Design and Finite Element Analysis of a Deep Groove Ball Bearing

Verification of the Stribeck's Equation

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***Abstract*:** Bearings are an integral part of any rotating machinery. They are crucial components of study from the viewpoint of tribology. Bearing strength and load bearing capacity is important when it comes to their application in precision tools and mega structures like airplanes. Their structural failure can result in drastic consequences. In this paper, a single row deep groove ball bearing design is selected after careful calculation of the major forces, torques and operating velocities involved in the IAE V2528-D5 engines which are used in many major airplanes like Airbus A320 family and McDonnell Douglas. The single deep groove ball bearing design was modeled for a bore diameter of 110mm in CATIA. Finite element analysis of 3-D model was done using ANSYS software. Furthermore, the verification of Stribeck's equation for load bearing capacity using the versions of the bearing design; firstly, based on the number of balls in a specific bearing design and secondly, based on the diameter of the ball in the bearing was achieved.

***Index Terms* —Stribeck's equation, IAE-V2500 engine, deep groove ball bearing, finite element analysis, AnSys.**

I. INTRODUCTION

The purpose of a bearing is to provide relative positioning and rotational freedom while transmitting a load between two structures, usually a shaft and housing [1]. There are two types of bearings, contact and noncontact.

Contact-type bearings have mechanical contact between elements, and they include sliding, rolling, and flexural bearings. Mechanical contact means that stiffness normal to the direction of motion can be very high, but wear or fatigue can limit their life [7]. Non-contact bearings include externally pressurized and hydrodynamic fluid film (liquid, air, mixed phase) and magnetic bearings. The lack of mechanical contact means that static friction can be eliminated, although viscous drag occurs when fluids are present [7].

Rolling elements like balls and rollers are used in Anti-friction bearings to reduce friction. The rolling elements are constrained between an inner race, an outer race and a separating cage that keeps the rolling elements spaced apart so they do not rub against each other which would result in skidding and excess friction. Full-complement bearings are fully loaded with rolling elements and have no cage, which enables them to carry greater loads at low speeds.

A deep-groove ball bearing is an anti-frictional bearing which is designed to support radial or bi-directional axial loads. When ball bearing works, it is usually that more than one rolling ball bears the load. When the load is zero, the contact area is a point, i.e., point-contact. When the load increases in running, the bearing inner ring, outer ring and rolling elements bring forth plastic deformation in the contact area, so the point-contact becomes face-contact [2]. Deep groove ball bearing has a low frictional loss due to point contact between balls and races and the resultant rise in temperature is less. Therefore they are widely used ball bearings even in high-speed applications.

International Aero Engines AG is a Zürich-registered joint venture manufacturing company founded in 1983 to develop an aircraft engine. The collaboration, between four of the world's leading aero engine manufacturers, i.e., Pratt & Whitney (USA), Pratt & Whitney Aero Engines International GmbH (Switzerland), MTU Aero Engines (Germany) and The Japanese Aero Engine Corporation(Japan) produced the V2500 series – the second most successful commercial jet engine program in production today in terms of volume, and the third most successful commercial jet engine program in aviation history. IAE V2528-D5 engine is a two-shaft high-bypass turbofan engine used in McDonnell Douglas MD-90.

II. OBJECTIVES

A single row, open type deep groove ball bearing design was selected for IAE V2528-D5 engine from the catalogue of NTN Corporation [3]. The selection was made on the basis of load calculation from the specifications of this engine obtained from European Aviation Safety Agency report [4].

The design was ultimately used for the verification of Stribeck's equation for load bearing capacity of ball bearing:

- By varying the diameter of the balls,
- By varying the number of balls in a single specific design.

Again, Finite element analysis of the balls was done for two material combinations:

- ASTM A485 Grade 1, an alloy

- Silicon Nitride (Si3N4), a ceramic material

CATIA software was used for 3-D modeling and ANSYS 15.0 software was used for FE analysis.

III. STRIBECK'S EQUATION

The Stribeck's equation gives the static load capacity of the bearing. It is based on the following assumptions:

- The races are rigid and the circular shape is retained
- The balls are equally spaced
- Upper half of the bearing does not support any load
- Single row of balls is used [5].

$$Co = (K\, d^2\, z)/5 \qquad (1)$$

Where,
Co= total load
d=ball diameter
z= number of balls
K= constant which depends on radius of curvature at the contact point and nature of material.
Therefore, Co is proportional to square of diameter, d2.
Co is proportional to number of balls, z. In either case stress decreases proportionally.

