Chapter 4

Cryogenic mechatronic design of the HIFI Focal Plane Chopper

The difficulties encountered during the development of the HIFI-FPC, motivated us to study the possibility to apply more advanced control strategies for application in future chopper mechanisms to further improve the performance of these mechanisms, as has been discussed in Section 1.3.1. These efforts resulted in the hybrid control strategy, which has been described in Chapter 3. In Chapter 5 we discuss the synthesis and application of this new control strategy to the HIFI-FPC and we show how this can lead to a large improvement in performance without the need for detailed redesign of the hardware.

This chapter presents the mechatronic design of the HIFI-FPC and several technical considerations in achieving nominal operation at 15 K with strict performance requirements and environmental constraints. It shows how the constraints in material choice, differences in CTE, etc. influence the design, assembly and test campaign of the hardware and gives a flavour of this field of engineering/research. The performance of the flight model of the HIFI-FPC, before integration with the HIFI instrument and during operation in space, are presented applying the original controller. The issues discussed here are directly applicable to the development and testing of the MCCD which are discussed in Chapter 6.

In Section 4.1, the design of the HIFI-FPC is given focusing on the mechatronic components and the control of the system. The different aspects, related to the development of the HIFI-FPC mechanism for operation in cryogenic conditions, are discussed in Section 4.2. In Section 4.3, the performance of the HIFI-FPC both in the test lab and in space is presented. We conclude with an outlook on the demands on thermal behavior of mechanisms in future space missions.

The results in this chapter are published in [26].

4.1 HIFI Focal Plane Chopper

4.1.1 HIFI-FPC requirements

Table 4.1 summarizes the HIFI-FPC design requirements related to the dynamical performance of the mechanism. This is not a complete overview of the requirements but gives the relevant parameters for the mechatronic and control design of the instrument. The required chop frequency of the mechanism, for chopping between an astronomical source and a background position, is 5 Hz. The settling time of the mechanism is limited to 40 ms in order to minimize the dead time when chopping between the on- and off-source positions. Table 4.2 gives a list of the standard chopper positions. The associated orientations of the telescope beam on the sky and on the internal calibration loads are also given. The stringent settling time requirement
is only applicable to the $4.9^\circ$ chop range for chopping between different sky positions. This requirement is relaxed for chopping to the calibration source.

The performance requirements, given in Table 4.1, in combination with the design limitations introduced by the cryogenic environment, demand a careful mechatronic design of the mechanism.

Table 4.1: HIFI-FPC requirements and realized performance. Measurements were performed in the lab at an operating temperature of 9 K.

<table>
<thead>
<tr>
<th>Description</th>
<th>Requirement</th>
<th>Result</th>
<th>Unit</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos. stability</td>
<td>&lt; 30</td>
<td>2</td>
<td>[&quot;]</td>
<td>$1\sigma$</td>
</tr>
<tr>
<td>Pos. repeatability</td>
<td>&lt; 90</td>
<td>17</td>
<td>[&quot;]</td>
<td>Max. allowed offset</td>
</tr>
<tr>
<td>Pos. resolution</td>
<td>≤ 60</td>
<td>25</td>
<td>[&quot;]</td>
<td></td>
</tr>
<tr>
<td>Settling time</td>
<td>≤ 40</td>
<td>38</td>
<td>[ms]</td>
<td>0.5% criterion</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>≤ 2</td>
<td>2</td>
<td>[mW]</td>
<td>for 5Hz chop over $4.9^\circ$</td>
</tr>
<tr>
<td>Chop range</td>
<td>15</td>
<td>✓</td>
<td>[&quot;]</td>
<td></td>
</tr>
<tr>
<td>LVDT resolution</td>
<td>&lt; 30</td>
<td>1</td>
<td>[&quot;]</td>
<td></td>
</tr>
<tr>
<td>LVDT linear stroke</td>
<td>9</td>
<td>✓</td>
<td>[mm]</td>
<td></td>
</tr>
<tr>
<td>LVDT noise level</td>
<td>≤ 0.9</td>
<td>✓</td>
<td>[mV]</td>
<td></td>
</tr>
<tr>
<td>Pivot lifetime</td>
<td>&gt; $10^8$</td>
<td>✓</td>
<td>[cycles]</td>
<td>over $5^\circ$ chopangle</td>
</tr>
</tbody>
</table>

Table 4.2: Relation between the chop angle of the HIFI-FPC and the actual orientation of the HIFI beam. The total chop range of $15^\circ$ is limited by the end stops. CBB stands for Cold Black Body and HBB stands for Hot Black Body.

