L_S / L_A)^{y}$$

Where,
L_S = Dynamic load rating of bearing, lbf
L_A = Equivalent radial load rating on bearing, lbf
y = a constant, 3.0 for ball bearings

- The L_{10} life can be converted to hours with the following

$$L_{10h} = 10^6 / 60n \times (L_S / L_A)^y$$

Where,
L_{10h} = Bearing life (at 90% reliability), operating hours
n = Operating speed, rpm

- Failure rate of bearing, failures per million hours (λ_{BE}) is given by

$$\lambda_{BE} = \lambda_{BE,B} . C_R . C_V . C_{CW} . C_t . C_{SF} . C_C$$

Where,
$\lambda_{BE,B}$ = Base failure rate, failures/million hours
C_R = Life adjustment factor for reliability
C_V = Multiplying factor for lubricant
C_{CW} = Multiplying factor for water contamination level
C_t = Multiplying factor for operating temperature
C_{SF} = Multiplying factor for operating service conditions
C_C = Multiplying factor for lubricant contamination level

After establishing the base failure rate of the bearings, reliability of bearings are arrived by applying the failure rate (λ) to an exponential distribution. Exponential distribution is used in the reliability analysis of electrical components or mechanical systems.

Results and Discussion

A. Failure rate of output side ball bearing

The calculations for all the six types of bearings were carried out by considering various factors such as operating speed of each bearing which used in different locations of the actuator, its dynamic load capacity. A bearing from the output side of the actuator is taken for computation of failure rate. The bearing taken calculation has a dimension of 15 (ID) x 32 (OD) x 9 (W) mm, and has a dynamic load rating of 5600N.

B. Failure rate computation of output side ball bearing

- Bearing dimension, 15x32x9mm
- Bearing life with reliability of 90%, millions of revolutions (L_{10}), is given by

$$L_{10} = (L_S / L_A)^{y}$$

L_S = Dynamic load rating of bearing, lbf
= 5600N
= 1258.8 lbf
L_A = Equivalent radial load rating on bearing, lbf = L_S
= 5600N
= 1258.8 lbf
$L_A = L_S$, radial load is predominant, axial load is negligibly small.
y = a constant, 3.0 for ball bearings

$$L_{10} = (1258.88 / 1258.88)^{3} = 1$$

- The L_{10} life is converted to hours (L_{10h}):

$L_{10h} = 10^6 / 60n \times (L_S / L_A)^{y}$
$L_{10h} = 10^6 / (60\times120) \times 1$
= 8333.33 operating hours.

Where, n = Operating speed is 120rpm

- Failure rate of bearing, failures per million hours (λ_{BE}) is given by

$$\lambda_{BE} = \lambda_{BE,B} . C_R . C_V . C_{CW} . C_t . C_{SF} . C_C$$

(a) $\lambda_{BE,B}$ = Base failure rate, failures/million hours
= $1/L_{10h}$
= 1/8333.33
= 0.00012 failures/million hours

(b) C_R = Life adjustment factor for reliability
= 1.00, considering L_{10} life and for 90%
Reliability (c) C_V = Multiplying factor for lubricant

$$= (v_O / v_L)^{0.54}$$

Where, v_O = viscosity of specification lubricant, lb-min/in2
v_L = viscosity of lubricant used, lb-min/in2;
It is assumed that the specification lubricant and lubricant used are having same properties, $C_V = 1$
(d) C_{CW} = Multiplying factor for water contamination level
For, $CW \leq 0.8$, $C_{CW} = 1.0 + 25.50\,CW - 16.25CW^2$
For, $CW \geq 0.8$, $C_{CW} = 11.0$
Where, CW =% of water in the lubricant
It is assumed that these bearings are designed for water based lubricant, hence CW=0, therefore $C_{CW} = 1.0$

(e) C_t = Multiplying factor for operating temperature

$C_t = 1.0$ for $T_O \leq 183$ °C,
$C_t = (T_O / 183)^3$ for $T_O \geq 183$ °C

Where, T_O = Operating temperature of bearing
The operating temperature of the bearings used in these actuator is 25 °C, which is well below the range of 183 °C, hence multiplying factor for operating temperature, $C_t = 1.0$

