

Hydrodynamic Thrust Bearings for Downhole Mud Motor Use

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Abstract

A thrust bearing employing advanced ceramics has been developed using hydrodynamic technology which minimizes wear and significantly decreases bearing frictional losses. Consequently, downhole bearing longevity and reliability is increased resulting in a significant reduction in costly premature motor pulls.

The use of mud motors is common in directional drilling for oil and gas where thrust bearings are exposed to severe operating conditions including high shock loads, misalignment, and abrasive lubrication. This paper covers the use of a hydrodynamic tilt-pad thrust bearing design which was optimized to operate in downhole motor environments. This patented bearing was tested and compared to conventional ball bearings and polycrystalline diamond compact bearings.

Hydrodynamic bearings provide a fluid film that separates the relative moving parts and eliminates the sliding wear conventional bearings experience. The fluid film also significantly reduces frictional loss which directly leads to more torque available to the drill bit.

After theoretical evaluation, lab testing and field trials were performed to study the possible advantages of load, power efficiency, and endurance that may be attained using a hydrodynamic design. Testing showed that at motor speeds, a fluid film layer is developed resulting in insignificant wear and low frictional losses.

Introduction

Drilling for oil and natural gas frequently involves the use of mud motors. The primary components used in such a tool typically include a power section, coupling, and bearing assembly. The mud motor is connected to the drill string and is used to direct the drill bit. Mud motors are subjected to extremely harsh operating environments including abrasive drilling fluid, load, shock, vibration and temperature. One heavily stressed component in such tools is the thrust bearing assembly, typically located near the drill bit. Speeds, or revolutions per minute (rpm), of the motor are dependent on the power section and the frictional drag of the system. For example a progressive cavity power section with a 5/6 lobe configuration may operate efficiently at 80-120rpm, a 1/2 lobe configuration may operate in excess of 800+ rpm, and a turbine power section may experience speeds much higher. Frictional drag due to bearings, transmission section and bit

also affect speed, i.e. a more efficient bearing section directly relates to more torque available to drive the bit.

Significant consideration needs to be given to the design and specification of the thrust bearing, particularly in the case of higher speed motors.

Bearing Types

Rolling Element Bearings

Rolling element bearings, or ball bearings, (Figure 1) have conventionally been used to react thrust, or axial, loads in downhole mud motors. When low rpm power sections are used in the application such bearings provide sufficient life and reliability. However, bearing component fatigue causes life to decrease linearly as speed increases. This fatigue makes ball bearings unsuitable for high rpm motors.

Standard engineering practice dictates that ball bearings are specified according to L10 life, or the number of revolutions a group of identical bearings is expected to sustain before 10% fail. As revolutions are related to speed, bearings operating in a higher speed motor will fail before those operating in a low speed motor, e.g. one could roughly expect a 90% reduction in bearing life if speed was increased from 100 to 1000 rpm.

In addition to life, friction and horsepower losses are often of interest in drilling. Ball bearings are referred to as frictionless bearings due to the rolling nature of the elements, however in practice frictional losses exist due to rolling resistance and sliding. An order of magnitude approximation of the coefficient of friction (cof) for an angular contact bearing operating in ideal non-abrasive lubricant conditions is 0.0032.¹ In drilling mud, the cof can be assumed to be significantly higher.

Sliding Bearings

Polycrystalline Diamond Compact (PDC) bearings (Figure 2) have historically been utilized in high speed motors as they are not subjected to the same fatigue mechanism experienced by rolling element bearings. These bearings operate in a sliding manner and rely on low coefficient of friction to allow the relative moving parts to transmit load. Common PDC bearing designs use an array of round PDC pads mounted to a ring. Two rings are used in operation, one which stays stationary and one which rotates with the rotor.

