Optical bi-stable shutter development / improvement

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ABSTRACT

Two of the VLT instruments (Giraffe and VIMOS) are using the large magnetic E/150 from Prontor (with an aperture diameter of 150 mm). As we were facing an unacceptable number of failures with this component some improvement plan was discussed already in 2004. The final decision for starting this program was conditioned by the decision from the constructor to stop the production.

The opportunity was taken to improve the design building a fully bi-stable mechanism in order to reduce the thermal dissipation.

The project was developed in collaboration between the two main ESO sites doing the best use of the manpower and of the technical capability available at the two centers. The project took advantage of the laser Mask Manufacturing Unit and the invar sheets used to prepare the VIMOS MOS mask to fabricate the shutter petals.

Our paper describes the development including the intensive and long optimization period. To conclude this optimization we proceed with a long life test on two units. These units have demonstrate a very high level of reliability (up to 100 000 cycles without failure which can be estimated to an equivalent 6 years of operation of the instrument)

A new bi-stable shutter driver and controller have also been developed. Some of the highlights of this unit are the fully configurable coil driving parameters, usage of braking strategy to dump mechanical vibration and reduce mechanical wearing, configurable usage of OPEN and CLOSE sensors, non volatile storage of parameters, user friendly front panel interface.

Keywords: Shutter, Optical instrument, Spectrograph.

1. INTRODUCTION, HISTORIC

Optically the best location to place a shutter is in the pupil plane, this design ensures a perfect performance of the instrument and specially the same exposure time for every point of the field. This leads to rather large shutter in the case of some high efficient instruments. This was the case for two major instruments of the VLT: Giraffe and VIMOS, which have a 150mm pupil. They were both originally fitted with Prontor E/150 shutters equipped with electro-magnetic actuators.

A first design foresaw the implementation of a cooling circuit to remove the heat dissipation generated by the holding current on the mono-stable actuator coil. For safety reason this was never installed and VIMOS was suffering from the beginning from this thermal disturbance in the close vicinity of the optical path. This shutter had also from the beginning some reliability problem as well as most of the instruments shutter.

The final decision was trigged when trying to procure some spare we discovered that this model has been de-scoped from the fabrication. Then in order to also satisfy the VLT obsessive down time hunting it has been decided to launch our own production with a solid improvement and testing program. The plan which was also part of the general VIMOS improvement project in view of heavy intensive survey program includes a long life time test and reliability qualification under realistic operational conditions. The instruments being already installed and having the most serious experience at Paranal it was decided to have this project as a jointed project ESO Europe and Chile.

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2. MECHANICAL DESIGN AND IMPROVEMENT

2.1 Original design

The first idea was simply to copy the mechanic of one of the old Prontor shutter. One has been dismounted and every part has been carefully measured in order to elaborate suitable manufacturing drawings. The design of some specific parts was modified in order to adapt to manufacturing technology better suited for single to low number production.

The principle remains the original principle with the four petals driven by a rotating ring via a set of four articulated actuators. Figure 1 shows a schematic which can help explaining the principle: a short angular rotation of the driving disc (red) move the attachment points of the four actuators arm from “A” shutter close to “B” shutter open. The four lever actuators are attached on one side onto the driving ring and on the other end onto the every of the four petals. This movement forces the petals to rotate around the rotation axis mounted onto the base plate. We see that the position of the petals in the position “B” is such that the aperture marked with the green circle is free: The shutter is open.

