NEW CONCEPTS AND PERFORMANCES IN AZIMUTH CONTROL OF LARGE BALLOON GONDOLAS

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ABSTRACT

This paper describes a new type of azimuth bearing to be used for orientation and stabilization of balloon gondolas. This device has been developed for the rather heavy (2.5 tons) French PRONAOS experiment but it can be used for any experiment which needs performant azimuth control. Instead of using a classical activated ball thrust bearing, this new bearing is torque-controlled. Besides providing weight economy and mechanical simplification over classical systems, it overwhelms some of their intrinsic defaults that is : high variation of azimuth-loop gain versus temperature, low maximum torque and above all, high electrical consumption.

After a technical description, test results obtained on a model at the Geneva Observatory show that the prototype works down to -60 ^{0}C with no significant loss in performances thus achieving a 95% linearity over the $\pm$ 4.5 [Nm] domain, a 0.02 [Nm] sensitivity while consuming 17 [W] that is to say a $\frac{1}{10}$ th of what was previously needed by activated bearings !

Keywords: Torque controlled bearing, torque-meter, coarse azimuth control.

1. PRONAOS' STABILISATION CONCEPT

1.1 Goal

The goal of PRONAOS' stabilization is to maintain the payload within 5 [arc sec] from the desired direction (Ref. 1). In our case the payload is a 2 [m] submilimetric telescope coupled either to a multi-band photometer or an heterodyne spectrometer and it weighs $\sim$ 400 [kg].

To meet the requirements of the stabilization specs, the gondola is 5 axis stabilized and 3 axis oriented that is:

- Roll (X), yaw (Y), azimuth (Z) elevation and cross-elevation stabilization.
- Azimuth, elevation and cross-elevation orientation.

1.2 Coarse stabilization

Azimuth, roll and yaw are controlled by a stabilization unit mounted on the basic structure of the gondola. This unit has wide requirements of 30 [arc sec] RMS (Ref. 2). As actuators it has reaction wheels, the azimuth bearing and oil dampers and for the measure it has a magnetometer and gyrometers.

1.3 Fine stabilization

Mounted on the stabilized basic structure is a second gimbal providing the two last degrees of freedom to the payload that is elevation and cross-elevation. This gimbal is controlled by torque motors helped by mobile counterweights for low frequency modes. Its position is measured by 3 rate inegrating gyros and a star-tracker is correcting the long term drift.

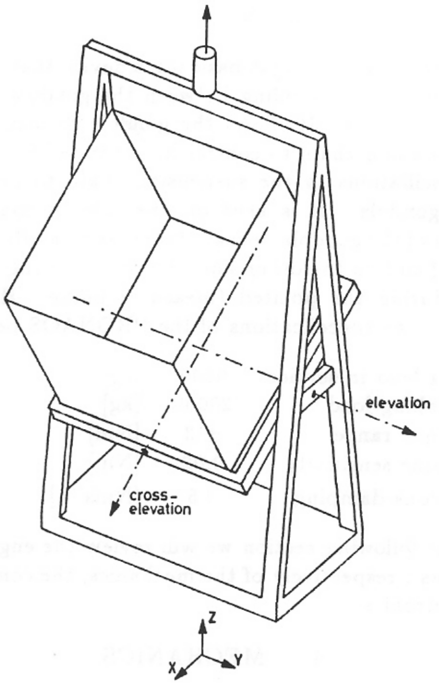

Figure 1. Axis definition of the stabilization system

2. COARSE AZIMUTH CONTROL

2.1 Azimuth stabilization

High frequency perturbations on the azimuth axis are due to payload motions on the cross-elevation axis. Indeed, as long as the telescope is neither inertially stabilised, nor pointed to zenith, there is a coupling between the cross- elevation and the azimuth axis. At float we have two types of these perturbations (Ref. 1):

- The centering of the guide star by the star traker (1 [Nm] during 1.4 [s])

- The offsetting of the telescope to 10' to measure the background noise (0.8 [Nm] during 2 $\times$ 3 [s])

Low frequency perturbations are due to the effect of a vertical wind gradient on the assymetrical shape of the gondola and to the rotation of the balloon. To counteract these two types of perturbation two actuators are tandem mounted on the azimuth axis : a reaction wheel and a motorized bearing. The wheel features high-pass

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correction (limited by speed saturation in the lower frequencies) and the bearing is a low cut-off device which covers the spectrum from 0 to a few tenths of Herz.