<table>
<thead>
<tr>
<th>Chop angle</th>
<th>HIFI beam orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4^\circ$</td>
<td>Endstop position (outside observing range)</td>
</tr>
<tr>
<td>$-2.45^\circ$</td>
<td>-1.5° on the sky</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>0° on the sky</td>
</tr>
<tr>
<td>$+2.45^\circ$</td>
<td>+1.5° on the sky</td>
</tr>
<tr>
<td>$+8^\circ$</td>
<td>HIFI internal CBB</td>
</tr>
<tr>
<td>$+10.4^\circ$</td>
<td>HIFI internal HBB</td>
</tr>
<tr>
<td>$+11^\circ$</td>
<td>Endstop position (outside observing range)</td>
</tr>
</tbody>
</table>

4.1.2 Instrument description

Fig. 4.1 shows the final flight model of the HIFI-FPC. The mirror can rotate around its vertical axis over a total angle of 15 degrees. The total weight of the HIFI-FPC is 520 grams, the rotatable mirror assembly weighs 125 grams. The height of the chopper is 140 mm.
In Section 4.1.2 - 4.1.2 the critical components which support the rotation of the mirror are described. In all cases frictionless contacts between the frame and mirror assembly have been used. The reason for this choice will be discussed in more detail in Section 4.2.2.

**Voice coil actuators**

The movement of the mirror is provided by two voice coil type actuators working together in pushpull configuration. Two instead of one actuator have been used for redundancy and to reduce the required power for the rotation of the mirror. The actuators are fed by a current source providing a maximum current of 23.7 mA each. The current limiter is applied to minimize the heat dissipation through the coils.
Fig. 4.2 shows the design of the actuator. The shape of the soft magnetic core as well as that of the permanent magnet is chosen to allow for the required rotational movement of the coil holder in the actuator housing. This non symmetrical shape slightly reduces the efficiency of the actuator but avoids the necessity of a complex construction using various pivotal points that would be needed to convert the rotational movement of the mirror assembly into a translational movement of the actuator coil.

![Figure 4.2: Left: Schematic drawing of the HIFI-FPC actuator. Right: Cross section of HIFI-FPC actuator; 1 = Soft magnetic actuator housing, 2 = Permanent magnet, 3 = Coil, 4 = Soft magnetic core of the actuator housing, 5 = Aluminum coil holder attached to the mirror assembly.](image)

The actuator coils, consisting of 2600 turns of Posyn-TH copper wire with a diameter of 50 µm, are stacked in an orthocyclic pattern to optimize the fill factor of the wiring. The wires are isolated using Polyimid insulation with a thickness of 3 µm. The copper wiring is soldered with Sn50Pb48Cu1.5 tin/lead solder depleted with copper to avoid that the copper of the small diameter wire is dissolved in the solder.

To limit the mass and moment of inertia of the mirror assembly, the voice coils of the actuators are attached to the back side of the Chopper mirror. A drawback of this design is that the generated heat is dissipated onto the mirror assembly and that an electrical connection to the movable part of the mechanism has to be created. BerylliumCopper (BeCu) straps have been used to make the electrical connection between the frame and the mirror assembly. The design considerations for using the voice coil as actuator for the HIFI-FPC are presented in Section 4.2.2. The choice of placing the actuator coils on the mirror assembly and not on the HIFI-FPC frame is justified in Section 4.2.3.
4.1. HIFI Focal Plane Chopper

LVDT position sensors

In order to accurately determine the orientation of the chop mirror, the instrument is equipped with two linear variable differential transformer (LVDT) type position sensors (see Fig. 4.3). A schematic drawing of the cross section of these sensors is given in Fig. 4.4. The LVDT sensor consists of three coils that are placed in line. The center coil is excited with an alternating voltage and creates a constantly changing magnetic field inside the LVDT unit. The magnetic field is picked up by the two secondary coils generating an alternating current in the electrical circuitry of both coils. A soft iron core, attached to the mirror assembly of the chopper, is placed inside the coil assembly of the LVDT. The coupling of the magnetic field to the two secondary coils is dependent on the actual position of the core in the coil assembly. Therefore, after calibration of the system, the differences in the amplitude of the generated currents in both secondary coils can be used to determine the orientation of the mirror. The HIFI-FPC is calibrated in an optical setup using a theodolite to accurately relate the angular orientation of the mirror to the LVDT readout.

The LVDT response is affected by the temperature-dependent characteristics of the sensor circuitry and the carrier frequency must be chosen carefully in order to reduce its sensitivity to temperature changes. This will be discussed further in Section 4.2.3. In the final design of the HIFI-FPC, the carrier frequency is 2.6 kHz, which is far away from the resonance frequency of the sensor circuitry. Similar coils as for the actuators are used in the LVDT. Only the dimensions and number of windings (2000 turns for the primary coil and 4000 turns for the secondary coils) are different. Only one sensor is active during the operation of the instrument, the other sensor is provided for redundancy.

Figure 4.3: HIFI-FPC LVDT position sensor; 1 = Aluminum arms attached to mirror assembly; 2 = Stainless steel casing; 3 = Aluminum interface block for integration with HIFI-FPC frame.
Flexural pivots

For supporting the mirror assembly and guiding the rotational movement of the system, Inconel 718 flexural pivots from the C-flex Bearing Company have been used. Fig. 4.5 shows a schematic drawing of the type of pivot used for the HIFI-FPC. The two cylindrical parts of the pivots can be rotated with respect to each other without introducing any friction between the two components. One cylinder is clamped inside the chopper frame and the other cylinder is clamped in the mirror frame (see Fig. 4.6). Clamping instead of gluing or soldering creates the opportunity for alignment of the mirror after the final assembly of the unit.
The pivots are thought to be the most critical components with respect to the reliability of the mechanism. When damaged, these units form a single point of failure in the functioning of the HIFI-FPC. The strong demands on their resistance to fatigue and the extreme vibration loads during the launch of the telescope set high requirements on these components.