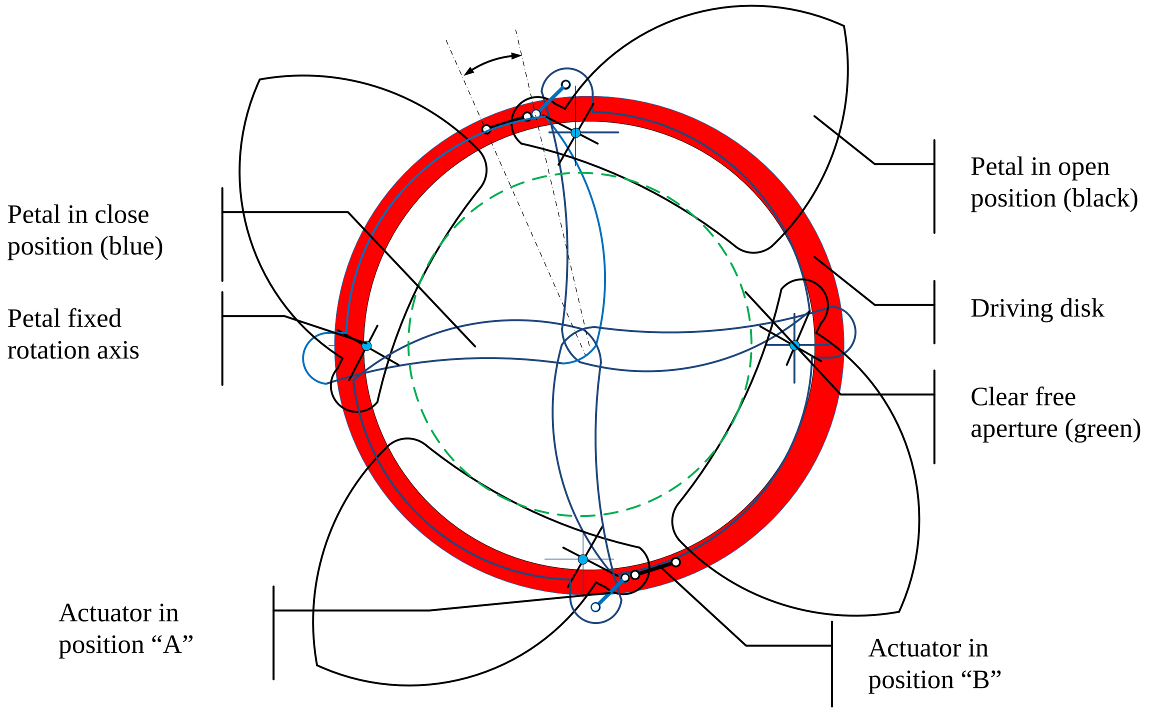

Figure 1: Shutter petal drive principle

If the principle has been fully kept a number of modifications have been necessary in order specially to meet the very strong reliability requirements. These modifications which are of various natures and at various level (Material choice, implementation, guiding improvement..) are described and justified in the following chapters.

Only the drive mechanism was strongly modified in order to have a bi-stable system allowing to keep the shutter in “Open” or “Close” state without any dissipation. For the drive two mono-stable magnet actuators were implemented. Figure 1 show the drive mechanism with the implementation of the two mono-stable magnet actuators. A permanent magnet integrated at the end of the coil maintains the driving iron cylinder in position. Then the electro-magnetic forces are only used to initiate, control and decelerate the movement. The translation of the two cylinders is transferred to the driving discs via the drive level system and driving arms.

Figure 2: Electro-magnet drive system

2.2 Manufacturing

One of the first challenges we had to face was the production petal of the iris. They should be cut in a thin rigid metal foil and be coated with a robust black coating. There we got a direct help from the VIMOS instrument it-self which is using focal plane mask. The masks are produced directly at Paranal using a computer driven laser cutting machine. This machine has been used to cut the petal in the 0.1mm invar foil used for the manufacturing of the VIMOS masks.

Figure 3: Iris petal

The actuators arms were the second parts which gave us some serious problems with the manufacturing and procurement. The original ones (Figure 4, left) are built in three parts: the plate and the two axis which are assembled by crimping. The crimping or seaming technology required some experience and special tools which are well adapted to serial production but were not affordable for our small number. A first attend were done with an assembling by brazing (figure 4, right). This was not fully satisfactory due to an-avoidable radius at the base of the axis. Finally the parts have been mailed directly in solid stainless steel plates (Figure 4, middle).

