TOUCHDOWN/LAUNCH-LOCK MECHANISM FOR MAGNETICALLY SUSPENDED CONTROL MOMENT GYROSCOPE

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ABSTRACT

In the event of power failure in a magnetically suspended Control Moment Gyroscope (CMG), a mechanical touchdown bearing is required to prevent contact between the rotor and various magnetic actuators. Additionally, a launch-lock system must be provided to suspend the rotor during launch, when power is not applied to the CMG. Honeywell Inc. has incorporated both of these functions into one system.

This paper describes the patented system, including pertinent design details, and summarizes bench- and brass-board CMG testing results. Described in design information is an essential aspect of the bearing design, a conical clutch that acts as both contact interface and launch-lock mechanism. Test results summarize materials used for critical interface between the touchdown system and rotor, as well as results of durability tests (1000 touchdowns at various loads) in a bench test rig, and planned and unplanned touchdowns in the CMG test bed.

Predominant lessons learned include the discovery of:

- At least one successful material combination for high-speed, high-load contact
- The affect of lubrication on contact interfaces
- How grease lubricated bearings work at very high acceleration rates to speeds up to 1.1×10^6 DN
- Unexpected reasons for over designing bearing load capacities, for this type of application

INTRODUCTION

In the quest for achieving minimum emitted disturbances and maximum life from a CMG, Honeywell is developing a large, magnetically suspended device capable of a torque output of 43.8 N-m (3100 ft-lbf). No one has built such a large, magnetically suspended CMG, although the Soviets have flown a low-output, 2.1 N-m (150 ft-lbf) CMG on the Mir Space Station.

Any magnetically suspended device requires a backup system in case of primary suspension failure; generally, this takes the form of mechanical bearings. The touchdown system prevents damage to magnetic actuators and other components in the event of power loss or other magnetic suspension failures. The most common touchdown system consists of a mechanical bearing, through which a shaft feature extends from the rotor. Adequate clearance is provided between the shaft and bearing Inside Diameter (ID) to allow the magnetic suspension to function normally. Should a magnetic suspension failure occur, the shaft will contact the bearing ID before contacting the actuators. An axial-thrust bearing is added to this radial bearing to prevent excess axial excursions. The mechanical bearings that contain shaft excursions are most commonly ball bearings, although roller or sleeve bearings may also be used.

While most mechanically suspended momentum devices take launch vibration loads through bearings making a separate launch-lock system unnecessary, a unique problem posed by a magnetically suspended CMG occurs during launch when suspension is not powered up and normal operating clearances provide an unacceptable opportunity for the rotor to rattle around. Left unchecked, this leads to high-impact loads and damage during launch vibration. Additionally, if magnetic suspension fails during operation, the rotor would continue to rattle around for the remainder of the mission, causing significant shock and vibration whenever the vehicle moved. Therefore, a magnetically suspended CMG requires a locking system to support the rotor during launch.

Launch-lock systems are commonly used on many types of space hardware, usually taking the form of a device that clamps hardware to a structural member by means of an actuator. Common actuators include pyrotechnics, paraffins, solenoids, and motors. A magnetically suspended CMG's rotor is quite massive (86 kg, 190 lbm), and common launch-lock techniques would be heavy and complex.

DESIGN

The design objective was to combine functions of touchdown bearings and the launch-lock device into one system, reducing weight and complexity. The solution, illustrated in Figure 1, was designing a female conical feature at each end of the rotor that mates with male conical housings supported by duplexed pairs of angular contact ball bearings. In normal operation, the rotor is suspended by magnetic actuators (not illustrated in Figure 1). A sufficient gap is available between female cones of the rotor and male cones of the touchdown system to allow the rotor to move within operational range of the magnetic suspension system. Should magnetic suspension fail, or loads are applied to it that are beyond capacity, the rotor will traverse the gap and the cones will touch. When this occurs, the male cone suspended by ball bearings is accelerated to rotor speed.

