High Speed, Low Weight Momentum/reaction Wheels

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Abstract

Advancements in several critical areas have made possible lightweight, strong and highly reliable momentum / reaction wheels. The development of reliable bearings with design features that allow high speed operation for space flight applications has significantly altered the weight / speed / wheel design considerations. Current designs typically operate at speeds at or below 6,000 RPM. The new retainerless can achieve speeds 10 times that and meet or improve all other significant bearing operating parameters. These bearings offer a design life of 20 years or greater and are free of retainer caused anomalies. The development and test of these bearings has been ongoing for several years and have only recently become commercially available.

Composite rotors for these wheels are required since they operate at speeds greater than the fatigue limit of metal rotors. Speeds of 100,000RPM are attainable. Composite rotors have several advantages compared to metal rotors including
Strength, thermal resistance and a zero fatigue rate.
These rotors are made from space qualified resins and fibers with a space history.

By combining retainerless bearings with composite rotors tremendous advantages in mass, size, power and reliability make possible for a new generation of space instruments which will help push forward the race for miniturization.

INTRODUCTION:

We will discuss several breakthrough technologies which should prove critical to the future miniaturization and exploration of space.

First we will discuss bearing failure modes and how current bearing designs place limits on reliability and size. We will then discuss retainerless full complement bearings and how they offer particular advantages to the satellite community.

To take advantage of the higher speeds and capabilities of these retainerless bearings we will discuss composite rotors. Finally we will put the composite rotor together with a high speed retainerless bearing and show how these technologies will impact miniaturization, reliability, weight and size of future satellites.

RETAINERLESS BEARINGS TECHNOLOGY AND ADVANTAGES OF FULL BALL & FULL ROLLER COMPLEMENTS FOR SPACE

During a span covering 20+ years, more than 150 wheels have accumulated more than 15 years each in space with no anomaly.

In order to accomplish this an extensive bearing screening program was required. This screening was long, tedious and very expensive. It is impractical for today's market. Roughly 50% of all bearings flunked these screening test and were discarded.

The discarded bearings were identical to the acceptable bearings in every measurable way. They just did not run well.

Over time a quantitative, predictable, repeatable and successful theory of instrument bearing failure was developed. When this theory is applied to retainerless bearings a definite life with guaranteed stability results.

Retainerless bearings based on this theory have run for years (with periodic tear down inspection) without any failure or internal damage. In addition these bearings need not be screened. They are all good.

It is these retainerless full complement bearings that we believe offer unique advantages to the Small, Micro and Nano satellite community.

What are the major failure modes of instrument bearings?

Instrument bearings do not fail by fatigue. The contact stress is too low.

Instrument bearing failure is caused by:

Retainer Instability

Lubricant Breakdown

Retainer instability accounts for failure or serious “anomalies” in approximately 40% of all bearings manufactured. This major failure mode is absent in retainerless bearings.

In about 10% of manufactured instrument bearings the failure mode results from lubricant breakdown. What is the mechanism of this failure mode?

Suppose that 2 identical instrument bearings are manufactured at exactly the same time with identical conditions. By every measurable, analytical technique they are identical. The first bearing passes extended run test. But the second bearing fails in a few hours when its lubricant turns to sludge. What happened?

It failed because its Parched ElastoHydrodynamic Lubricating film (PEHL) has become too thin.

Polymerization reactions in the lubricant are activated by mechanical shear energy. This reaction rate is exponential with decreasing film thickness.

Lubricant film thickness cannot be set or controlled in a conventional retainered bearing.

Film thickness can be analyzed and controlled in a retainerless bearing using PEHL considerations.

Calculate the lubricant crossflow rate, load, speed and film thickness.

Determine a lubricant thickness sufficient for negligible friction polymer formation.

Supply fresh oil from a reservoir to the bearing track at the same rate that oil flows out.

The bearing lubrication cartridge designed to perform this works with a duplexed full ball complement angular contact ball bearings.

This bearing is oiled by One shot, oozing flow-lubricator.

Advantages of Full Ball complement/Oozing flow lubricator cartridge bearings.

Operates in a vacuum

Offers a definite design life

Lube demand is calculable

Friction polymer formation eliminated

Churning losses eliminated

No oil jags

Lubricant supply rate can be tested prior to bearing assembly

Can be smaller than conventional bearings

High speed capacity

High external load capacity

No degradation during shelf storage

Hollow roller bearings use solid lubrication which eliminates the weight, cost and testing of lubricant systems. These lubricating systems provide increased longevity, reliability and performance.

Hollow roller bearings

advantages for space instruments

Hollow roller bearings use hollow cylindrical rollers in place of solid balls or rollers. These hollow rollers are always preloaded.

Preloading the hollow rollers results in several advantages when compared to typical ball or roller bearings. Some of these advantages are:

High speed operation at great reliability and life

High degree of radial stiffness

Extremely low radial runout

Significant vibration dampening

All of these qualities are enhanced in hollow roller bearings because the preloaded rollers are positively driven at all times by the rotating inner ring and cannot skid or twist.