Figure 4: Actuator arms

2.3 Improvement

The first improvement was driven by the first result of the life test and was basically and generally on the guiding of the various moving parts. The mounting of the driving level has been changed from a plain bronze bearing to a set of ball bearings (see figure2). Three ball bearings have been added to maintain and guide the rotation of the driving disk (see figure 5), some phosphoric bronze bushings have been installed in order to improve the guiding of the actuator arms in the driving ring. Finally the guiding of the actuator arms in the iris petal has also been improved using lubricant loaded bushings (see figure 3).

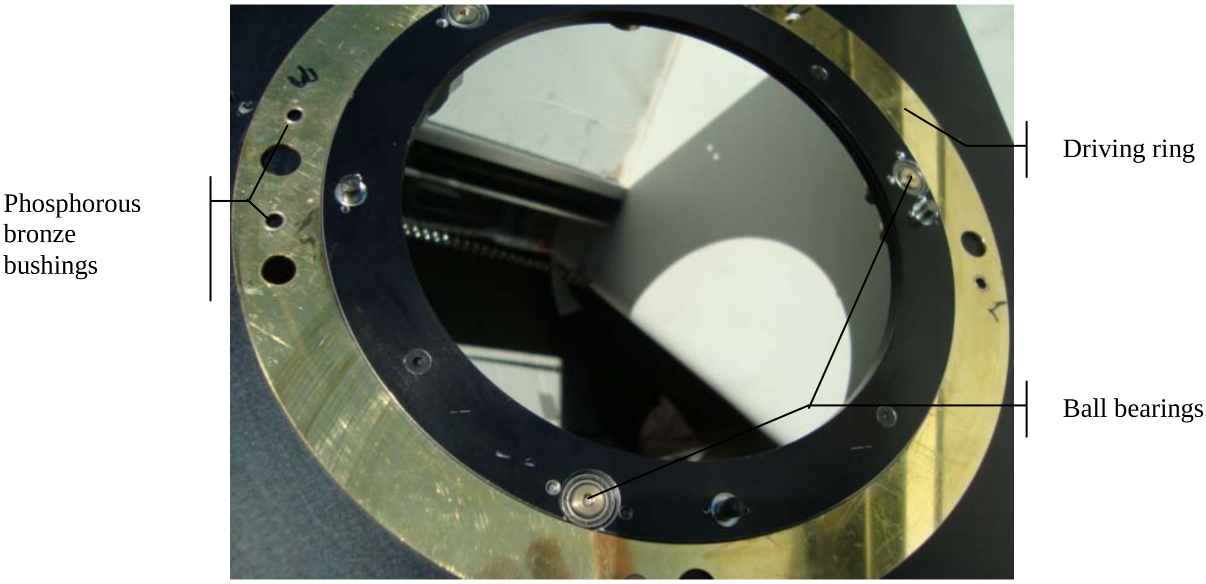

Figure 5: Guiding of the driving disk

The second level of improvement was on the damping at the end of the range. Figure 6 shows the Sylomer damping system. In the rest position, the lever is kept in soft contact with the Sylomer block. The shock caused by the driving ring button is directly damped by the Sylomer block.

Figure 6: End of the range mechanical damping

3. SHUTTER DRIVER AND CONTROLLER UNIT

The new bi-stable shutter required a driving electronic which was not compatible with the drivers provided with the original VIMOS mono-stable shutters. The existing bi-stable controllers used in GIRAFFE were not longer in production and not enough spare parts were available so it was decided to design a new bi-stable shutter controller based on the functionalities of the GIRAFFE one but introducing same improvements based on the long experience gained through the years in the Observatory.

The bi-stable shutter controller was based in the PIC18F452microcontroller, which allowed us to program the device in C. The microcontroller provides enough I/O signals and computational power to sense the status signals from the shutter, display and read information on the front panel. The software is based on a Finite State Machine, which ensures that the shutter state and transitions are well defined.