IV. DESIGN ASPECTS

Formulae are given in standards for calculating static load carrying capacity of different types of bearings. However, while selecting a bearing, it's not necessary to use these formulae. The values of static load carrying capacities are directly given in manufacturer's catalogues that are based on the above criterion [5].
Reference [4], suggests the specifications of the IAE V2528-D5 engine as mentioned in the table below.

Table 1Engine specifications

Properties	Values
Weight (Excludes Exhaust Nozzle)	2,595 kgf
Take-off thrust	127,550 N
Maximum constant thrust	114,140 N
Maximum starter torque at zero r.p.m	63.7 daNm
Maximum continuous power at any engine speed	131 KW
Average running speed	5,000 r.p.m

The net force acting on the engine will be the resultant of Take-off and weight of the engine, i.e.

$$\textbf{Total Force, Nf} = \sqrt{(127550)^2 + (2595)^2} = 124{,}577\ \text{N} \qquad (2)$$

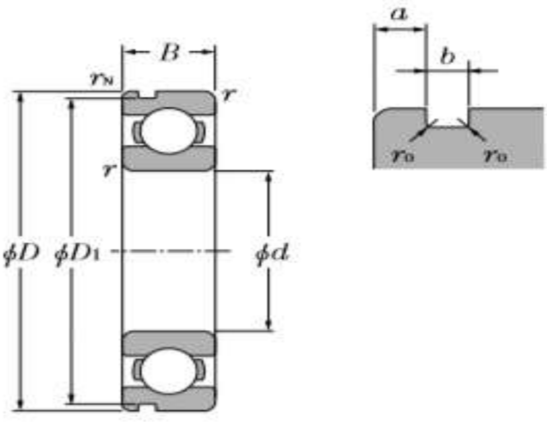
Now,
Actual force on the aircraft in high shock [3] conditions (k=1.5),

$$\textbf{Kactual = k. Nf = 186,865.54 N \textasciitilde{} 1.8687e005 N} \qquad (3)$$

Based on the above-obtained value of total force and the operating velocity of 5000 r.p.m, a single row, open type deep groove ball bearing is selected [3].

Table 2 Dimension of initial design of ball bearing [3]

d	110 mm
D	240 mm
B	50 mm
r	3 mm
D1	183.64 mm
a	5.69 mm
b	3.5 mm
ro	0.6 mm



Bore Diameter	110 mm
Ball Diameter	36 mm
Groove radius	20 mm
Number of balls	8

FIGURE 1 TWO-D LAYOUT OF THE BALL BEARING [3].

Properties of material used in the FE analysis are as follow:

Table 3 ASTM A485 Grade 1

Physical Properties	Values
Density	7.7e-006 Kg/mm3
Young's modulus	2.0e+005 Mpa
Poisson's ratio	0.29
Bulk modulus	1.5873e+005 Mpa
Shear modulus	77579 Mpa
Tensile yield strength	350 Mpa
Tensile ultimate yield strength	650 Mpa
Thermal co-efficient of expansion	1.0e-005/◦C

Table 4 Silicon Nitride (Si_3n_4)

Physical Properties	Values
Density	3.31e-006 Kg/mm3
Young's modulus	3.17+005 Mpa
Poisson's ratio	0.29
Bulk modulus	1.9568e+005 Mpa
Shear modulus	1.2866e+005 Mpa
Tensile yield strength	679 Mpa

V. METHODOLOGY

According to the methodology followed in [6], the finite element analysis of the ball bearings is done with medium smoothening, default meshing. The inner ring is subjected to quadrilateral mesh element whereas the balls and the outer rings are subjected to triangular mesh element. The reference temperature is 22° Celsius.

The outer ring is fixed and the inner ring is subjected to a radial loading of **1.8687x105 N**.