In the case of PDC the value of coefficient of friction can be estimated by 0.05 to 0.08.²

Hydrodynamic Bearings

Hydrodynamic, or fluid-film, bearings function by separating the bearing faces by a layer of viscous fluid. A conventional hydrodynamic tilt-pad bearing was modified for use in downhole operation. The modification includes the use of spring mounted silicon carbide pads which:

1. allow pads to tilt for fluid entrainment into the bearing surface as shown in (Figure 6)
2. allow deflection in the axial direction for efficiently sharing thrust load among pads and between stacked bearings
3. resist mud abrasion due to hardness of the advanced ceramic

This separation is caused by a pressure which is built up by the relative motion of the moving and stationary rings. The primary difference between Hydrodynamic bearings and PDC bearings is the use of tilting pads and a continuous surface used for the rotating ring. The tilting action of the pad allows for an ideal angle to promote the flow of fluid into the bearing surface (Figure 6). The continuous surface allows for a stable pressure profile whereas alternating round pads used in PDC bearings lose this pressure buildup each time a pad moves from one opposing pad to the next.

Coefficient of friction, f , for hydrodynamic bearings can be estimated using the following formula:³

$$f = 11.7 \frac{h_0}{l}$$

Where h_0 is the minimum oil thickness in inches, and l is the length of a bearing pad in inches.

The minimum film thickness, h_0 , is calculated using the following equation:³

$$h_0 = 0.0341 \sqrt{\frac{\mu u l}{P_{avg}}}$$

Where μ is absolute viscosity in lb-sec/in², u is the linear velocity of runner at mean diameter of bearing, in/min, l is the length of a bearing pad in inches, and P_{avg} is the average pressure on the bearing pad, lb/in²

Using the above two equations, the coefficient of friction for the designed bearing operating in water can be estimated to be 0.0004.

Lab Testing

Testing was performed on the 3 styles of bearings using the setup shown in Figure 7. A hydraulic cylinder applied axial force to the thrust bearings while a 20HP motor with variable speed drive provided torque to the rotating bearing element. All testing was performed in a water flooded bearing compartment. Recorded data included hydraulic pressure

(applied load), temperature, and motor amperage. Motor amperage recordings were used as a comparative measure of torque required to overcome the frictional drag generated by the test thrust bearing.

Test parameters were the following:

- Bulk fluid temperature of 150F
- Thrust load ramp to 7000 lbf
- Speed, ball bearing: 150 rpm
- Speed, PDC bearing: 1000 rpm
- Speed, Hydrodynamic bearing: 1000 rpm

Test specimen dimensions:

- Ball Bearing
 - 2.46" ID x 4.12" OD x 1.13" Height
 - 16 balls, 5/8" diameter
- PDC Bearing
 - 2.45" ID x 4.11" OD x 2.00" Height
 - 18 pads
 - Total area 3.37 in²
- Hydrodynamic Bearing
 - 2.46" ID x 4.12" OD x 1.49" Height
 - 20 pads
 - Total area 2.16 in²

Test Results

Lab test results are shown in Figures 8 through 10. All bearings were in fully operational condition after testing with wear under 0.0001" on the bearing surface.

Test Bearing	Coefficient of friction	Tested motor current draw at 7000 lbf load, amps
Ball Bearing	0.0032 ^a	9.55
PDC Bearing	0.05 – 0.08 ^b	17.05
Hydrodynamic Bearing (theoretical)	0.0004	9.33

a: Design of Machine Elements, Faïres

b: US Synthetic, Sexton et. al.

Test Bearing	% change in motor current draw vs ball bearing baseline
Ball Bearing	N/A
PDC Bearing	+78.5%
Hydrodynamic Bearing	-2.2%

Field Trials

After lab testing, field trials were performed downhole in a mud motor. Due to confidentiality agreements in effect, run data is not available for publishing. Further, it would not be practical to obtain a bearing coefficient of friction value in actual downhole drilling. Post-run hydrodynamic bearings are

shown in Figures 11 and 12.

Conclusions

The modified hydrodynamic tilt pad bearing design demonstrated that it should be considered the new standard for high speed positive displacement mud motors and turbine mud motors. The nature of hydrodynamic operation results in the bearing exhibiting insignificant wear and less frictional losses which translate into more torque available to the bit, higher rates of penetration and increased reliability.