As there were no standard pivots available which could satisfy all the HIFI-FPC requirements, an elaborate development program was set up in close collaboration between C-flex and SRON. During this program different alloys were examined on strength, resistance to fatigue, quality of welded joints, spring rate, hysteresis and manufacturability. Because of its favorable properties, Inconel was chosen for the flight batch of the pivots.

To guarantee the homogeneity of the production process of all 50 pivots from the flight batch, the same lots of materials were used and the same production procedure was applied to all components by the same operator. Furthermore, to maximize reliability, the units went through an extensive lot acceptance test program as described in Table 4.3.
Table 4.3: Lot acceptance test program for pivot flight production batch of 50 pieces.

<table>
<thead>
<tr>
<th>Lot acceptance test</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials and plating certification inspection</td>
<td>Braze appearance, cleanliness, damage</td>
</tr>
<tr>
<td>100% visual inspection</td>
<td></td>
</tr>
<tr>
<td>100% dimensional inspection</td>
<td>Outer dimensions, spring clearance, element alignment</td>
</tr>
<tr>
<td>One randomly selected piece destructive physical analysis for braze and material inspection</td>
<td></td>
</tr>
<tr>
<td>Two randomly selected pieces for random vibration testing</td>
<td>Qualification loads in a flight representative configuration</td>
</tr>
<tr>
<td>Three pieces tested on hysteresis, torsional spring rate and shear load capacity</td>
<td></td>
</tr>
<tr>
<td>Two pieces life time tested for 1e5 cycles at +/- 11.4° deflection</td>
<td></td>
</tr>
<tr>
<td>Two pieces life time tested for 1e7 cycles at +/- 6.7° deflection</td>
<td></td>
</tr>
</tbody>
</table>

4.1.3 Control design

Mathematical modeling

A mathematical model of the mechatronic system has been identified for the development of a controller for the HIFI-FPC. Fig. 4.7 shows the mechatronic block diagram of the HIFI-FPC which contains the dynamical model of the mechanism, the power amplifiers, the LVDT preprocessing electronics, the converters and the digital controller.

The dynamics of the HIFI-FPC mechanism are described by the following differential equation:

\[
(J + 2mr^2)\ddot{\theta} + 2d\dot{\theta} + 2k\theta = 2rBlI \tag{4.1}
\]

where \(\theta\) is the angular displacement of the mirror, \(I\) is the input current to the voice coils, \(J\) is the moment of inertia of the mirror assembly (including the two LVDT cores), \(m\) is the mass of the voice coils, \(r\) is the perpendicular distance from the center of rotation (pivot axis) to the line of action of the actuator force, \(d\) is the eddy current damping in the aluminum coil holders of the actuators, \(k\) is the spring constant of the pivots, \(B\) is the magnetic flux in the voice coils and \(l\) is the total length of the wire in the coils. We remark that the damping component is dominated by the eddy current friction in the voice coils. The mechanical friction is negligible due to the use of pivots and the lack of air friction (see also Section 4.2.2). The right hand side of 4.1 describes the voice coils torque and is proportional to the applied electrical current \(I\).

The values for \(J, m, r\) and \(l\) in 4.1 are taken from the mechanical model of the mechanism. The spring constant has been measured for different angles @ 300 K and 4K and the magnetic...
field strength is based on values supplied by the magnet manufacturer. Finally, the damping in the system has been tuned w.r.t. the open loop response of the HIFI-FPC to a step signal at a temperature of 9 K. This open loop response, together with the simulated response, is given in Fig. 4.13. The identified transfer function of the mechanism is given by 4.2 where the poles are located at -18.4 and -95.5.

\[
H_{FPC}(s) = \frac{2811}{s^2 + 113.9s + 1757.2}
\]  

We remark that the given transfer function of the HIFI-FPC is only valid when the mechanism is operated at cryogenic temperatures. It has been observed that the dynamical behavior of the HIFI-FPC mechanism at cryogenic temperatures differs from that at room temperature. In Section 4.2.3, the effects of temperature changes on the physical characteristics of the HIFI-FPC are described.