2.2 Azimuth orientation

To reach the first celestial target and during the transition from a target to the next, the gondola may have to be reoriented several tens of degrees. From the control point of view, that means sustaining the maximum torque during a minute or more. This is obviously impossible with the reaction wheel and has to be done by the bearing.

3. FUNCTIONAL SPECIFICATION OF THE AZ-BEARING

The azimuth-bearing is basically a device that achieves an unidirectional coupling between the gondola and the suspension chain. It allows the gondola to lean against the suspension chain to control its attitude but does not allow oscillations in the suspension chain to propagate to the gondola. It is used on one side to control the azimuth of the gondola in case of large scale shifts (several degrees) and on the other side to desaturate the reaction wheel during the pointed (measure) phase. Here is a subset of the speccfications of the PRONAOS bearing :

Max load in service	6000	[kg]
Breaking load	20000	[kg]
Torque range	± 3	[Nm]
Torque sensitivity	0.02	[Nm]
Viscous damping	0.5	[Nms^{-1}]

In the following section we will review the engineering problems : respectively of the mechanics, the control and the electronics .

4. MECHANICS

4.1 Selecting a bearing type for a large gondola

Traditionaly in the last two decades, balloonists have been using activated bearing for azimuth control. This device works the following way : the gondola is connected to the suspension chain by a double thrust ball bearing. A motor drives the intermediate race regularly back and forth thus applying the static friction of the thrust ball bearing alternatively in one direction and in the opposite. By varying the time ratio between both direction, a non-zero mean torque can be applied to the gondola. Of course the maximum torque available is equal to the friction of the bearing.

For PRONAOS, this system was abandoned because of the following drawbacks :

- High power consumption (< 60 [W])
- Balls lubrication problems at low temperature and high rotating speed
- Microphonic noise of the gear
- Alternating torque
- High variation of loop gain versus temperature

The proposed solution to the azimuth orientation problem is to build a torque controlled bearing : A torque sensing element is mounted on the top beam of the gondola. A motor drives the relative position between the base of the suspension chain and the gondola so as to maintain the torque applied on the gondola equal to the command coming from the attitude regulator. In case of a zero command for example, the bearing would not allow any torque to be applied from the suspension chain to the gondola.

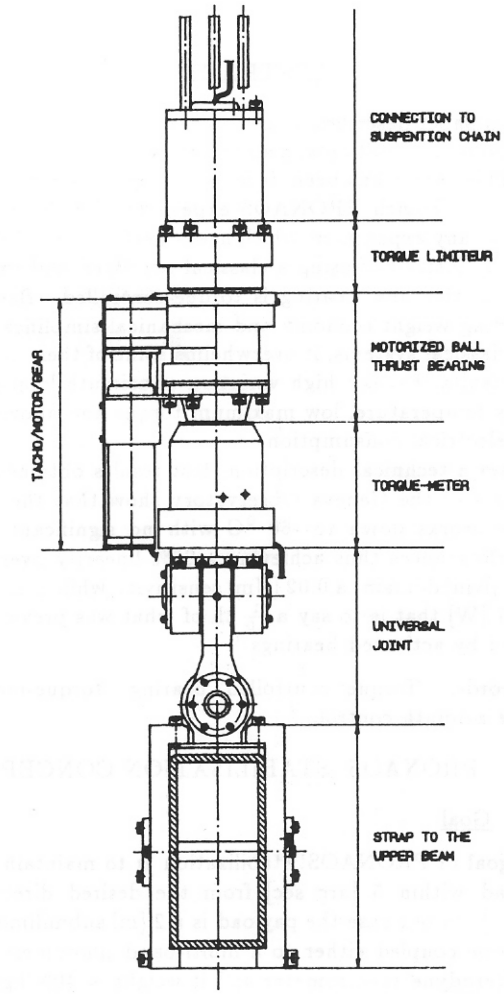

Figure 2. Side view of the azimuth bearing

Let's take a closer look at the new type of bearing (figure 2). From bottom to the top there are :