Additionally such bearings should be considered as an alternative to ball bearings in lower speed motors. Frictional losses are comparable to ball bearings, however the design exhibits lower wear which would lead one to conclude it could offer longer runs between failure, higher reliability and lower cost. Additional evaluation should be performed in low speed configurations.

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2. T.N. Sexton, C.H. Cooley: "Polycrystalline Diamond Thrust Bearings for Down-hole Oil and Gas Drilling Tools", *Wear* (2008)
3. *Marks' Standard Handbook for Mechanical Engineers, Ninth Edition*, pp 8-124 - 8-125 McGraw-Hill Book Company, New York



Figure 1. Rolling Element Bearing



Figure 2. PDC Bearings



Figure 3. PDC Bearing Side View, Braze Inserts



Figure 4. Hydrodynamic Bearing (right) and Rotating Runner (left)



Figure 5. Hydrodynamic Tilt-Spring Elements

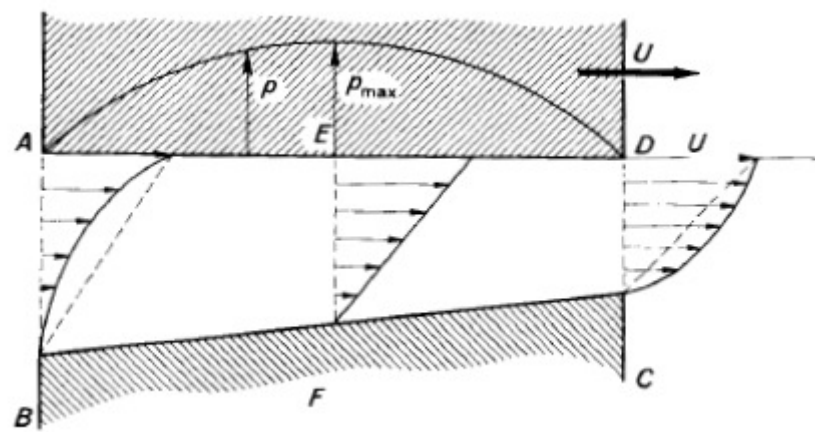


Figure 6. Tilting Pad Pressure Profile (V.M. Faires et al. 1967)