The voice coil is driven by a current stage in order to minimize the influence of the electromotive force (emf), generated by the movement of the actuator coil, on the controller. The current stage is designed such that it has a bandwidth of 2400 Hz or 15,000 rad/s and a phase lag at 20 Hz $\lesssim 1$ deg. The resulting current stage is modeled as a second-order low-pass filter, where the input is the driving voltage and the output is the electrical current to the voice coil. Its transfer function, which is identified based on the open-loop frequency response of the current stage, is given by the following equation:

\[
H_{cs}(s) = \frac{547997173}{s^2 + 10880s + 231233600}
\]  

The LVDT circuitry, which consists of the LVDT and the LVDT signal conditioning, is used to demodulate the LVDT signal and to filter out high frequency components. The filter is designed such that it has a cut-off frequency at 3550 rad/s. The circuit is modeled as a second-order low-pass filter which is identified using the open-loop frequency response. The transfer function of the LVDT circuit is given by the following equation:

\[
H_{LVDT}(s) = \frac{5877581}{s^2 + 928s + 5597696}
\]  

In contrast to the HIFI-FPC mechanism, the electronics are placed outside the cryogenic chamber and they are always operated in room temperature conditions. In other words, there is no thermal effect on the electronics.

**Feedback controller design**

Based on the necessary exponential decay of the response to reach the 40 ms settling time requirement, the minimal bandwidth of the overall system had to be at least 20 Hz. The bandwidth of the closed loop system without a controller installed was 17 Hz. To be able to increase the bandwidth, while keeping a stable system, phase compensation by a differentiating term was introduced. This adds phase margin to the system. A pole was added to this differentiator to limit its high frequency gain. The high requirement on the positional accuracy
(steady state error) of the mechanism required an integrator in the controller. This integrator adds a phase lag of $90^\circ$ which had to be compensated by a second differentiating term in the controller.

For fine tuning after launch and to be able to implement different control parameters if redundancy would be lost, it was decided to utilize a digital instead of an analog controller. The sampled data controller was designed by discretizing the plant and then tuning the controller. The plant discretization was based on the step-invariant transformation method [10]. The sample frequency for the z-domain was 1.5 kHz. The final controller is a lag-lead compensator which is given by:

$$C(z) = \frac{K_1 (z - a) K_2 (z - b)}{2 (z - 1) 32 (z - c)}$$

where $a = 0.9863$, $b = 0.8643$, $c = 0.1455$, $K_1 = 18$ and $K_2 = 200.992$.

When both components of the compensator are placed in the forward path of the closed loop system the performance is limited by the differentiating term in the second compensator. In this configuration a satisfactory settling time can be reached but the overshoot of the response is too big ($\sim 40\%$). This can be dealt with by introducing a prefilter [15] of the form given in (4.6) into the system.

$$\frac{32 (z - c)}{K_2 (z - b)}$$

The filter eliminates the zero of the second compensator in the complementary sensitivity function while maintaining the same DC gain. The closed loop structure with the prefilter is equivalent to a structure where the second compensator term is placed in the feedback path of the control loop.

In order to deal with the saturation in the current stage, an additional anti-windup strategy [21] has been added to compensator 1. The final configuration with the two compensators is given in Fig. 4.7.

![Figure 4.7: Block diagram of the closed loop chopper system showing the dynamical model of the mechanism, the power amplifiers, the LVDT pre-processing electronics, the converters and the digital controller. Anti-windup is present in Compensator 1.](image-url)
To model the computational delay introduced by the quantization process, a one-step delay \( z^{-1} \) was added to the discrete time model.

Fig. 4.8 shows the root locus of the overall system. \( K_1 \) and \( K_2 \) are chosen such that the closedloop system has a damping ratio close to 0.5 (Q closed loop = \( 1/2 \), \( \beta = 1 \)). The bandwidth of the overall system is 66.6 Hz which is well above the required 20 Hz bandwidth. The bode plot of the loop gain including the phase and gain margins of the system is shown in Fig. 4.9. The gain margin is 7.16 dB (at 112 Hz) and the phase margin is 34.5 (at 52.7 Hz). With these settings the system meets all its performance requirements and stability is guaranteed.

![Root Locus Plot](image)

Figure 4.8: Z-domain root locus plot of the complete HIFI-FPC system including the compensator. Red crosses and black circles indicate respectively the pole and zero locations of the tuned system.

Figs. 4.10, 4.11 and 4.12 show the experimental results which characterize the static open loop response of the mechanism for nominal use (both actuators active with prime LVDT at an operating temperature of 4 K). Non-linear behavior in the HIFI-FPC mechanism is observed at the outer regions of the chopper stroke (see Fig. 4.10). This non-linearity is mainly the result
of the actuator coil partly moving outside the densest regions of the magnetic field created by the permanent magnet of the actuator when the mirror is rotated over large chop angles (see Fig. 4.11). The LVDT delivers a relatively small contribution to the total non-linearity in the response (see Fig. 4.12) and the pivot stiffness is linear over the complete chop range.

Figure 4.10: Static open loop relation between the actuator current and the LVDT readout of the HIFI-FPC.
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Figure 4.11: Static open loop relation between the actuator current and the chop angle of the mechanism. The on sky chop range (from -2.45° to 2.45°) and the CBB and HBB positions are indicated in the figure.

Figure 4.12: Static open loop relation between the chopper angle and the LVDT readout.