- A stirrup piece fastening the bearing itself to the top beam of the structure.
- An universal joint decoupling the two proper frequencies of the compound pendulum made by the gondola and the suspension chain.
- A torque-meter, which allows closed loop control of the torque applied to the gondola.
- A motor-reduction gear unit.
- A motorised ball thrust bearing connecting the rotating part to the part fastened to the gondola.
- A torque limiting element (Actually a low quality roll thrust bearing) necessary not to overtwist the suspension chain.

Each part of the bearing is made of high resistance steel (100 [kg/mm^2]) except the torque-meter which is made of very high resistance maragin alloy (200 [kg/mm^2]). All rotating parts were machined with special cares in order to minimize static friction and torque bias. All components were ultrasound and X-ray checked. In short we can say that this device responds to very high quality standards.

5. THE TORQUE METER

It is not staightforward to design a torque-meter that can sense less that 10^{-2} [Nm] on one hand and that resist a 20 tons load on the other hand. The cross-section being given by the breaking load, the shape of the piece had to be established. The final choice is a cylinder which surface is splitted in several segments parallel to the axis. For the same cross-section, the thinner the segments are, the more flexible is the torque-meter. Being limited by stiffness problems during the machining our torque meter has 11 segments for a diameter of 50 [mm] and a cross section of 198 [mm^2]. See figure 3.

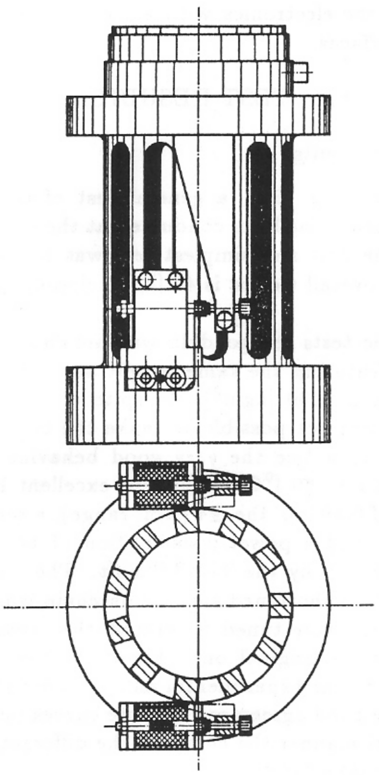

Figure 3. Top and side views of the torque-meter

The axial torsion of the torque meter is measured by 2 LVDT's of which coils are bound to its base and which cores transmit the motion of the top. In order to reject a possible bias due to transaxial flexion, we make a *differential* measure by mounting 2 LVDT's in opposition on both sides of the torque-meter. See bottom drawing of figure 3.

6. CONTROL

Before going any further, it has to be clear that - from a global point of view - the torque-controlled bearing is only an actuator. In addition, the whole azimuth loop involves a magnetometer, a gyrometer and a numeric regulator.

In order to be able to see in which way the torque control will affect the behaviour of the suspension chain, we have to have a model of this chain. From the operational configuration seen on figure 4 (left) we propose the model you can see on figure 4 (right) which takes only in account the torsion modes of the suspension chain.

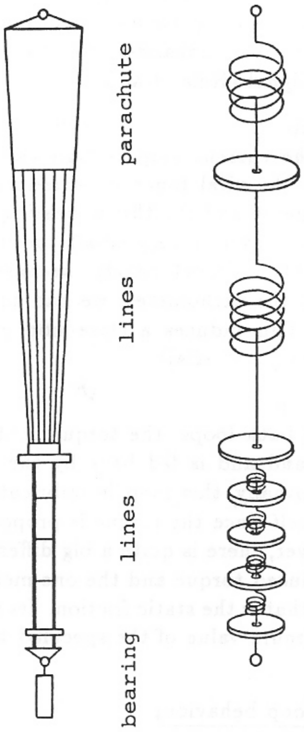

Figure 4. The suspention chain and its model

The bottom inertia is the sum of the inertia of the suspension-chain-to-bearing interface and the inertia of the DC motor ' multiplied by the square of the reduction ratio.