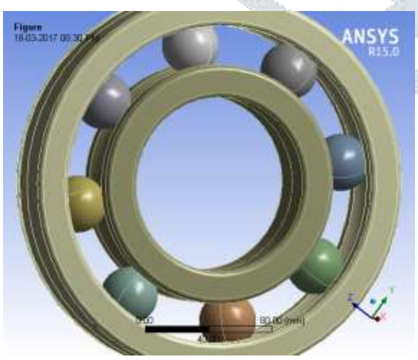


FIGURE 2 THREE-D MODEL OF BALL DIAMETER=18 AND Z=8

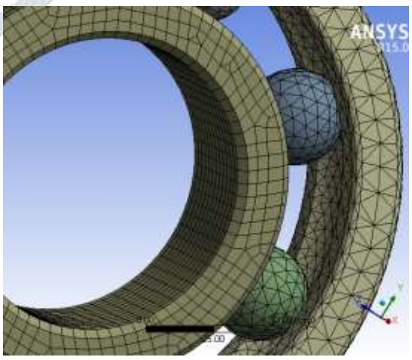


FIGURE 3 MESHING OF THE MODEL IN ANSYS

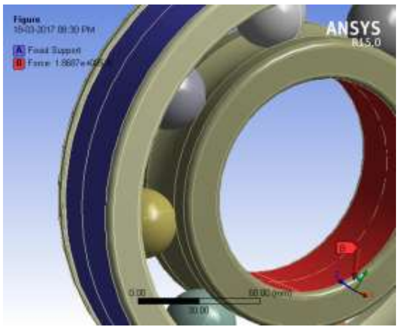


FIGURE 4 BOUNDARY CONDITION

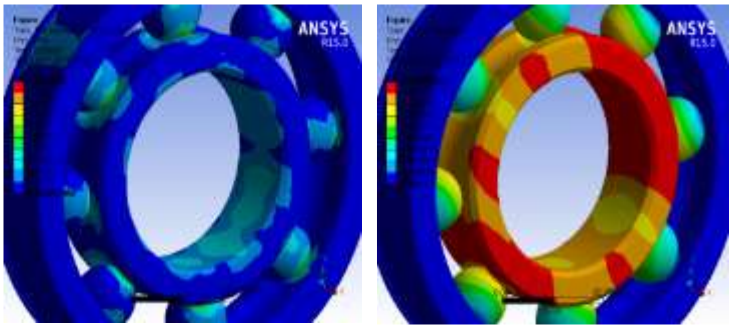


FIGURE 5 VON MISES STRESS AND TOTAL DEFORMATION

VI. OBSERVATIONS

6.1 Stribeck's equation verification based on number of balls,'z'

6.1.1 The material used is ASTM A485 Grade 1, bore diameter=55mm, ball diameter=36mm, groove radius= 20mm.
Weight of outer race: 4.6824 Kg
Weight of inner race: 2.7743 Kg

Table 5 Tabulation of Observations Based on Number of balls,'z'(Initial design)

S. No.	No. of balls	Mass (Kg)	Volume (mm3)	Maximum Equivalent stress (Mpa)	Maximum Total Deformation (mm)
1.	6	8.5853	1.1150e+006	261.60	4.0762e-002
2.	7	8.7734	1.1394e+006	199.04	3.3346e-002
3.	8	8.9615	1.1638e+006	180.50	2.6920e-002
4.	9	9.1496	1.1883e+006	174.42	2.3438e-002
5.	10	9.3377	1.2127e+006	158.22	2.1027e-002
6.	11	9.5258	1.2371e+006	128.55	1.8692e-002
7.	12	9.7139	1.2616e+006	121.71	1.7636e-002
8.	13	9.9020	1.2860e+006	114.13	1.5791e-002

6.1.2 The material used is ASTM A485 Grade 1 for the inner race and outer race, Silicon Nitride (Si_3N_4) for balls; bore Diameter=55mm,
Ball Diameter=36mm
Groove Radius= 20mm.
Weight of outer race: 4.6824 Kg
Weight of inner race: 2.7743 Kg
Results were obtained in similar manner:

Table 6 Tabulation of Observations Based on Number of balls,'z'(composite)

Properties	Diameter 24	Diameter 28	Diameter 32	Diameter 36	Diameter 40
Mass (Kg)	7.2408	7.4692	7.7387	8.1036	8.4124
Volume (mm3)	9.7338e+005	1.0225e+006	1.0833e+006	1.1638e+006	1.2453e+006
Maximum Equivalent Stress (Mpa)	435.37	226.86	242.18	214.86	171.05
Maximum Total Deformation (mm)	2.6644e-002	2.5177e-002	2.3328e-002	2.2674e-002	2.0267e-002

6.2 Stribeck's equation verification based on diameter of balls,'d'

6.2.1 The material used is ASTM A485 Grade 1 for the inner race and outer race, Silicon Nitride (Si3N4) for balls; bore diameter=55mm. Keeping the number of balls=8, Diameters of the balls are varied. Results were obtained in similar manner for five diameter variations:

Table 7 Tabulation of Observations Based on Diameter,'d' (composite)