In order to deal with this problem, the controller was tuned for an optimal performance over the 4.9° chop range in which the chopper is pointing the telescope beam to the sky (see also Table 4.2). In this chop range the non-linearities are small, which makes it possible to reach the 40 ms requirement on the settling time of the mechanism. Large chop angles are required...
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to deflect the HIFI beam to the internal calibration sources. Despite the nonlinearity in the actuator, the controller is still able to steer the chopper to these large angles albeit with larger settling time. The chopper takes approximately 80 ms when it has to move to these positions. However, the requirements for chopping to the calibration source are less stringent and also for this mode of operation the performance stays well within the specifications.

4.2 Considerations for cryogenic HIFI-FPC design

In general the space environment is very hostile to satellites. Depending on its distance from the earth, the satellite is affected by the earth's magnetic field, is subjected to extreme temperature changes and vacuum conditions, is exposed to atomic oxygen in low earth orbit, is electrostatically charged by what is left of earth's atmosphere and is subjected to direct ultraviolet radiation from the sun. Furthermore, it is vulnerable to collisions with man-made space debris and is bombarded by cosmic rays, the solar wind, and micrometeoroids [64, 72].

The HIFI-FPC mechanism we are considering here is placed inside the Herschel cryostat and is well shielded from most of these influences. However, the cryogenic environment inside the cryostat itself puts various constraints on the design and testing of the mechanism. Not only the low temperature but also the vacuum conditions limit the possible design options. Here the different aspects related to the design and functioning of the HIFI-FPC in the cryogenic environment are discussed. In Section 4.2.1, the general impact of the environment on materials is described. Then, in Section 4.2.2, cryogenic design considerations applied to the HIFI-FPC and the FPU are given. Thermal issues related to the control of the mechanism are discussed in Section 4.2.3. In Section 4.2.4, we describe the difficulties involved with the testing of the mechanism in cryogenic conditions.

4.2.1 Impact of cryogenic environment on material choice

Possibly the biggest impact of the cryogenic environment on the design of the instrument is the limited choice of materials and lubricants. Some metals and most organic materials start outgassing under vacuum conditions. The evaporated material can contaminate optical components or cause problems in electrical instrumentation. Most lubricants freeze up when they are cooled down to these extreme temperatures.

The physical characteristics of common structural materials abruptly change when being cooled down below a temperature where a phase transition takes place. When the lattice of the material changes from face-centered-cubic (fcc) to body-centered-cubic (bcc), the character of the material changes from ductile to brittle. For structural components in particular, the use of brittle materials should be avoided as their strength is unpredictable.

For most materials, the strength and the resistance against fatigue increase when they are cooled down. These properties are of great importance for cryogenic mechanisms and are utilized throughout the HIFI-FPC design. Stainless steel from the 300 series possesses these properties. This is also true for Al-6061, which is used for the frame and mirror of the mechanism, and for the Inconel pivots [46].

The thermal conductivity as well as the heat capacity of the materials drops off quickly when the temperature is brought down to cryogenic temperatures. At these low temperatures
4.2. Considerations for cryogenic HIFI-FPC design

The thermal conductivity is strongly dependent on the chemical composition of the material, e.g., purity where metals are concerned [43]. This has to be taken into account when thermal cycles of the mechanism are performed (see also Section 4.2.4).

The electrical resistance of pure metals goes down with a decrease in temperature. For the copper wiring of the LVDT and the actuator coils the resistance drops off a factor of approximately 100 between room temperature and 4 K. This helps very much to reduce the operational dissipation.

In Section 4.2.2 it is explained how these considerations are taken into account in the mechanical design of the HIFI-FPC.

4.2.2 Cryogenic mechanical design of the HIFI-FPC

In Section 4.1.2 it was already stated that frictionless contacts have been chosen for all interfaces between the rigid structure and the rotatable mirror assembly of the mechanism. The relative movement of the flexural pivot cylinders is realized through the bending of the spring blades. In the LVDT, there exists no contact between the core and the coils of the system. In the actuator, the contact between the mirror and the structure of the HIFI-FPC is only through the BeCu straps. In this case, the relative movement is allowed by the bending of these straps instead of any frictional movement between the components. These design choices have been made to avoid the use of lubricants and the negative effects of hysteresis and wear in the system.

As stated in Section 4.1.2, Inconel 718 has been used as pivot material because of its favorable mechanical properties (strength and fatigue) in cryogenic conditions. Unfortunately this alloy has a poor thermal conductivity. The consequences of this design choice for the thermal behavior of the mechanism are discussed in more detail in Section 4.2.2.

Whenever stainless steel is required for structural components of the mechanism, alloys from the 300 series are to be preferred. However, the magnetic permeability of this material becomes very low at cryogenic temperatures. The magnetic permeability of stainless steel from the 400 series remains high in cryogenic conditions. Therefore, and because the mechanical loads on the LVDT are very low even during the launch of the satellite, stainless steel from the 400 series has been applied as core material and for the casing of the LVDT. This optimizes the magnetic field in the assembly and reduces stray interfering fields.