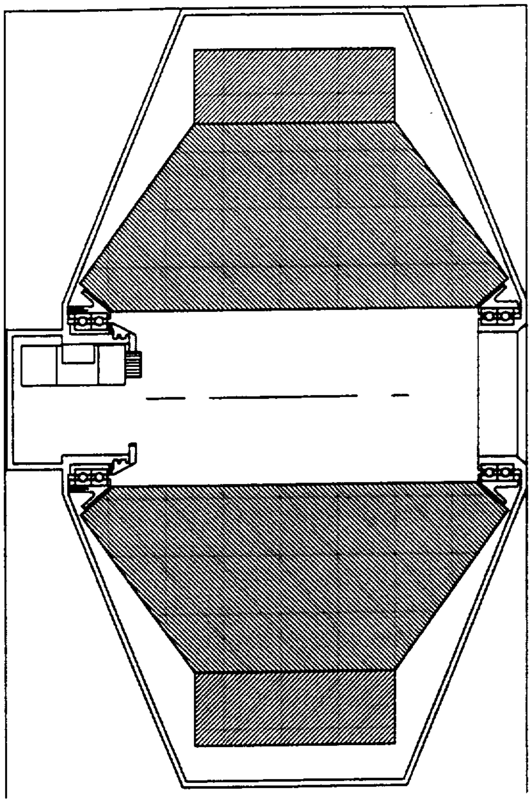

Figure 1. Touchdown/Launch-lock System

Acceleration rate is dependent on the bearing's drag torque, mass inertia of the male cone-bearing assembly, friction coefficient between the two cones, and contact force. Between the time that initial contact is made, and the time that the male cone assembly matches rotor speed, sliding occurs between the two cones. Because of sliding, it is important to select wear-resistant surfaces for both cones. There are two particularly significant effects of this wear. First, static or dynamic rotor balance may be affected by removing material from, or adding material to, the female cone that is part of the rotor. Second, excess wear will produce debris that must be contained.

This system serves as a touchdown system and a method of supporting the rotor during launch including occurrences when magnetic suspension is inoperative. In Figure 1, the fixed bearing-cone assembly is solidly mounted to the structural housing. A floating bearing-cone assembly is mounted to a shaft-like feature of the structural housing. This allows the floating bearing-cone assembly to be translated axially until the rotor is captured between fixed and floating bearing-cone assemblies.

While axial actuation may be accomplished by a number of methods, the method illustrated in Figure 1 uses a motor-driven, threaded actuator. In this implementation, a gear motor turns the floating bearing-cone assembly through a planetary gear. The inboard end of the floating bearing-cone assembly interfaces with the structural housing through an ACME thread. As the motor turns the planetary gear, the floating bearing-cone assembly moves axially by means of the ACME thread.

Once the launch-lock feature is engaged, the rotor is free to turn about its rotational axis on touchdown bearings. Touchdown bearings have an adequate load capacity to withstand launch vibration in all three axes and the impact loads that might be encountered if magnetic suspension fails when the CMG is gimbaled.

CONICAL CLUTCH DESIGN

Material selection was the most difficult part of conical clutch design. Design criteria dictated that the clutch had to endure 1000 touchdowns with a minimum of debris generation and weight change on the rotor (female) side. Soft materials (e.g., brake and clutch friction materials) were considered and abandoned because of the quantity of debris generated. Facing unlimited choices of hard materials and coatings, yet limited time and budget, candidates were narrowed to five.

In early design stages, it appeared that the selection of female cone material was going to be limited by rotor design considerations; therefore, Maraging 250 became the first test material. Maraging 250 is very soft (Rc50), so a hard coating over the Maraging was chosen as the second candidate. Titanium Nitride (TiN) coating was selected because of the considerable experience base available using this material. A hard bearing material, 440C, was selected as one of the mating candidates. The 440C material was chosen over other bearing materials because of its relatively high corrosion resistance, and the community experience in applying surface treatments to it. The fourth candidate was 440C, plated with chromium, followed by nitrogen ion implantation. While there are many implantation candidates, this choice was primarily dictated by budgetary considerations. The final choice was Nitronic 60, an austenitic stainless steel that was developed for wear resistance.

The only reasonable way to choose among candidates was to perform a comparative test series. These tests, called the contact interface tests, are described later in this paper.