A computer program simulating the suspension chain calculated the position output to a torque impulse (Ref. 3). A Fourrier transform of this output gives an insight on the proprer frequencies of the chain. In our case there are two well-marked peaks on the transform, namely 0.42 and 1.9 [Hz]. For following analytical study of the control loops, we will admit a suspension chain damping of $\frac{1}{e}$ in 20 pseudoperiods.

6.1 Structure of the control loops

The control of the bearing involves three overlapping control loops : a current loop, a speed loop and a torque loop (see figure 5).

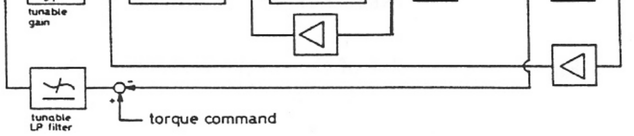

Figure 5. Diagram of the control loops

6.1.1 Current loop

As the bearing's high performance DC motor has a low rotor resistance, the drive needed some sort of current limitation anyway. Because of its good dynamic properties and the elimination of visc ous characteristic of voltage controlled supply, we use a current loop to drive the power amplifier. This linearizes the motor torque with the command signal (Refs. 4 & 5).

6.1.2 Speed loop

On top of the current loop, a high gain high cut-off speed loop has the vital function of reducing the static friction of the gears and the thrust bearing. Indeed, due to the high gain, even a very small speed command is followed correctly. Unfortunately, because of the very poor quality of the tachometer, we had to low-pass the speed signal. This induces a close-loop gain excess at high frequencies (> 50 [Hz]).

6.1.3 Torque loop

Overlapping both loops, the torque control generates a speed command and is fed back by the torque meter signal. Conceptually this loop is imbricated up to the current loop itself since the torque is proportional to the current. However, there is quite a big difference between the current induced torque and the one measured by the torque-meter, that is the static friction. Its value is about twice the maximum value of the specified torque range !

6.2 Closed loop behaviour

Figure 6 shows a theoretical Bode plot of the overall system including suspension chain whose proper frequencies can be recognised easily. It appears that this torque controlled bearing - though being the low frequency actuator of the azimuth control - has indeed a very large pass-band. Eliminating frequencies above 50 [Hz] where voltage saturation and backlash may play a role there is still enough bandwidth to compete with a reaction wheel at high frequencies. This is due to the fact that at high frequencies, the suspension chain has no time to twist and the bearing is leaning against the inertia of the motor to furnish the demanded torque.

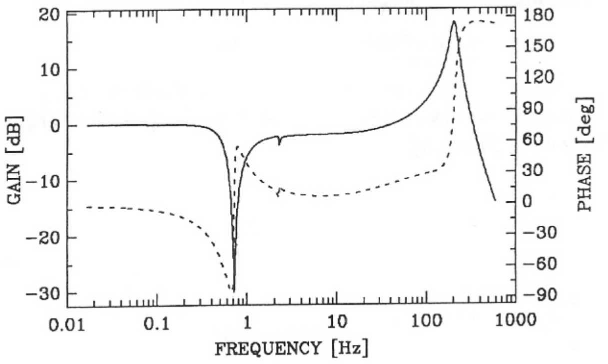

Figure 6. Bode plot of the torque response of the bearing

However, if this high frequency behaviour is not desired, it is possible to make the motor rotate in the opposite direction to the base of the suspension chain by adding one more gear to the reductor. Positive accelerating inertia and negative accelerating inertia would be balanced and so, the dynamics of the motor would not influence the overall behaviour of the bearing.