For high speed and accurate actuation, piezo actuators are often used in mechanisms. Yet, it is known that the performance of piezo actuators quickly drops when they are operated at cryogenic temperatures [44, 55]. The driving voltage of the actuator has to be increased dramatically when the actuator is used at these temperatures. This, in combination with the large required throw of the mirror makes this type of actuator unsuitable for the HIFI-FPC. The voice coil actuator is chosen because of its favorable performance characteristics in cryogenic conditions in combination with the frictionless movement between the parts.

Differences in Coefficient of Thermal Expansion

The differences in the Coefficient of Thermal Expansion (CTE) [43] of the various materials that are used in the mechanism create a real challenge for the mechanical designer of the instrument. This is particularly important during the cool down and warm up process of the mechanism, as temperature differences can easily rise above 100 K if this process is not actively controlled.
For compactly built units such as the LVDT, that contain very different materials, large internal stresses or even fracture can occur if the design does not allow for differential expansion between the parts. When a problem in the electrical circuit of such a unit arises at cryogenic conditions, troubleshooting can be very difficult as the broken interconnection may be deep inside the complex assembly and may be difficult to detect without destructive disassembly. This can lead to costly repairs and large time delays during the test program of the mechanism. To prevent this from happening the LVDT design allows for differential shrinkage between the parts.

The mirror assembly of the HIFI-FPC is thermally isolated from the frame of the mechanism. The only contact between the mirror assembly and the frame is through the spring blades of the pivots and the BeCu-straps. The thermal conductivity of the pivots is very low because of the small cross sectional area of the blades and because of the relatively low specific thermal conductivity of the Inconel. The specific thermal conductivity of the BeCu material is high but the cross sectional dimensions of the straps (thickness = 20 µm; width = 1.4 mm) are kept very small to limit their stiffness, thereby avoiding any significant influence of these components on the dynamical behavior of the mechanism. Unfortunately this also limits the thermal conductivity of these parts. Thermal strapping (i.e. creating a strong thermal link between different mechanical components by the use of a metal (typically copper or aluminum) strap) of the mirror to the structure is avoided, as this will also influence the dynamical characteristics of the system.

The thermally isolated mirror assembly can cause problems during the thermal cycling of the mechanism. During the cool down and warm up process, the differences in temperature between the HIFI-FPC frame and the mirror assembly can induce mechanical stresses in the components. This can lead to changes in the orientation of the mirror or even deformations of the structural parts, which influence the optical quality of the instrument by changing the surface quality or the alignment of the mirror.

Thermal gradients between the structure and the mirror assembly can also affect the clamping forces on the pivots. When the mirror assembly is lagging behind in temperature during the cool down process of the system, the difference in shrinkage between the mirror and the pivots reduces the clamping force on the pivots. The lower clamping force further reduces the thermal contact between both parts. In this situation the system is susceptible to changes in the mirror alignment caused by external forces on the system. The gravitational force is not big enough to cause an effect but mechanical shocks during handling of the cryostat and the forces introduced by the differences in shrinkage of the structure and the mirror assembly can change the mirror alignment.

In order to deal with these issues, the following restrictions were introduced on the thermal cycling of the mechanism: A limit of 20 K/h was set on the cool down and warm up speed of the HIFI-FPC, the allowed temperature differences between the structure and the mirror assembly were restricted to ΔT = 40 K and handling of the cryostat was prohibited during the cooling down and warming up process. Verification measurements of the alignment of the HIFI-FPC mirror were performed before and after the different thermal cycles during the qualification program of the mechanism to ascertain that the optics had remained unchanged.

The HIFI-FPC temperatures were monitored using PT1000 sensors. These are standard resistive thermal devices using platinum as the resistive component. The use of temperature sensors on the mirror assembly has been avoided because of their influence on the dynamical charac-
4.2. Considerations for cryogenic HIFI-FPC design

teristics of the mechanism (stiffness of wiring, change in moment of inertia). Instead, the ohmic resistance of the actuator coils was measured during the thermal cycles. As the temperature dependence of the resistance of the coil wiring was known, this gave a rough but sufficient value for the temperature of the mirror assembly.

Thermal mechanical design verification of the HIFI-FPC

During the design phase of the mechanism, thermal-mechanical calculations in steady state conditions @ 4K have been performed to determine the effect of the differences in CTE of the materials on the mechanical integrity of the mechanism, the heat dissipation and the to be expected temperature differences in the instrument during operations. The knowledge about the thermal properties of the different materials is based on the given references complemented by lab experiments of the thermal conductivity of aluminum and copper and that of different thermal contacts. For complex assemblies, like the actuators and LVDTs, the reliability of the thermal calculations is limited because of insufficient knowledge about some of the parameters involved (for example the thermal contact resistance between the coils and the structure is not accurately known). To get a complete overview of the effects of the cryogenic environment on the mechanism, the HIFI-FPC was subjected to an elaborate test program (see Section 4.2.4).

Transient analysis of the thermal effects on the mechanism is not required because of the steady state conditions in which the operation of the mechanism takes place. The potentially large temperature differences during the cool down and warm up of the mechanism are limited by actively controlling this process.

General mechanical thermal design solutions implemented in HIFI

For completeness, the general thermal design considerations that were applied in the HIFI FPU are shortly discussed in this subsection.

