SPIRE

SPIRE Shutter Design Rationale

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SUBJECT:	**SPIRE Shutter Design Rationale**

INTRODUCTION

The original specification for the SPIRE shutter required that "Any failure of the shutter mechanism must result in the vane relaxing to the locked position" (IRD-SHUT-R04). It is recommended that this requirement be changed to a reliability requirement of 0.9999. This memo addresses the issues which make it necessary to design a highly reliable and robust mechanism instead of a fail-safe mechanism. It also discusses a concept proposed by Doug Griffin, and reviews the stepper motor vs. rotary solenoid design option.

DISCUSSION

Fail-Safe vs. Highly Reliable Design

The most critical aspect of the shutter reliability is that the shutter not fail in the beam. It is vitally important that the shutter vane be properly stowed and secured before launch so that the vane does not move and block the beam. Also, since it is very difficult to access the shutter prior to launch, it is desirable to have a design which would automatically go to the locked launch position should any failure occur. Unfortunately with the other design requirements and constraints, this did not appear to be a realistic requirement.

A major driver in the shutter design was the requirement to operate in any orientation (IRD-SHUT-R06), and specifically the consequence that the shutter must operate against gravity. This was identified early in the design development and an investigation was pursued to determine whether this was necessary. The investigation concluded with the issue of document SPIRE-USK-NOT-000827 which describes the operating scenarios. It was determined that the shutter must operate against gravity, especially in the RAL test facility.

Since the shutter is reasonably large (approximately 8 cm x 15 cm, mass 90 grams) with the motor offset by 2 cm from one of the corners, the torque requirement to move the shutter against gravity is significant. The only way to move the shutter with a motor was to use a very large motor or to increase a smaller motor's torque capacity using a gear train. Since the large motor would not fit in the prescribed volume and had a large mass, a gear train was chosen for the design. Based on heritage, simplicity, and efficiency, a planetary drive was selected with a gear ratio of up to 200:1.

With the large torque and gear ratio required to move the shutter vane, the fail-safe spring return became an unrealistic design requirement. In order to back drive the planetary gear train against the motor detent with a sufficient torque margin (at least 2:1), the spring would need to have a very high torque. A larger gear train would then be required to move the shutter since the motor would now also need to work against the spring. This results in a vicious circle as the motor and spring continue to drive the size of the other part.

If it were possible to achieve a balance such that a reasonable sized motor and spring could be achieved, then other complications would arise, such as:

1. The allowable current supply to the motor is 30 mA (TBC). The motor vendor ascertains that the current required to move the shutter vane against gravity is approximately 100 mA with redundant windings. We are currently in negotiations to obtain this higher current. If a spring return and higher motor torque is required, then the current requirement would be considerably higher than 100 mA and would likely be unacceptable. This also applies to the higher power which would be required.

2. When the shutter vane is blocking the beam, the full retraction spring force would be acting to try to force the vane back to the latched position. The motor would then be required to be on at full power to keep the vane in the beam. This would require a large amount of power which would be dissipated in the motor windings. The majority of this heat would be conducted into the instrument cover which could cause the cover to over-heat.

3. If a motor failure occurred which caused a short in the windings, then the spring would retract. The shorted coils would create a damping field when the rotor turned through it, counteracting the spring torque. This could result in the vane not being properly latched since the retraction force might be less than required to fully engage the spring loaded latch pin.

Due to these design aspects, it was decided that a highly reliable design provided a more robust solution than the fail-safe design. A reliability figure of 0.9999 was determined to be an achievable requirement when redundant design features were accounted for. The motor without the spring design requires lower current flow and allows for the option of reducing the duty cycle (slowing down the motor) to reduce the average power requirement. When the vane is in the beam, the motor detent is sufficient to hold the vane in the proper position without power.

The redundant motor windings are effective in recovery from a winding or harness failure. In the case of a degraded bearing or gear performance, it may be possible to energize both windings to increase the motor torque capability to overcome the higher resistance. If the bearings or gears were to seize, then the redundant motor windings would not be able to recover the failure. In this scenario, the fail-safe spring would also be unable to recover the failure. In essence, the spring only accounts for a winding failure which is the same function as a redundant winding. For this reason, from a reliability viewpoint, the redundant windings are equivalent to the fail-safe spring.