S. No.	No. of balls	Mass (Kg)	Volume (mm3)	Maximum Equivalent stress (Mpa)	Maximum Total Deformation (mm)
1.	6	7.9419	1.1150e+006	243.66	3.6240e-002
2.	7	8.0227	1.1394e+006	232.87	2.8842e-002
3.	8	8.1036	1.1638e+006	214.86	2.2674e-002
4.	9	8.1844	1.1883e+006	192.75	1.9689e-002
5.	10	8.2653	1.2127e+006	162.76	1.7918e-002
6.	11	8.3462	1.2371e+006	132.78	1.5900e-002
7.	12	8.4270	1.2616e+006	125.21	1.5407e-002
8.	13	8.5079	1.2860e+006	113.31	1.3235e-002

VII. RESULTS

7.1 Stribeck's equation verification based on number of balls,'z'

7.1.1 The material used is ASTM A485 Grade 1, bore diameter=55mm, ball diameter=36mm, groove radius= 20mm.

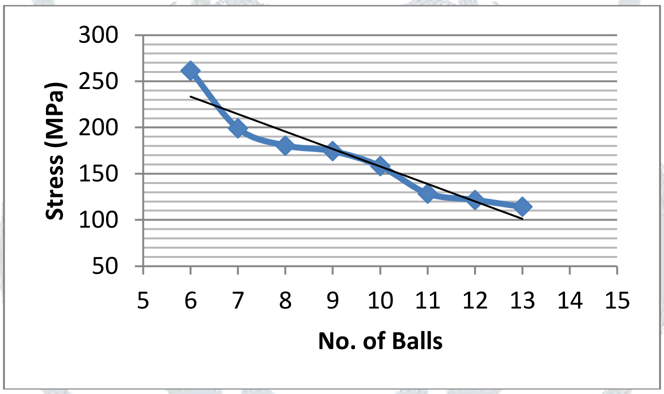


FIGURE 6 VARIATION OF EQUIVALENT STRESS BASED ON NUMBER OF BALLS

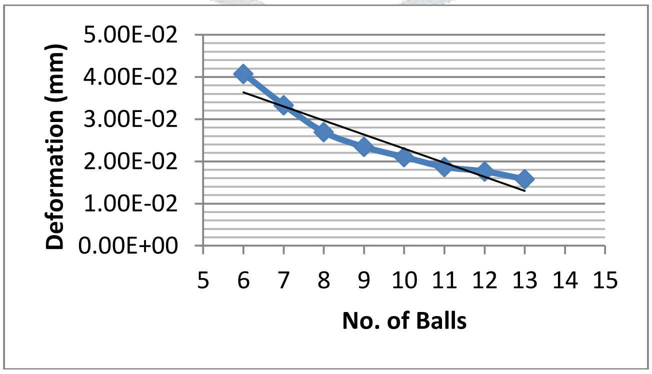


FIGURE 7 VARIATION OF TOTAL DEFORMATION BASED ON NUMBER OF BALLS

7.1.2 The material used is ASTM A485 Grade 1 for inner race and outer race, Silicon Nitride (Si_3N_4) for balls; bore diameter=55mm, ball diameter=36mm, groove radius= 20mm.