 Thermal strapping is needed to keep the detectors at the required operating temperature of 2 K leaving the rest of the HIFI instrument at 15 K. For the thermal strapping of the instrument, high purity (99.999%) aluminum has been used. The specific thermal conductivity of this material is comparable to that of high purity copper which is often used for thermal strapping. The match in CTE with respect to the aluminum structure (type: Aluminum-6061) clearly benefits the mechanical design of the instrument.

 The thermal contacts at interface points of the strapping have been optimized by creating large contact areas. In most cases bolted interfaces are required but for permanent connections solder joints have been used to further optimize the thermal conductivity of the strapping. Castolin 190 NH, which is an aluminum/silicon solder, was used for this purpose. Castolin 190 FL was used as flux material. The thermal conductivity of these contacts and their suitability for use in the cryogenic environment have been studied at an early stage in the project in a separate development test program. The results of these tests show an increase in thermal conductivity w.r.t. the bolted connection. These observations are confirmed by the literature [22]. No degradation of the contacts was observed during the development test program or during the extensive qualification program of the HIFI FPU.
For the structural support of the strapping, Vespel has been used. This material combines low thermal conductivity with ample mechanical strength. For thermal isolation of the HIFI detectors from the main structure, stainless steel tubes from the 300 series, with a diameter of 1.5 mm and a wall thickness of only 50 $\mu$m have been used. The relatively low thermal conductivity (in comparison with other metals) of the stainless steel in combination with its high strength makes it another good candidate whenever thermal isolation and structural support have to be combined.

4.2.3 Thermal issues in control design of the HIFI-FPC

Influences of temperature changes on open loop step response

Temperature changes can alter the physical characteristics of the mechatronic system which can in turn influence the performance of the mechanism. In Fig. 4.13 the open loop step response of the chopper at room temperature and at a temperature of 4 K are given. The differences in the response are caused by the differences in the eddy current damping in the aluminum coil holder of the actuators. This parameter becomes approximately 2.5 times bigger when going from ambient to cryogenic conditions. This has to be taken into account in the design and test program of the mechanism. A separate set of control parameters are used for the closed loop control at ambient and at cryogenic conditions.

Not only temperature changes in the mechanism but also in the harness and electronics of the system can be of importance. In Section 4.2.3 the influences of temperature variations on the LVDT response is discussed.

![Figure 4.13: HIFI-FPC open loop step response at room temperature (293 K) and at 4K. Also showing the simulation result (blue dotted line).](image)
4.2. Considerations for cryogenic HIFI-FPC design

Influences of temperature changes on LVDT response

The bode plot of the response for the original 10 kHz LVDT circuit design is given in Fig. 4.14. The frequency response of the LVDT circuitry has a resonance peak at approximately 15 kHz. In principle, the positional resolution of the LVDT will increase when a higher carrier frequency is used. However, when the carrier frequency of the LVDT is chosen too close to the resonance frequency of the system, small changes in the position and shape of the resonance peak, caused by thermal variations in the LVDT circuitry, strongly affect the coupling of the prime carrier signal to the secondary LVDT coils.

This problem was encountered during the test phase of the mechanism, where temperature changes in the five meter long harness of the HIFI-FPC, produced small changes in the harness resistance and the capacitive coupling between the different wires. As the harness is part of the electrical circuitry of the LVDT, these minor changes in the electrical characteristics of the wiring caused a shift in the location of the resonance peak. This produced a non-negligible change in the response of the LVDT. The problem was tackled by reducing the LVDT carrier frequency from 10 kHz to 2.6 kHz.

![Figure 4.14: a: Magnitude plot of the original 10 kHz design LVDT response. b: Phase plot of the original 10 kHz design LVDT response.](image)

Thermal design versus dynamical characteristics

In some cases there is a conflict between a good thermal design of the mechanism and the design considerations with respect to the dynamical characteristics of the unit. For example, the choice of placing the actuator coils on the mirror assembly of the HIFI-FPC, rather than the heavy magnet casing, has a clear advantage with respect to the control of the mechanism because it reduces the moment of inertia. However, the thermal effects are negative as the heat generated by the coils is collected by the thermally isolated mirror assembly. The CAD model of the mechanism indicated that the inertia of the mirror assembly could be reduced by more than a factor of three when placing the coils on the moveable part of the mechanism. A worst case estimate of the temperature rise in the mirror assembly, as a result of the heat dissipation in the coils, showed that this would be limited to five degrees. Comparing these results with the requirements of the mechanism, the choice was made to place the coils on the mirror assembly.
to optimize performance without jeopardizing the structural integrity of the mechanism.

Another example is the use of flexural pivots (no friction, low hysteresis) and the absence of thermal strapping attached to the mirror assembly. This makes the system suitable for control but limits the ability to get rid of the developed heat in the actuator coils. From the perspective of thermal stability and the thermal budget, the maximum heat dissipation by the actuators should be limited. This of course also limits the available power to control the mechanism.