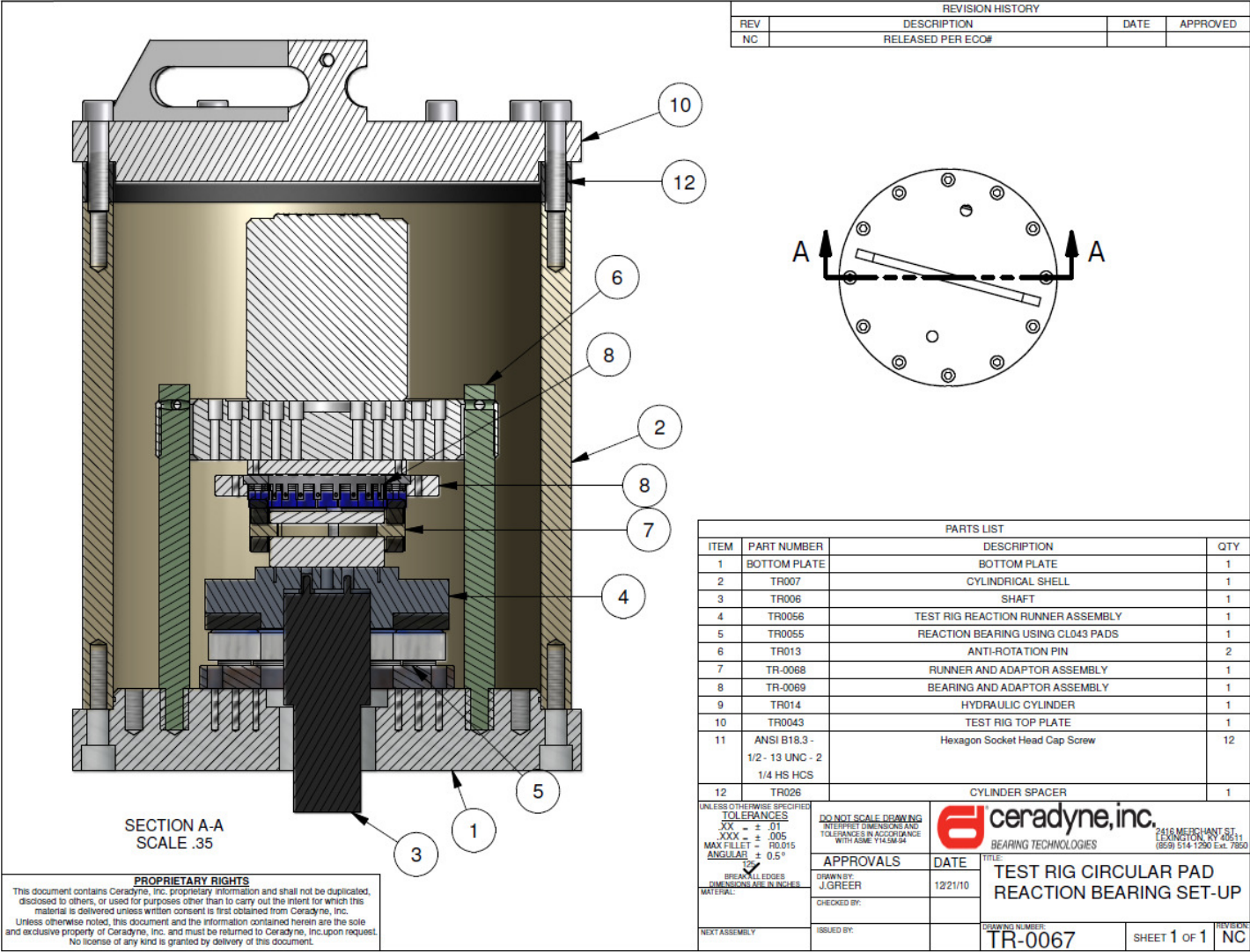


Figure 7. Test Setup

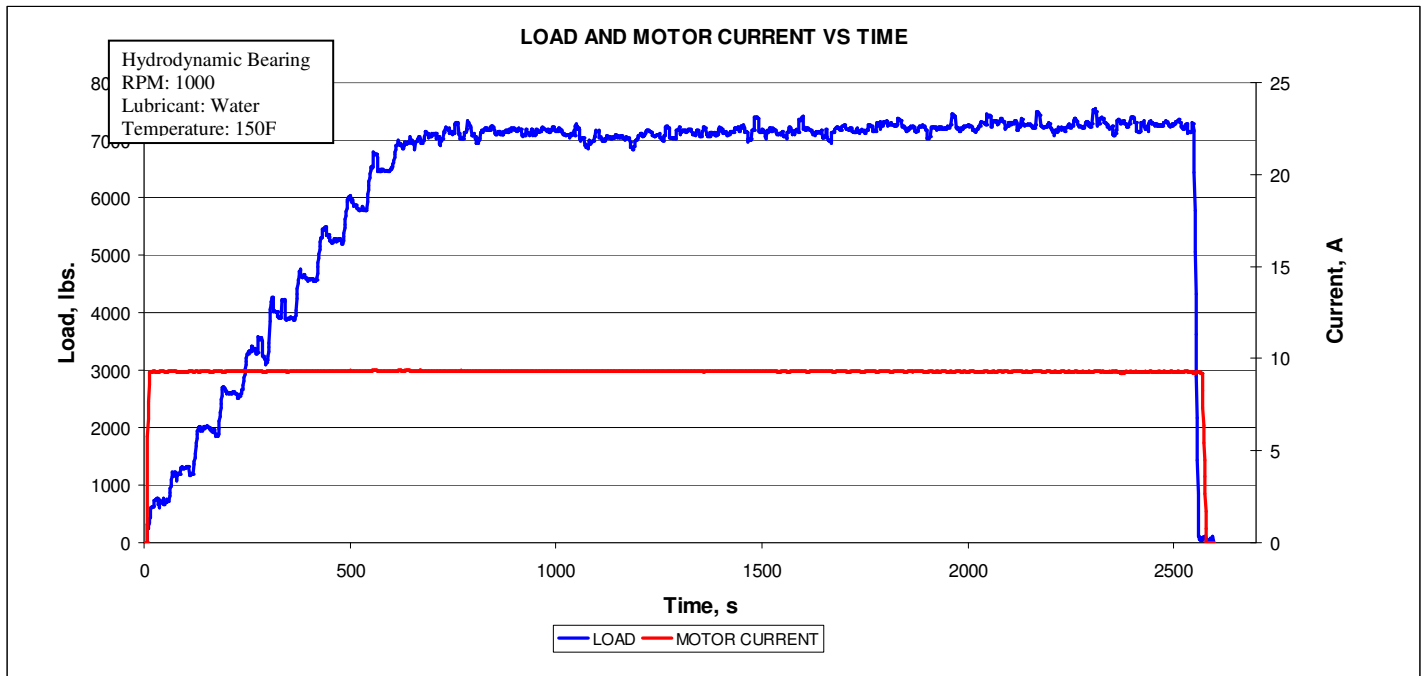