Hollow roller bearings have existed for 20 years in various spindle applications where speed and a high degree of accuracy are required.

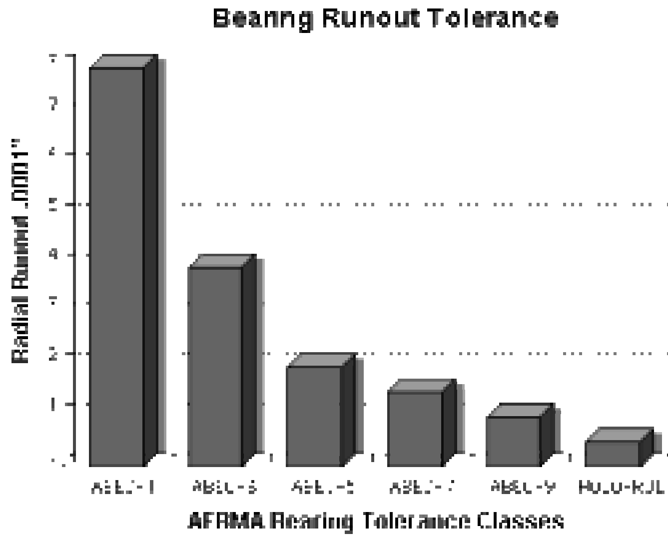
Bending stress in the hollow rollers is the primary factor in determining bearing life. Tensile stress is compared to stress limit data accumulated over decades of research and testing. With this data optimum bearing life for any speed and load is calculated very accurately.

The life of regular bearings is often limited by contact spalling. Not hollow roller bearings.
Contact stresses are low and brinelling is unlikely to occur because the flexible hollow rollers absorb shock loads such as occurs during launch.

Radial runout is a critically important measure of bearing accuracy. The variation in radial distance from the bearing bore surface to the bearing outside diameter, as the bearing rotates, is a measure of radial runout.

Accuracy measurement is used to select bearings for quality. Precision bearings are classed according to their radial runout as shown in the following chart. Bearing accuracy varies from a radial runout of .0008" (class ABEC-1) to .0001" (class ABEC-9).

Hollow roller bearings have a radial runout of only .00005". This is half the runout of a class ABEC-9 bearing.



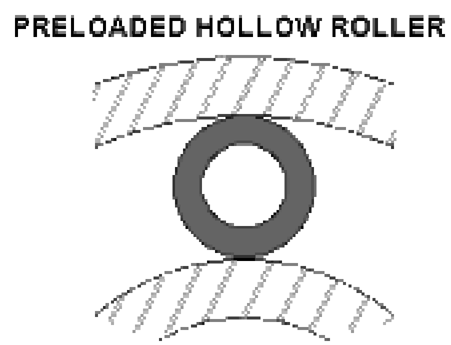
Three factors explain the high degree of accuracy obtained with hollow roller bearings.

1. Preloaded hollow rollers eliminate all internal radial clearance in the bearing.

2. Hollow rollers absorb minute variations in the ring surfaces and maintain a constant rotating center.

3. Hollow rollers are compressed to the same radial height and rotate as if they were all exactly the same diameter.

All rollers are selected to a diameter tolerance of .00005" or better. Total bearing runout is composed of two parts; repeatable runout and non-repeatable runout. The repeatable runout is the difference between high and low readings for one revolution of the bearing. This is often the result of concentricity error of the inner ring.



Hysteresis in Bending Causes Hollow Rollers to Damp Radial Vibrations

Non-repeatable runout is the difference between high and low readings as measured for one revolution of the complement of rollers or balls. Several shaft revolutions may be required to obtain the maximum difference. Hollow roller bearings have extremely

small non-repeatable runout, usually less than .00002”. The accuracy of hollow roller bearings is maintained throughout their life. Perfect for space instruments.
Hollow roller bearings automatically dampen vibration because the preloaded hollow rollers control the position of the shaft.