There are no clear design criteria to deal with these conflicting requirements. For every new case an optimal balance has to be found between the different aspects of the design. For the HIFI-FPC, analysis tools like for example Matlab-Simulink, Finite Element Methods (FEM) and MathCad have been used to optimize the design. The quality of the design has been verified in an elaborate test program in which all functional and performance requirements have been tested.

4.2.4 Cryogenic testing

From the preceding sections it is clear that a detailed understanding of the temperature dependent behavior of the mechanism is of crucial importance in order to develop a reliable and well performing mechanism, and although the engineer can make use of different design tools and the available knowledge about the temperature dependent properties of the materials used, an elaborate test program is thought to be absolutely essential to verify the cryogenic compatibility of the design.

An important part of the qualification test program for the HIFI-FPC consisted out of the thermal cycles to cryogenic temperatures. The mechanism first was cooled ten times to a temperature of 4K and after this, another six times to a temperature of 77 K. During this program different tests were performed in ambient and cryogenic conditions to verify the structural integrity of the mechanism.

Test campaigns can take a lot of time as the cooling down as well as the warming up of the test setup should be executed in a well-controlled manner avoiding large temperature differences in the setup (see also Section 4.2.2).

Designing a good setup for testing in cryogenic conditions is not a trivial task. In Section 4.2.4, the considerations for the design of the HIFI-FPC test setup are described.

It is not always necessary to perform the tests at cryogenic conditions. In Section 4.2.1 it has been described that in general the strength and material resistance to fatigue become better when the material is cooled down. This was of great use for the extensive lifetime test program of the pivots. Although the better fatigue properties are partly canceled by the increase in internal stresses in the material with the same angular deflection at cryogenic conditions, lifetime testing at ambient conditions could be considered as worst case. This justified a pivot lifetime test program at ambient conditions which greatly simplified the test setup and thereby the reliability of the measurements.

Test setup

For the test program of the HIFI-FPC we used a cryostat to create a test environment at stable temperatures of 77 K and 4 K. The closed cryostat is provided with a window which allows optical tests to be performed on the HIFI-FPC mirror surface in cryogenic conditions.
4.3 HIFI-FPC performance

As already mentioned in Section 4.2.1, in cryogenic conditions the specific heat capacity of the materials used is very low. Therefore, the thermal balance is easily influenced by power dissipation in the components, parasitic heat input through the harness of the test setup and radiative heat input through the windows in the cryostat vessel. Temperature measurements can be affected by radiative heat input on the temperature sensors and parasitic heat input via the wiring of the sensors.

Using adequate radiative shielding of the sensors and using baffles around the cryostat windows one can limit the influence of radiative heat input. For the wiring an optimal balance between the thermal conductance of the cabling and the heat dissipation developed in the wiring has to be found. For the HIFI-FPC test setup manganin wiring has been used. The thermal conductivity of this material is low and, although the impedance of the wiring is relatively high, the heat dissipation is limited because the currents running in the system are reasonably low. To further reduce the parasitic heat input by the wiring, heat sinks to intermediate temperature stages have been used.

4.3 HIFI-FPC performance

The final performance of the HIFI-FPC flight model has been determined in the lab before integration of the mechanism with the HIFI instrument. The test results are summarized in the third column of Table 4.1. The requirements are given in the second column of the same table. It can be seen that all performance requirements are met.

After the launch of the satellite, a health check of the HIFI-FPC has been performed in which the structural integrity and the dynamical behavior of the unit have been checked. No anomalies were found in this test. Fig. 4.15 shows the closed loop step response of the mechanism after launch.

The response of the chopper has evidently not changed as a result of the launch or because of the small differences in operating temperature (9 K lab environment w.r.t. 15 K space conditions). Therefore it has not been necessary to change the digital control parameters, a contingency that had been built into the satellite operational system.
4. Cryogenic mechatronic design of the HIFI Focal Plane Chopper

Figure 4.15: Closed loop step response of HIFI-FPC mechanism in space. Measurement performed every 3 ms.

4.4 Concluding remarks

In this chapter, thermal issues that were important for the design and development of the HIFI-FPC and which can be relevant for the development of future mechatronic systems in cryogenic conditions have been discussed.

In general, the choice of material is critical and the use of lubricants should be avoided if possible. Material properties can vary considerably in the temperature range from ambient to cryogenic temperatures. The control strategy has to be insensitive to changes in the physical parameters as a result of thermal variations in the system.

The HIFI-FPC is performing well within the defined requirements for the mechanism. However, with respect to the settling time, the margins between the performance and the requirements are only small.

The general demand for more stringent performance requirements and in most cases the increase in complexity of chopper mechanisms, ask for further optimization of the mechatronic design of the instruments where all aspects of the system should be developed in parallel in an integrated design approach [2, 68].

It should be clear that thermal issues play an important role in the final performance of the mechanism and should be taken into account during the design and test program of the instrument.

Considering the different building blocks of mechatronics (mechanics, electronics, computer systems and control) and the discussed hardware limitations which are imposed by the cryogenic environment, we believe that the biggest progress can be made by the application and further development of advanced control strategies for these mechanisms.