7. ELECTRONICS

The control unit of the bearing features mainly the different control loops, LVDT signal conditioning and temperature drift correction of the torque-meter. It also processes some telemetry signal as temperature, current, torque etc... It is realised in analog technology.

The telemetry-telecommand unit which links the bearing to the gondola's central managment unit is a standard unit aboard PRONAOS. It has digital-to-analog converters for the torque and offset commands and a bunch of analog-to-digital channels for telemetry purposes. A 115 [kbit/s] RS 422 interface links this unit to the main computer. This standard unit was chosen for maintenance reasons and because of its readiness. Unfortunately it is overdimensioned and dissipate as much energy as the whole rest of the bearing. Figure 7 shows a diagram of the electronics with all its mechanical and electrical interfaces.

8. TEST RESULTS

8.1 Ground results

In may and june 1990, a general test of the torque controlled bearing has been conducted at the Geneva observatory. The first and simplest test was to weigh the bearing. The overall weight is 49 [kg] including electronics.

For dynamic tests the gondola was simulated by concrete blocks featuring the same weight and inertia, that is 2600 [kg] and 6000 [kgm^2]. In spite of difficult test condition (it was not possible to make the test indoor), we were able to notice the very good behaviour of the bearing down to - 60 [^{0}C]. It has an excellent linearity (correlation of 0.999 on the ±4 [Nm] range), a sensitivity of 0.017 [Nm] and a power consumption of 17 [W] half of which is needed by the TM-TC unit. The tests were conducted with a shortened suspension chain which stiffness and inertia were tuned to exhibit the same proper frequencies as the original one. Figure 8 shows a comparison between the experimental and the simulated step response. The good agreement of those curves justifies in an a posteriori manner the choice of the different models used in the control loops.

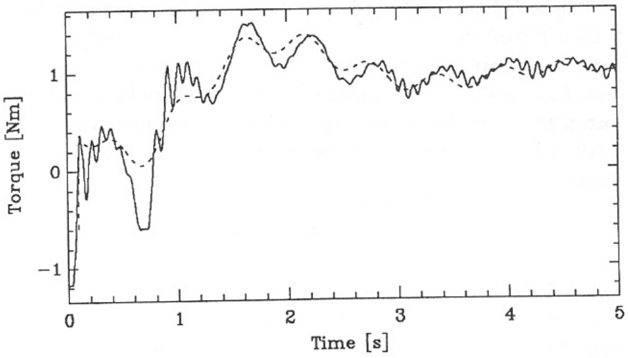

Figure 8. Step response of the torque loop (experiment and simulation)