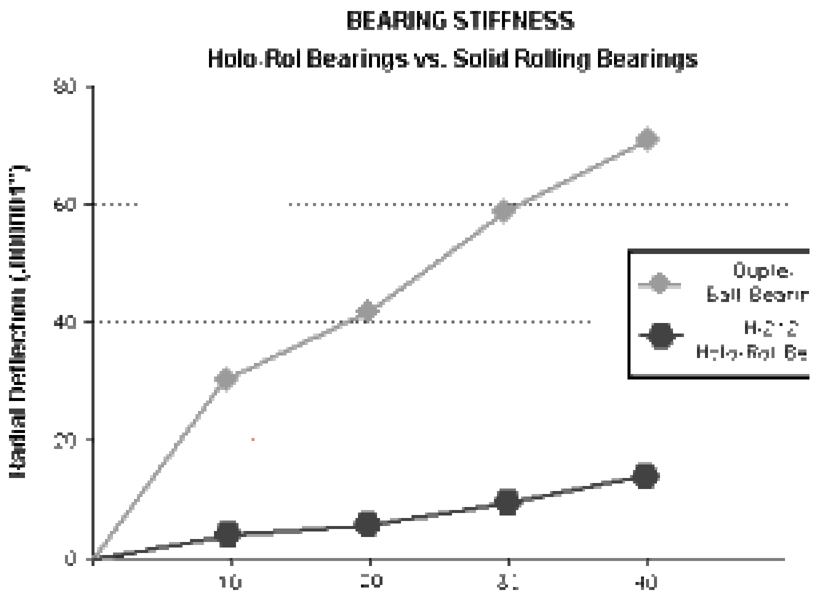
Preloaded hollow rollers are essentially stiff springs. Resistance to bending makes them act as shock absorbers, dampening radial movement of the spindles.

Hysterisis in bending causes the rollers to resist rapid changes in shape, and produces a strong centering force on the spindle. This centering action also counteracts centrifugal 9unbalanced) forces that cause vibration.

Vibration in hollow roller bearings is greatly reduced when compared to ball bearings.
Deflection Resistance is a measure of a bearings radial stiffness. Increasing radial stiffness produces greater accuracy.

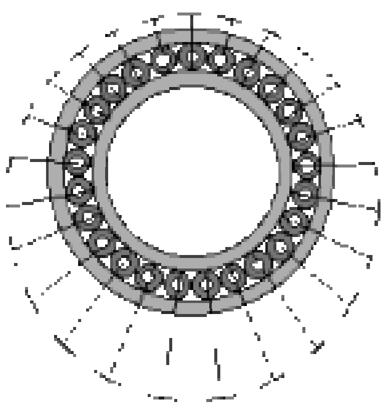
Hollow roller bearings have several times greater radial stiffness than regular bearings. This is achieved by radially preloading the hollow rollers.

Two effects produce this high degree of stiffness. First, all rollers are in tight contact with the bearing rings and all work together to carry the load.

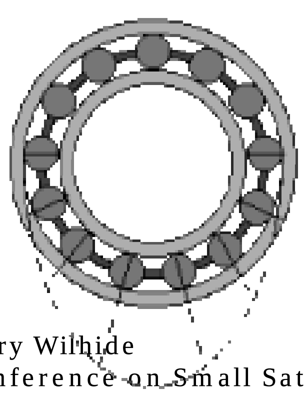


secondly, roller contact deflection against the rings is taken up before a load is applied to the bearing.

The following graphic shows the difference in load carrying patterns between hollow roller bearings and regular ball bearings.



Roller Loads in Preloaded Hollow Roller Bearings



Regular ball bearings must have some internal clearance for lubrication, with the result that less than half the rollers carry the radial load.

Angular contact ball bearings can be preloaded, but the ball contact area is small and allows for further radial deflection. In fact, the rapid ball deflection causes vibrations.

The final technology we will discuss is composite rotors for reaction or momentum wheels.

Composites are 10 x stronger than metal rotors. The expansion due to thermal variance is zero. Composite rotors do not fatigue.

In addition to these advantages composite rotors in quantity are far less expensive to manufacture compared to metal rotors.

In looking for composite components for space applications these are the criteria which we feel to be most important.

First the fiber and resin system must have a space heritage. Particular classes of materials may have one that is acceptable for space whereas the remainder in that category will all fail to some unacceptable degree. Previous knowledge and experience is critical in selecting the proper composite system.

When the proper composite wheel is designed and fabricated it has the ability to safely operate at speeds of 75,000 rpm or greater. When this high speed composite rotor is combined with a high speed bearing significant reductions in mass and size occur.

For example take a rotor operating at 4,000 rpm producing 8N-m-s. A composite rotor and retainerless full complement bearing running at 10,000 rpm producing 8 N-m-s could weigh 40% less and have a size reduction of 33%.

This is just a brief review of some technologies which we believe will form the foundation of reliable lightweight, low cost and low power space instruments now and for the future.

Now let us take a look at the benefits resulting from the use of instruments designed with these concepts.

	Regular Bearing Metal Rotor	High Speed Retainerless, Composite Rotor
Housing	Partial Pressure with seal	Not Required
Lubricant	Oil	Solid lubricant
Rotor speed Maximum	9,000 rpm	100,000 rpm
Vibration Dampening	No	Yes
Spin during Launch	required	Not required
Retainer Jittering	Present	Absent
Radiation Tolerance	Low to Mod.	High
Bearing Life	5 to 7 years	>20 years

It is clear that the technology now exist for a new generation of momentum/reaction wheels which will help to reduce size, weight and power consumption. By utilizing this technology further improvements to small, nano and microsats will occur.