The main characteristics of shutter driver and controller unit (SDCU) are:

- Front panel with LCD, LEDs and buttons to ease the field configuration and debugging.
- Configurable pulse width to OPEN and CLOSE coil.
- No power dissipation to keep the shutter in OPEN or CLOSE position.
- Hardware watch dog to limit the maximum pulse width to the coils to prevent damaging the coils if the micro controller units fail.
- All configuration parameters are stored in non-volatile RAM.
- Back compatible with SESO shutter drivers. Only a minor modification in the wiring to the shutter is necessary to drive the UVES and GIRAFFE shutters.
- Configurable sensor availability, allowing the shutter to function even if one or both status sensor is broken.
- Petal braking strategy to reduce mechanical vibrations. Programmable through front panel.
- Special charging circuitry to limit the inrush current needed to load the storage capacitors used to deliver the current to the coils.
- Hardware and software watchdogs to prevent coil damage due to failures of the microcontroller.
- Back compatible with SESO shutter used in GIRAFFE.

The SDCU is composed of 4 boards inside a metallic box having a U3 form factor. The front panel has a LCD of 8x2 characters, 5 LEDs and 3 buttons that allow the interaction of the operator with the device.
The back panel is fitted with 4 labeled connectors, the CONTROLLER one is used to interface the SDCU with PULPO which provides the TTL level that instruct the SDCU to open and close the shutter. The SHUTTER connector is used to connect with the bi-stable shutter, the +24VDC is used to get the 24VDC from a power supply to the units and the RS-232 is an optional connector used to control the shutter directly from a serial link, without the need to use a PULPO.

Figure 7: SDCU front and rear view

The SCDU consist of 4 electronics boards: the Mother Board, the microprocessor and shutter driver board and the LCD and keyboard interface board.
The Mother Board is a PCB of 147x100 mm, which contains connectors to install the Microprocessor PCB and the Shutter Driver PCB. It also has a couple of big capacitors (22000 µF each) to store energy which is released to the shutters coils during the OPEN and CLOSE operation.
The Mother Board has also a special circuit to limit the loading current to the capacitors. The maximum current is 2 A, and the objective is to avoid tripping the over-current protection in the power supply during the charging of the capacitors. The shutter coils have a DC resistance of 7 Ohms, so the driver must be able to supply 3 A at 24VDC during the coil activation.
The Microprocessor Board is based in the Micro Chip PIC18F452 controller. The board is fitted with a RTC chip, a 512kbytes serial EEPROM and an RS232 level adapter chip. The controller is programmed in the CCS C compiler.
The Shutter driver boards provides interface between the TTL control signal from the microcontroller and the high current needed to activate the coils. It receives the opto-isolated signals from the shutter status (OPEN and CLOSE) and level shifts them to TTL level needed by the microcontroller. A watchdog system implemented with an NE555 timer guarantees that the current to the coil will not be activated by more than 350 ms.
The board has a power stage consisting in one power MOSFET per coil, which enables the current from the internal 24VDC storage capacitors.
The keyboard interface is a very simple board attached to the back of the front panel, and is used to hold the 3 front panel buttons and the 5 LEDs. A connector on the back of this board takes the signals to the Mother Board.
The front panel LEDs provides visual information of the current shutters state (Open, Close, Fail, Remote/Local, Open CMD), and the buttons and LCD implement a keyboard user interface (KUI) to allow setting up the working configuration: Open Pulse Width, Close Pulse Width, Remote or Local Mode, TTL or RS232 Open CMD, Braking or Normal Coil Control Strategy, length of braking pulse.
The bi-stable shutter has two coils, one to move the petals to the OPEN position and the other to move them to the CLOSE position. The coils have permanent magnets on one side in order to hold the driving rod in position once it's completely inside the coil, this is to avoid movements of the petals due rotation of the shutter unit and while the coil are not energized.