(f) C_{SF} = Multiplying factor for operating service conditions
The bearing in the actuator undergoes normal operation and is subjected to light shock load. The bearing service factor is taken as, $C_{SF} = 1.5$

(g) C_{SF} = Multiplying factor for lubricant contamination level It is assumed that the contamination condition is of high cleanliness in which the oil is filtered through a fine filter of ≤10µ. For bearing diameter <100mm, the multiplying factor is taken as, $C_C = 1.4$

- Failure rate of bearing, failures per million hours (λ_{BE}) is given by

$$\lambda_{BE} = \lambda_{BE,B}.\ C_R.\ C_V.\ C_{CW}.\ C_t.\ C_{SF}.\ C_C$$

$$= 0.0012 \times 1 \times 1 \times 1 \times 1 \times 1.5 \times 1.4$$

$= 2.52 \times 10^{-4}$ failures / million hours.

C. Reliability estimation from failure rate

Reliability of the bearing is estimated by applying the failure rate in the following exponential distribution function. The reliability function for the exponential distribution is given by:

$$R(t) = e^{-\lambda t},$$

Where,
λ = Failure rate of bearing, failures / million hours
t = time in hours
The operational time of the bearing during is 200sec, ie. t=0.0555hrs. Hence the reliability of the bearing is

$R(t) = e^{-\lambda t}$
$= e^{-(2.52E\text{-}04/1000000)*(0.0555)}$
$= 0.9999999999860$

Similarly, the failure rates of the remaining 5 types of bearings were computed and are tabulated below:

Table 2: Failure rate of bearings

S. N	Bearing Location	Bearing Size (mm)	Failure rate of bearing, failures/million hours (λ_{BE})
1	Input Side	15x24x5	1.23×10^{-2}
2	Gear Box-Type 1	10x26x8	1.76×10^{-3}
3	Gear Box-Type 2	10x19x5	4.23×10^{-3}
4	Gear Box-Type 3	10x19x5	6.05×10^{-4}
5	Gear Box-Type 4	12x24x6	1.76×10^{-3}

The reliability is also computed for all the remaining five types of bearing based on the calculated base failure rate. The reliability values computed are provided in the table given below:

Table 3: Reliability of bearings

S. N	Bearing Location	Bearing Size (mm)	Reliability
1	Input Side	15x24x5	0.9999999993140
2	Gear Box-Type 1	10x26x8	0.9999999999020
3	Gear Box-Type 2	10x19x5	0.9999999997648
4	Gear Box-Type 3	10x19x5	0.9999999999664
5	Gear Box-Type 4	12x24x6	0.9999999999020

Conclusion

The failure rate prediction is generally carried out in the design stage itself which provides the measure of product performance. Reliability prediction of mechanical components like bearings, gears, valves etc are carried out using failure rate prediction models mentioned in the Handbook of Reliability Prediction Procedures for Mechanical Equipment. Reliability prediction models are available for components as well as for sub assemblies.
The present work is limited to establish the failure rate of deep groove ball bearings used in the rotary actuator. The failure rate was applied to the reliability function for an exponential distribution which provides the reliability of the corresponding bearing. The failure rate values computed for the bearings depend upon the assumptions made for various multiplication factors. For the same type bearing, having similar dimensions and load carrying capacity, the failure rate are subjected to vary depending on its mode of operation, load to which the bearings are subjected and duration of operation. For the use in the rotary actuation system, the bearings are found to be reliable, based on certain assumptions made.

For future work, the reliability prediction has to be done for all the components of the actuator like the gears in the planetary gear train, DC motor, sensor, structural elements etc. Once the failure rate for all the components are established, the reliability also needs to be found out by applying appropriate distribution. For the components having redundancy, the reliability has to be established considering the redundancy scheme also. This is mainly applicable for electronic components like motor, sensor etc.

Acknowledgment

F.A. Author takes this opportunity to express my deep sense of gratitude and sincere thanks to all who helped to complete the project successfully. F. A. Author thanks Shri. Maruthi S. S., Engineer at M/s. Vikram Sarabhai Space Centre for his excellent guidance and advice. Finally, F. A. Author thanks his family and friends near and dear ones who directly and indirectly contributed to the successful completion of this project.

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