In terms of the physical geometry of the conical clutch, the angle of conical surfaces was most critical. Selection of this angle was based on clearance requirements for axial and radial actuators. In this case, radial actuators are most significant for CMG performance, and axial actuator gap may be varied with less impact to the system, allowing there was a range of acceptable angles. Within this range, the following two considerations dominated the decision:

1. The amount of force required to disengage the launch-lock system is a function of the friction coefficient between the cones and cone angle. If the cone angle is less than 45deg, then it is possible that axial force will be required to disengage the cones unless the friction coefficient is low enough to do so. If the friction coefficient is less than the value of the tangent of half the cone angle, then the disengagement force will be zero. In terms of disengagement, the larger the cone angle, the better.

2. The force required to engage the launch-lock system when the shaft is horizontal in a 1g field is a function of rotor weight, cone angle, and friction coefficient. The lower the cone angle for a given rotor weight and friction coefficient, the better.

BEARING DESIGN

Selection of bearing size was driven by accommodation requirements for magnetic suspension system components. These components dictated relatively large, thin-section bearings. It was, therefore, easy to provide plenty of load capacity margin from the start. This allowed flexibility to incorporate certain design features that would help in other areas. Silicone Nitride (Si_3N_4) balls were selected because of low mass, as compared to steel. This minimized ball group inertia and, subsequently, the amount of skidding during rapid acceleration. Additional advantages of using Si_3N_4 balls include a substantial reduction in bearing component wear by the elimination of adhesive wear between ball and raceway, and the reduction of outer ring loading, as the greatly reduced ball mass minimizes ball centripetal force.

M50 tool steel was chosen for the rings due to a superior resistance to sliding wear (compared with 52100) and common availability. Since this project was completed, substantial development work has been done with Vim CRU 20 tool steel for bearings of this type, ref. 1. This material is much harder than M50 (Rc 66 compared to Rc 60), has a higher modulus (34 E6 psi compared to 30 E6 psi), substantially lower wear rates, and at least five-times fatigue life.

An inertially biased phenolic cage was designed to provide optimum stability throughout speed range, with minimum mass inertia. Curvature ratios were kept relatively tight to maintain low stress levels, even under maximum loads, and to consider differences in moduli between the steel ring and ceramic balls. Rheolube 2000 grease was selected for the lubricant because of low vapor pressure and drag torque. Minimum grease quantity was required because bearings are only used intermittently and minimizing the viscous drag component at these very high DN numbers is desirable. The low vapor pressure of Rheolube 2000 allows low lubricant quantities without concern for excessive lubricant loss.

Because of concerns over ball skidding under very rapid accelerations, a series of bearing acceleration tests were planned. Later, these tests were combined with contact interface tests by installing a sensitive speed-measuring system that measured the rate of acceleration during contact tests. This system, along with test results, is described in the Contact Interface/Bearing Acceleration Testing section of this paper.

LAUNCH-LOCK ENGAGEMENT SYSTEM DESIGN

The launch-lock engagement system consists of a multi-pass gear drive motor that drives a pinion to engage an internal gear. The principle parameters that trade off in this system design are weight, power, engagement time, and size. Of these, size and weight are dominant. Power is not critical because the drive motor uses only a small fraction of the CMG allotment. Engagement time is not critical because the touchdown system is designed to work with the launch lock completely disengaged. The launch-lock system is functionally independent of the touchdown system and, thus, devoid of time constraints.

The motor was sized on the basis of output torque required to translate the floating system axially in a 1g field with the rotor in any orientation. The rotor weight resists this translation by acting through gear friction, ACME thread, cartridge/shaft interface, and conical clutch interface. The current motor provides adequate power to engage the launch-lock system in approximately 15 seconds.

CONTACT INTERFACE / BEARING ACCELERATION TESTING

As the design of the magnetic CMG touchdown system evolved, two areas of concern emerged. The first was the contact interface between the female conical feature on the rotor and the male conical housing of the touchdown bearings. With the wheel spinning at 6000 rpm and gimbaling as rapidly as 2.25 radians-per-second (assuming a control system failure), the touchdown is violent with great potential for cone damage or wear. The second concern was the bearings' acceleration rate. Calculation at touchdown proved that the bearing may be called upon to accelerate from 0 to 6000 rpm in as little time as 40 ms, depending on the friction coefficient at conical interface. Although the bearing was designed with light-weight Si_3N_4 balls and a phenolic cage to minimize ball set inertia, including preload selected to impede ball skidding, a test was still needed. A fixture was designed that would spin a female cone while forcing a male cone, supported by touchdown bearings, against it. A series of tests were conducted using various materials and loads at 6000 rpm. Later in the program, consideration was given to increasing rotor speed to 9000 rpm, and additional tests were conducted at that speed with a commensurate increase in applied loads.