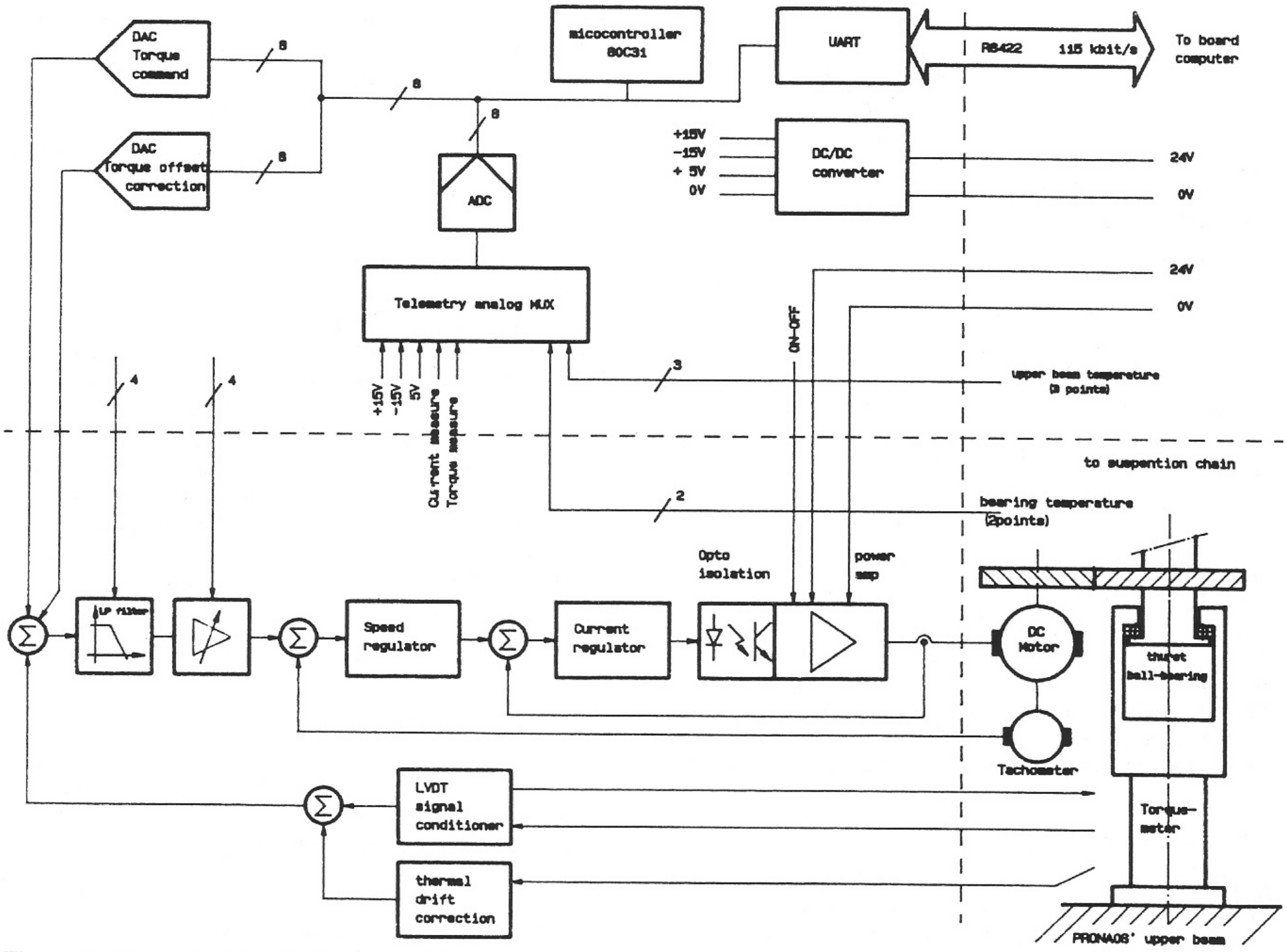

Figure 7. Diagram of the electronics and interfaces

8.2 Flight results

The firt launch of the new bearing is schedulded for june 1991. It will be a test of the low pressure behaviour of the bearing and hopefully, a validation of its thermal model. For this purpose we will launch by night to have a night-to-day transition at float. This way the bearing will work in the largest temperature range possible.

In flight, we will rotate the gondola by shifts of 90 degrees with an azimuth control. At each shift because of saturations we will be able to check successively the torque, speed & position step responses.

As the flight takes place in France, the maximum load will be 500 [kg] instead of the 2.5 tons of the PRONAOS gondola. In addition, for technical reasons the suspension chain will be completely different of that of PRONAOS. The weight problem is insuperable and we won't have flight results at nominal load before the first flight of PRONAOS scheduled in may 91. The change of suspension chain, in the other hand, is not a real problem : A simulation of the system showed that no modification of the control electronics were required. This shows the versatility of this new device.

9. CONCLUSION

The torque controlled bearing appears to be a very good solution for azimuth control of balloon gondolas. It has a larger band width, a larger torque range than activated bearings. It has a very low sensitivity as well as a proper consumption (control electronics, power electronics and motor) an order of magnitude lower than its activated rivals. However, the weight problem has to be mentioned. This device was designed for a 2.5 tons gondola with a security factor of 10. It could not have been much lighter. For lighter experiments or for relaxed security requirements it would be possible to gain 10-15 [kg] by machining certain parts in aluminium instead of steel, still keeping the same design.

10. ACKNOWLEGEMENTS

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