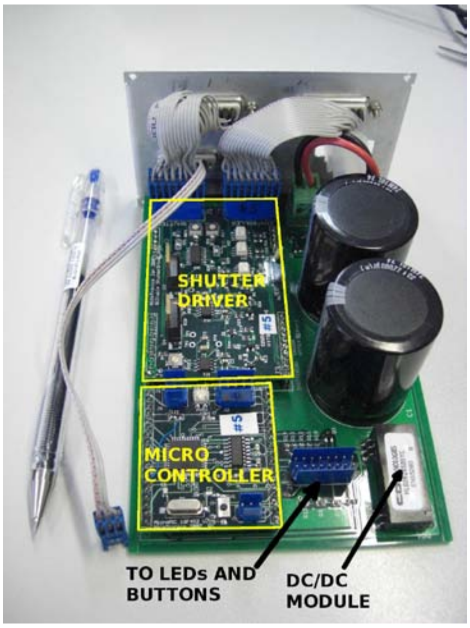

Figure 8: Mother board with microcontroller and shutter driver board

The coils have a resistance of 7 Ohms so the driver must be able to supply 3.4 A @ 24VDC to the coils. The travel time between CLOSE and OPEN position is approximately 70ms to 90ms, but the activation pulse must be at least 2 times the travel time to avoid the mechanical bouncing of the petals.

One of the main problems of these big aperture shutters is the strong mechanical impact of the moving parts against the structure of the shutter. In order to improve the system, apart of the mechanical dumping system, the SDCU has a Brake Strategy Mode to drive the petals. It consists in activating the opposite coil for 20 ms to 40 ms just before the shutter petals reach the final position.

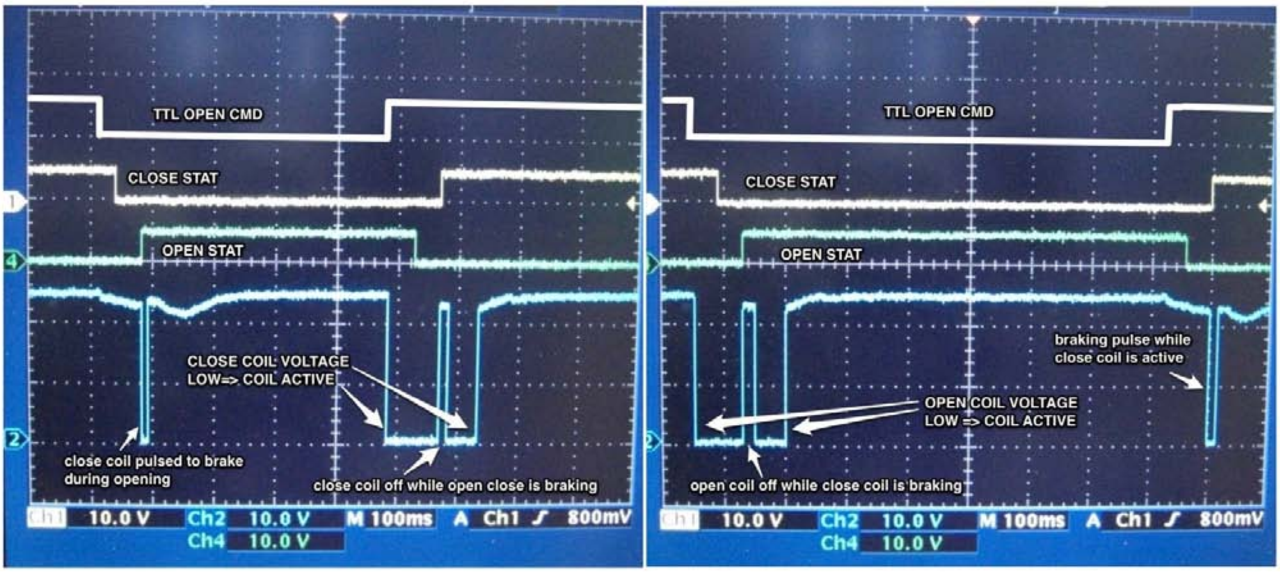

Figure 9: SDCU coil and status signal for braking mode

4. TESTS

In addition to all the tests required for tuning the controller and more specially for optimisation of the transition (opening and closing) times, an intensive campaign of test has been carried out in order to assess the reliability of this new shutter.