TEST SETUP

The test fixture, depicted in Figure 2, consists of a 1/2 hp synchronous motor that turns a shaft at either 6000 or 9000 rpm, depending on the toothed belt's pulley ratio. The shaft is mounted on a set of angular contact ball bearings: a single 206-size bearing at belt end and a 209-size bearing at test cone end. The female test cone is bolted to the shaft flange. A massive shaft, supporting the touchdown bearings and male cone, is mounted on a pivot so that when it is pulled down by the hydraulic ram, it will contact the female cone with both conical surfaces parallel.

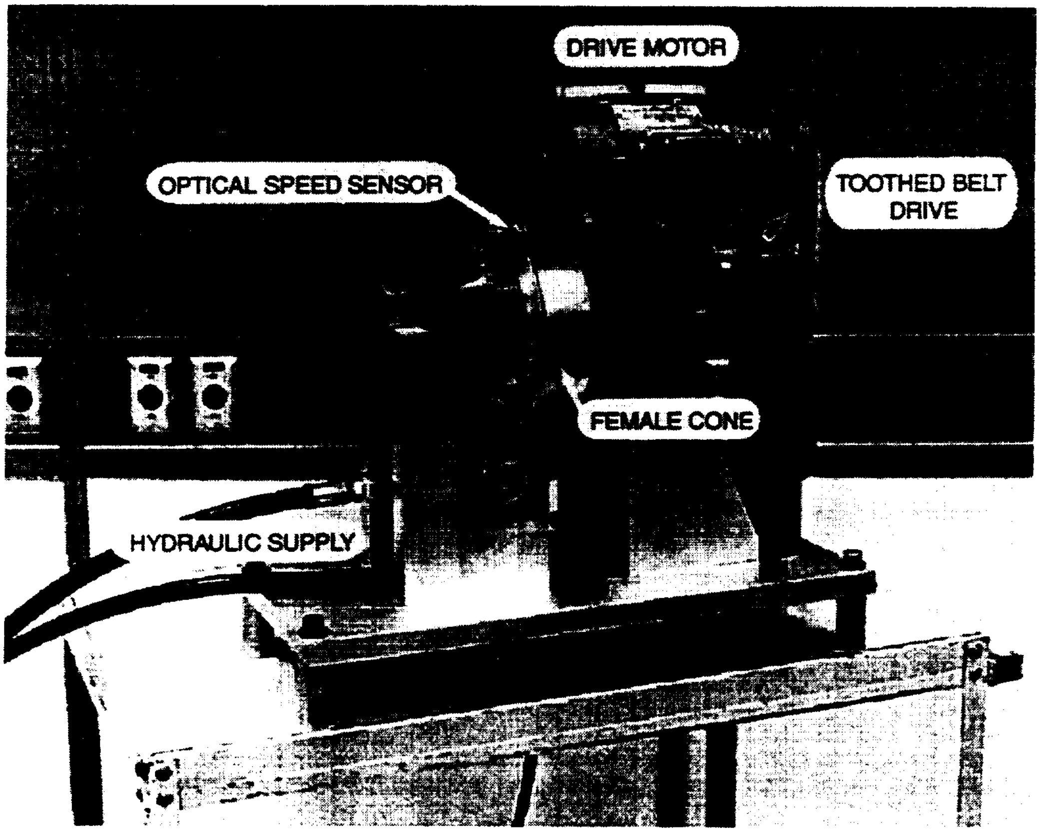

Figure 2. Touchdown Test Setup

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Contact force is adjustable by varying hydraulic pressure to the ram. A light-emitting diode and photo-diode, straddling an aluminum disk containing 360 equally spaced holes, measures rotational speed of the male cone by marking time on a running clock each instance the light of a passing hole strikes the photo-diode. Acceleration rate is obtainable from the speed-versus-time plot.

TEST PROCEDURE

Prior to any touchdown, a profilometer was used to record axial surface geometry, and three, equally spaced Tallyronds™ were taken to define the roundness of each part.