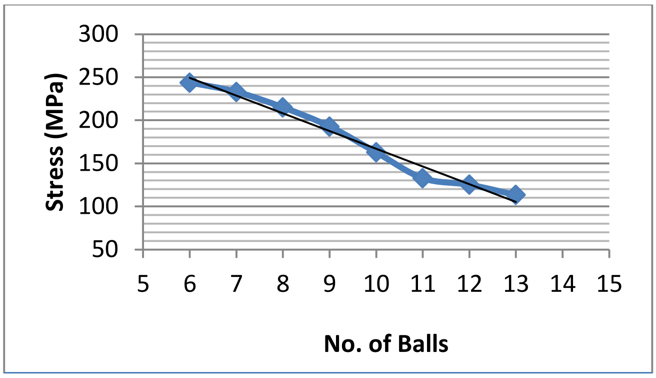


FIGURE 8 VARIATION OF EQUIVALENT STRESS BASED ON NUMBER OF BALLS

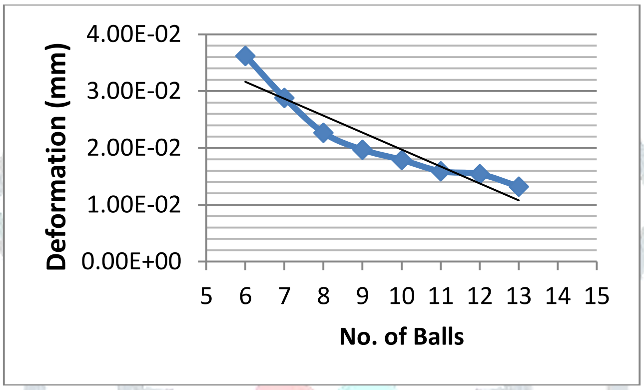


FIGURE 9 VARIATION OF TOTAL DEFORMATION BASED ON NUMBER OF BALLS

7.2 Stribeck's equation verification based on diameters

7.2.1 The material used is ASTM A485 Grade 1 for the inner race and outer race, Silicon Nitride (Si3N4) for balls; bore diameter=55mm. Keeping the number of balls=8, Diameters of the balls are varied.

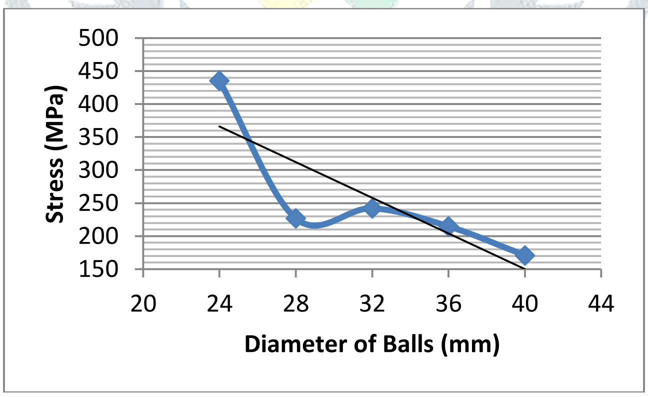


FIGURE 10 VARIATION OF EQUIVALENT STRESS BASED ON DIAMETER OF THE BALLS

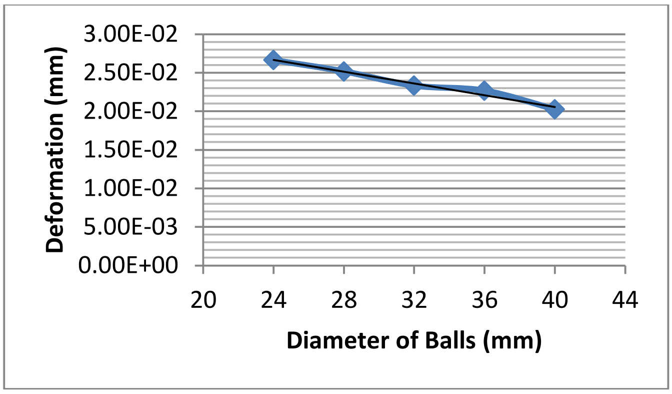


FIGURE 11 VARIATION OF TOTAL DEFORMATION BASED ON NUMBER OF BALLS

VIII. CONCLUSION

The maximum stress that has been recorded occurs in the Hybrid bearing of diameter 24 mm is 435.37Mpa is less than the ultimate yield stress of both materials. The factor of safety is maintained at 1.49 and above.

Total deformation due to static loading is minimal and mostly occurs in the inner ring and the balls.

The use of Silicon Nitride material for the balls leads to a decrease in overall bearing weight with a nominal increase in stress comparatively yet a slight decrease in total deformation is observed. Therefore, making it a better material than ASTM A485 Grade1.

The above-obtained set of results and graphs clearly show the decrease in stress and total deformation in the three cases thus suggesting the increase in load bearing capacity of bearing, proving the validity of Stribeck's equation based on both change in diameter of the balls as well as the number of balls in a specific design. Also, the change in materials doesn't affect the validity of the equation. Therefore, this equation is applicable for both alloys and ceramics.

Also, this paper provides a better criterion for the selection of bearing design for use in IAE V2528-D5 engine by narrowing down the selection procedure for precision and safety for a selected load.

IX. SCOPE FOR FUTURE RESEARCH

Further experiments can be done to obtain any direct relationship for the factor of safety with respect to the load bearing capacity of the bearing. Also different combination of materials like plastics, pure metal etc., can be used to test the universality of the equation. Stribeck's equation can be tested for elevated temperatures or for negative temperatures. A range of velocities can be considered to test the validity of the equation for dynamic conditions as well.

X. ACKNOWLEDGMENT

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