The first 3 units were used for debugging the mechanics and identification of the various modifications that have been described before. The unit number #4 can be considered as the first final model. It has been submitted to a qualification procedure including 100 000 operations cycles. As it passes successfully this first step, the test has been extended until the first failure occurs. Additional units have been submitted to the lifetime test and lifetimes up to 255000 cycles have been recorded.
This new shutter and controller have been installed at the four arms of the VIMOS instrument since almost 2 years (June 2010).
They are extremely reliable; the table below summarizes the amount of downtime generated by the old mono-stable shutters and the new ones during the same amount of time (11 month).

	Number of problem reports	**Accumulated Downtime** [min]
Mono-stable shutters June 2008 till May 2009	**41**	**1113**
Bi-stable shutters June 2010 till May 2012	**8**	**50**

Figure 10 illustrates the reliability of shutter. It displays the shutter failure statistic since VIMOS installation at Paranal. The year 2010 has been divided in 2010a and 2010b, as starting in 2010b the new bi-stable shutters has been in use.

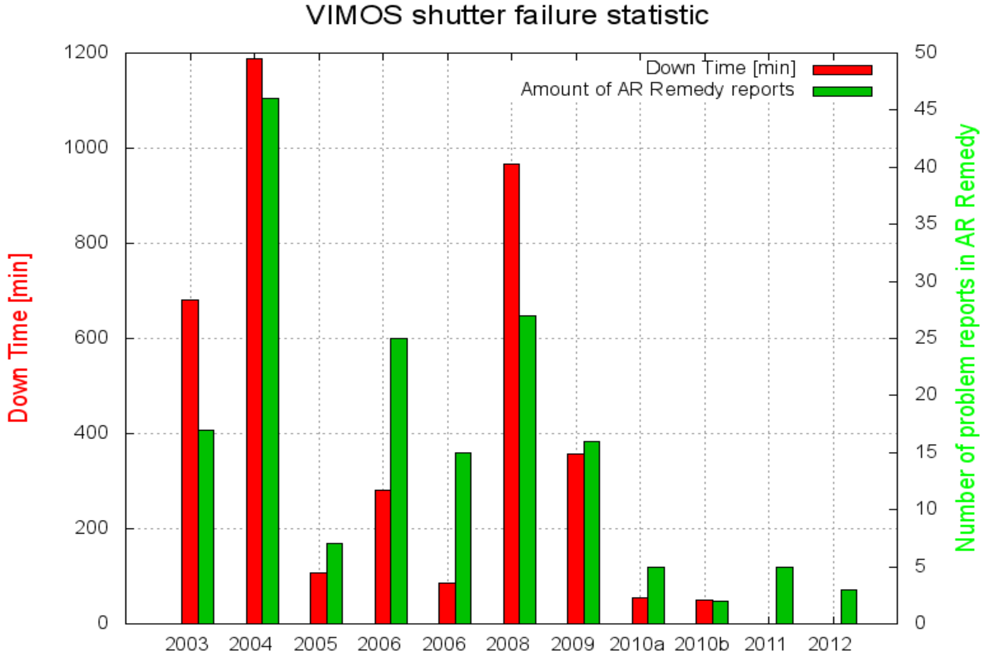

Figure 10: Shutter reliability

5. MAINTENANCE STRATEGY

The experience gained during the almost two years of operation and the close monitoring of the units has help to define parameters that give insight of future problems on the units due to wearing of mechanical parts. The Open Delay and Close Delay are adjusted to approximately 70 ms to 90 ms. These parameters are stored in the FITS headers for every science or calibration frame. The increase of these parameters by more than 20% triggers a preventive maintenance of the unit and until now, no mechanical parts have been replaced and a thorough cleaning,, oiling and adjustment of the sensors have been enough to keep the good performance.

AKNOLEDGEMNTS

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