Figure 8.

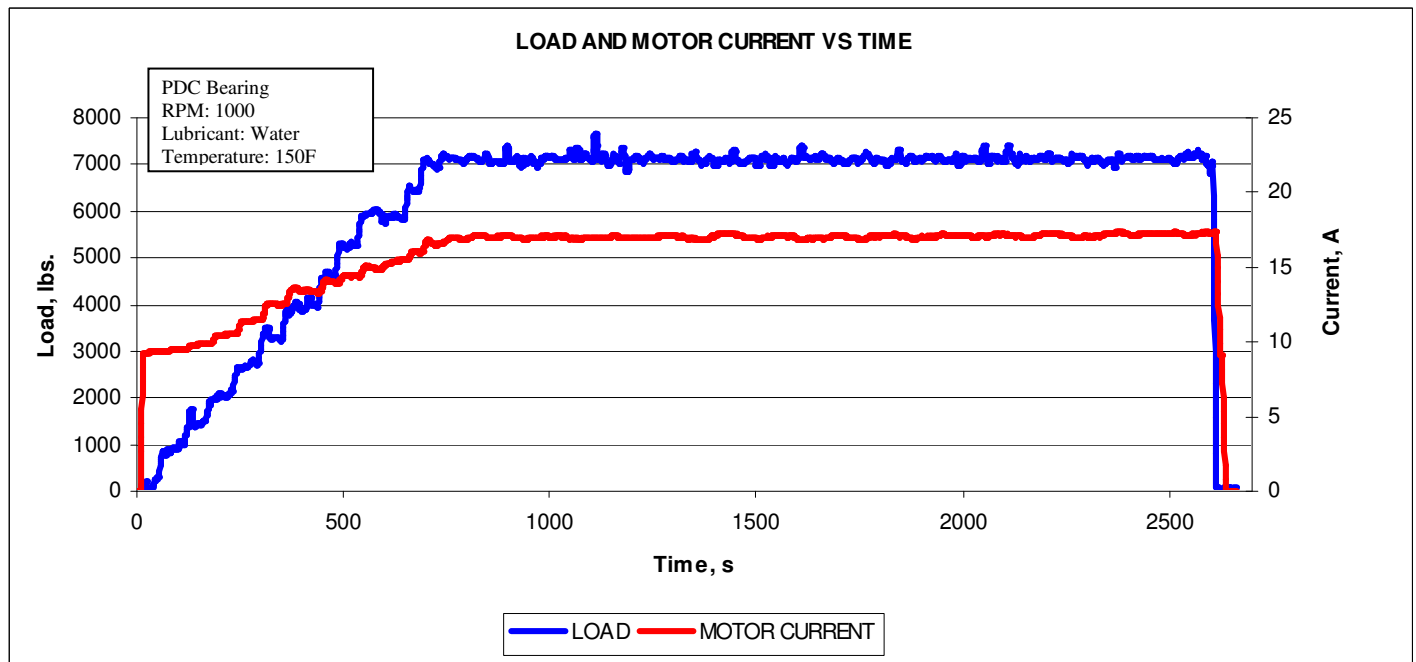


Figure 9.