In early tests, the fixture was configured as previously described with 6000 rpm pulleys in place. With cones of the desired material installed, hydraulic pressure was adjusted and the female cone brought up to speed. Once shaft speed stabilized and the speed-measuring computer program was zeroed, the solenoid valve was actuated to command the hydraulic ram to pull the male cone down into contact with the female cone. Tests were performed at various loads, from 150 to over 2000 lbf, to simulate touchdowns under different gimbaling conditions. When speed again stabilized, the motor was turned off and the rotating assembly was allowed to decelerate and stop. The hydraulic ram was then reversed to disengage the male cone. The male cone/touchdown bearing/shaft assembly was removed from the fixture and conical surfaces examined. Profile and roundness measurements were repeated to determine the dimensions of observed surface features.

As the testing program progressed, more load cycles were applied to test specimens before examination. Eventually, hundreds of touchdowns were performed between inspections.

After down selecting the material combination, an additional test was run at 9000 rpm. Tests were run with applied radial loads of 150 and 3500 lbf.

TEST DESCRIPTION

Initial tests were run using high loads, due to concerns about bearing acceleration. Acceleration times were measured at roughly 140 ms with high loads; this was three times the minimum calculated time, and caused no observed damage to the bearing. The opposite end of the spectrum was then investigated with contact forces of 150 lbf. This was the most difficult load range from the standpoint of damage to conical surfaces because of the duration of sliding at the interface. Acceleration times at 150 lbf were on the order of 500 ms.

Different material combinations were tried, as summarized in Table I, in an effort to find the combination that showed least wear. When combinations were found to show promise, multiple load cycles were performed between inspections. It was during this extended testing that some of the bearings' grease was expelled and migrated, by centrifugal force, onto the cone surface. It was discovered, when the test was stopped for a routine inspection after ten touchdowns, that the lubricated zone covered about one-third of the cone area. The inspection revealed almost no wear in the lubricated region and substantial wear over the remainder of the cone.

Tests that followed used only Pennzane 2000 oil, and Rheolube 2000 and Apiezon T grease. The application of lubricants increased run-up times considerably, affecting wear rates by various amounts (refer to Table I).

After the final candidate was selected, a separate set of tests was run at 9000 rpm to prove that the entire system would operate satisfactorily at that speed as well. A thousand touchdowns were performed at each of the radial loads tested (150 and 3500 lbf).

TEST RESULTS

Table I is a summary of the 6000 rpm test results. Table II is a summary of the 9000 rpm test results.

Table I. 6000 rpm Contact Interface/Bearing Acceleration Test Results

Test Number	Female	Male	Lube?	Results
1	Maraging	440C	No	Narrow contact zone – fixture alignment significant wear
2	TiN Maraging	440C	No	Significant wear – TiN removed
3	Nitronic 60	440C	No	Marks at two contact points
4	Nitronic 60	440Cc	Pennzane 2000	Wear similar to Test 3
5	Nitronic 60	CY-N 440C	No	Removed CY-N
6	Nitronic 60	Nitronic 60	Pennzane 2000	Separate wear bands
7	Nitronic 60	440c TCP	No	Lower wear – gummy debris
8	440C	TiN 440C	Rheolube 2000	All TiN removed by 1000 cycles 0.002 maximum wear - 0.001 maximum buildup at 1000 touchdowns
9	Nitronic 60	440C	Rheolube 2000	Low wear with grease (first 50 touchdowns) 0.0035 maximum wear - 0.0032 maximum buildup at 1000 touchdowns bearings – like new
10	TiN 440C	440C	Apiezon T	More wear and sparks

Table II. 9000 rpm Contact Interface/Bearing Acceleration Test Results

Test Number	Female	Male	Lube	Results
11	Nitronic 60	440C	Rheolube 2000	Low wear (0.0016 maximum wear after 1000 150 lbf touchdowns, 0.0163 maximum wear after an additional 1000 touchdowns at 3500 lbf)

TEST CONCLUSIONS

After examining the test results, the following predominant conclusions emerged,:

- The design was found adequate to support over 1000 touchdowns with at least two different material combinations. Bare 440C against TiN-coated 440C and bare 440C against Nitronic 60 tests endured 1000 touchdowns.