Doug Griffin Design Suggestion

A design option has been suggested by Doug Griffin to address the seized gears or bearings situation. In the proposed design, an additional gear system is mounted between the vane and the motor shaft. The gear train is spring loaded and the vane can rotate on the motor shaft. In normal operation the gear train is locked by a solenoid mounted to the vane. The locked gear train allows the motor torque to rotate the vane. Upon a failure of the motor, the solenoid pin is retracted which allows the spring loaded gear to rotate the vane out of the beam to the locked position.

While the proposed design overcomes the failure of drive train, there are a number of disadvantages and concerns with the system which include:

1. Increased mass and complexity of the design due to the additional solenoid, gears, and harness
2. The need for extra pins in the harness for the solenoid which are currently not available
   - This problem could be traded off against redundant motor windings
3. Increased number of wires through the flex harness
4. Solenoid pin side load would be significant and considerable power and/or a large solenoid may be required to remove the pin
5. Thermal impact would need to be addressed
   - Effect of gear in vane
   - Increased heat path through gears
6. Possible interference of the solenoid with the RAL test facility

The main impetus for this design suggestion is to remove the concern of the gear train or bearings seizing. This is essentially done by adding a redundant gear and bearing drive train which is highly preloaded. Whether this is warranted considering the negative impacts mentioned in the above list may be determined based on the likelihood of a drive train failure. Given the low number of operating cycles, the low loads, and the heritage of the design, COM DEV considers a drive train failure to be highly improbable. It is especially unlikely at the spacecraft level since this would follow all of the shutter protoflight level testing which would verify the robustness of the flight assembly.

Stepper Motor Design Approach

Another aspect of the COM DEV design which has deviated from the initial concept developed by the project team is the use of a stepper motor as opposed to a rotary solenoid. In its simplest form, a rotary solenoid can be considered to be a one-step stepper motor, with one step at an angle of 90°. As mentioned above, the vane requires a significant amount of torque to move it against gravity. A very large solenoid would therefore be required, since with only one step, a gear train would not be an option. The speed of the rotation is also a concern as the vane would swing 90° in a few milliseconds. As the vane carries a significant amount of inertia, this was not considered to be a preferred approach.

COM DEV produces thousands of RF switch units a year which essentially consist of rotary solenoids to route waveguide signals through redundant paths. Such a unit was used on the FUSE instrument to power a filter wheel. For the SPIRE application, however, this was not viewed as the best design compared to the stepper motor alternative. The stepper motor with a gear train provides the required torque at minimum current, provides adequate detent holding torque with no current, it moves the vane at a slow controlled speed, and the motor has proven heritage at 4K. In fact three different qualified vendors have been identified with "standard" cryogenic designs rated at 4K. The stepper motor was therefore chosen over the rotary solenoid.

CONCLUSION

Although the fail-safe spring seems like a good feature in the SPIRE shutter design, the design produces a number of problems. Principally, with the gear train requirements, it may not be feasible to back-drive the motor with a spring. If the design could be made to work, other factors such as increased motor current and excessive holding power (large heat load) indicate that the fail-safe spring is not an attractive option. From a reliability viewpoint, redundant windings offer an equivalent amount of reliability while eliminating the problems associated with the spring. Redundant windings therefore form the baseline design along with an overall reliability requirement of 0.9999 to prevent the possibility of a failure.

A design proposal for a redundant gear/bearing system was proposed. A number of negative impacts undermine this design, so its merits should be traded against the likelihood of a drive train failure. Given the low number of operating cycles, the low loads, and the heritage of the design, COM DEV considers a drive train failure to be very unlikely, especially at the spacecraft level.

A stepper motor with a gear train was chosen over a rotary solenoid since the stepper motor provides the required torque with minimum current, has adequate holding torque for zero current, it moves the vane at a slow controlled speed, and it has proven heritage at 4K.