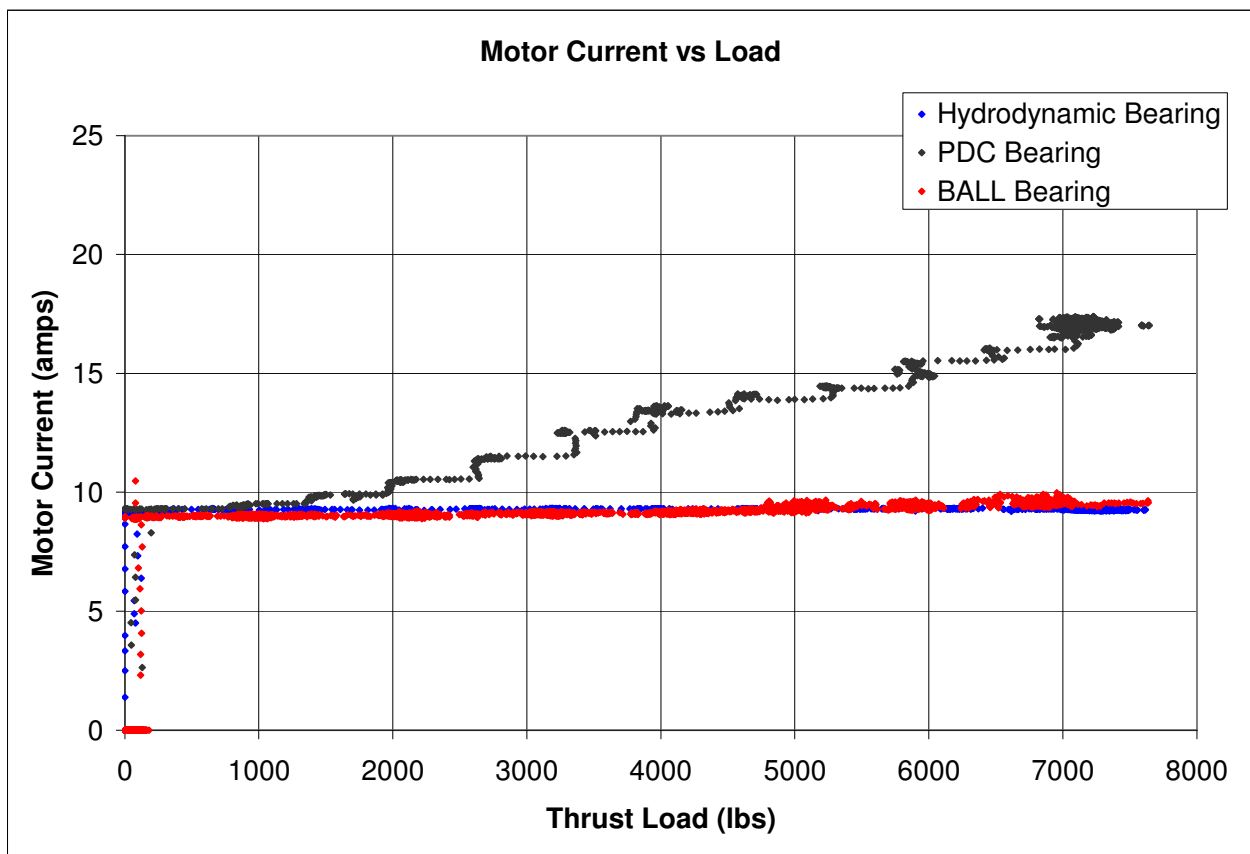


Figure 10. Motor current draw versus thrust load.



Figure 11. Post Field Operation Picture of Hydrodynamic Bearing (right) and Runner (left)



Figure 12. Close-up of Ceramic Components Showing Insignificant Wear