- Proper lubrication with grease also helped. At least 50 touchdowns were applied to grease-lubricated cones without observable wear. This was true for both material combinations that endured 1000 touchdowns.
- The test that ran 440C against TiN-coated 440C exhibited less total wear than the 440C against Nitronic 60 test.
- The test that ran Nitronic 60 against 440C had more wear but less debris than the 440C tested against TiN-coated 440C. This is due to material transferring from the Nitronic 60 and building up on the 440C. The transfer appeared to be uniform around the cone's circumference and should, therefore, have minimal effect on rotor balance.

By using a low-friction contact interface, a reduction in bearing-rate acceleration occurred. This effectively transfers the challenge of bringing the touchdown system up to speed from the bearing design to the clutch design. Additionally, skidding between the two conical surfaces continues for a longer time. This has the benefit of distributing wear more evenly around the circumference of contacting surfaces.

The system using a Nitronic 60 female cone against a 440C mail cone with a Rheolube 2000 grease film on each performed equally well at 9000 rpm.

CMG TEST BED RESULTS

Having made the final material selection based on contact interface testing, the system was designed into a CMG test bed. This unit evaluated all mechanical and electrical components, as well as control laws and overall system operation. As one might expect on such a complex system, everything did not work correctly the first time. Principle complexities existed in the control system, and every time the control system failed to control the suspended rotor, the touchdown system was tested. During the next year of testing, the CMG touchdown system was tested well over 1000 times. It was estimated that, when fully developed, a flight CMG would experience on the order of 10 touchdowns in a lifetime

Three significant touchdown system issues arose during this testing period. The first was the loss of an engagement motor, which was caused by operation at its rated load for too long a period. The motor selected was not rated for continuous operation or vacuum operation. The combination of high duty cycle and vacuum operation burned up a set of brushes.The solution was simple, a space-rated motor is available in the same chassis size.

The second problem appeared more significant. A thin, plastic film was applied to inner surfaces of magnetic actuators and, during a period of significant touchdown activity, plastic was transferred to the rotor, suggesting that the touchdown system failed to prevent contact with actuators. The ensuing investigation revealed that a control system instability had caused actuators to be energized in phase with rotor oscillations, causing touchdown loads that were twice the maximum design loads. Structural deflections caused by these loads were adequate to allow contact between rotor and actuators. No damage was done to the structure or touchdown system, partially due to a substantial bearing-load-capacity margin. Improvements in the control system prevented sympathetic actuator energizing, eliminating the possibility of overloading the touchdown system.

The third problem dealt with engagement and disengagement of the launch-lock system. The engagement motor provided substantial torque by using a high-ratio, gear box. This torque was necessary in order to engage the system in a gravity field, should the movable cone be located directly below the rotor. In the original design, however, no rotational stop existed, and the cone continued to move until the drive motor stalled. At this point, the cone driven into the rotor generated axial thrust that produced compressive strain in the rotor and engagement drive system, and tensile strain in the support structure. When a disengagement command was then given to the motor, it had to overcome increased friction in the ACME thread caused by engagement strain, proving too much for the drive motor. The solution was to install a limit stop to allow the driven cone to just engage the rotor, and hit the limit before being driven hard against the rotor cone.

SUMMARY

A unique system was designed to combine touchdown and launch-lock functions for a magnetically suspended CMG. The principle challenge encountered in this design implementation was selecting material for the conical clutch surfaces. Testing several material combinations produced an acceptable candidate, and proved that bearings can withstand required acceleration rates. This touchdown/launch-lock system has been included in a magnetically suspended CMG design, and a prototype successfully tested under actual operating conditions.

OBSERVATIONS AND RECOMMENDATIONS

While this system was developed for a CMG application that has unique requirements, it would be useful in other applications.

From the vantage of a touchdown function, the philosophy of separating contact surface function from bearing function is a key to success. Controlling contact interface [i.e., area (pressure), geometry, materials, and lubrication] separately from bearing design allows more optimum solutions to both.

While the material combination selected for contact interface surfaces worked satisfactorily for this application, the possibility remains that other material combinations may prove more successful. While examining a new application, consideration should be given to newer materials, for example, REX20 (CRU20), that have greater wear resistance.

Coatings on contact interfaces should be avoided. Contact interface is a violent environment, and coatings only complicate tribology and add new failure mechanisms and costs.

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