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# Mechanical Design and Qualification of IR Filter Mounts and Filter Wheel of INSAT-3D Sounder for Low Temperature

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## ABSTRACT

Next generation Indian Meteorological Satellite will carry Sounder instrument having subsystem of filter wheel measuring Ø260mm and carrying 18 filters arranged in three concentric rings. These filters made from Germanium, are used to separate spectral channels in IR band. Filter wheel is required to be cooled to 214K and rotated at 600 rpm.

This Paper discusses the challenges faced in mechanical design of the filter wheel, mainly filter mount design to protect brittle germanium filters from failure under stresses due to very low temperature, compactness of the wheel and casings for improved thermal efficiency, survival under vibration loads and material selection to keep it lighter in weight. Properties of Titanium, Kovar, Invar and Aluminium materials are considered for design.

The mount has been designed to accommodate both thermal and dynamic loadings without introducing significant aberrations into the optics or incurring permanent alignment shifts. Detailed finite element analysis of mounts was carried out for stress verification.

Results of the qualification tests are discussed for given temperature range of 100K and vibration loads of 12g in Sine and 11.8$g_{rms}$ in Random at mount level. Results of the filter wheel qualification as mounted in Electro Optics Module (EOM) are also presented.

## 1. OVERVIEW

INSAT-3D is a dedicated meteorological Indian Satellite with state of art payloads viz., Imager with enhanced capabilities and new instrument Sounder which will sense the parameters for atmospheric vertical temperature and moisture profiles, cloud height, surface temperature and ozone distribution. Sounder consists of 18 Infra Red channels, 7 in LWIR, 6 in SWIR and 5 in MWIR bands, as shown in Fig.1. Bidirectional scanning mirror reflects incoming radiation to the telescope where IR beams are separated by beam splitters and they pass through three concentric rings of a rotating cold filter wheel maintained at a constant low temperature of about 214K. Filter wheel is rotated in synchronization with the scanning mirror at 600rpm to acquire the image.

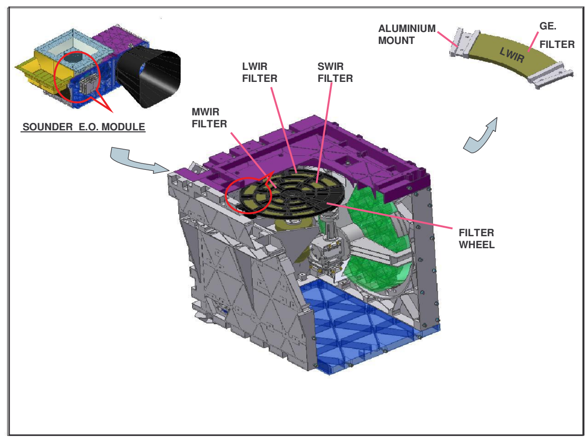



Fig.1 Filter Wheel Configuration and Filter Mount

Filter wheel, which inserts selected filters into the optical path of the detector assembly provides the IR spectral definition. The filters are arranged in three spectral bands on the wheel. The Wheel is a Ø260mm aluminum stiffened disk containing 18 filter windows of germanium substrates.

This paper deals with the mechanical design challenges faced in realization of their filter mounts and filter wheel.

## 2. MECHANICAL DESIGN OBJECTIVES

- Stress on germanium filters should be well within yield stress limit under given force conditions. Filter wheel will experience mainly thermal force, centrifugal force and vibration force.

Thermal force: Since filters are to be fixed at laboratory temperature of 298K and the wheel to operate at 214K, thermal contraction of filters and mounts will take place for this differential of 84K. This will be a prime criterion in mounting provision so as to minimize the stressing of germanium filters under compression force generated due to very high temperature difference.

Centrifugal Force: Due to wheel operating speed of 600 rpm, each filter will experience the centrifugal force, throughout its service life. Any misalignment under this force should be limited by proper mounting provision.

Vibration forces: These forces will be experienced during launch and the design should take care that loosening does not occur under these forces.

- Filter wheel to host 18 filters in Ø260mm, as shown in Fig.2. Design should be stiff and compact despite through cuts for transmission in 70% of the wheel membrane area.

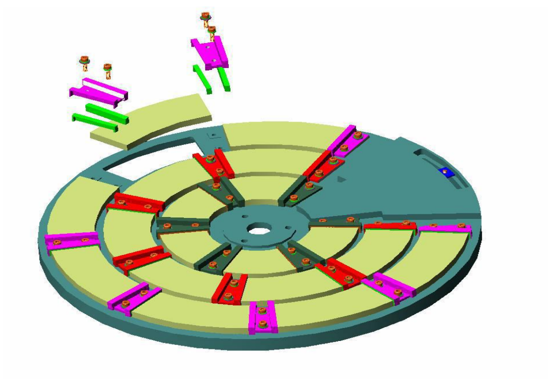


Fig.2. Filter wheel assembly

- Wheel with total germanium mass of 0.7 kg, will be mounted on 75mm long hollow shaft of Ø20 X Ø16 mm. Wheel assembly should be light in weight due to cantilever type mounting.
- Alignment of all filters should be within 5 arc-minutes.
- Assembly of each filter should be detachable from wheel, to facilitate replacement of filter in case of damage or under performance.
- All materials should be having space heritage to demonstrate long term stability especially under low temperature.

## 3. MATERIAL SELECTION

**Filter material:** Filters are made from Germanium having Coefficient of Thermal Expansion (CTE) of 6 ppm/K. This material is used for its good transmission properties in IR band.

**Filter wheel material:** Four candidate materials – Aluminium, Kovar, Invar and Titanium were considered, keeping above objectives in focus.

**CTE comparison:**
Due to large temperature change in orbit and during testing from the mounting condition, it is advisable to use the material having CTE closer to that of germanium. This if possible, can eliminate the requirement of intermediate mounts and filters can directly be fixed onto the wheel. Titanium and kovar has CTE of 8.8 and 5 ppm/°C respectively and is quite closer to germanium CTE as compared to aluminum and invar with 23 and 1 ppm/°C, respectively.

**Density comparison:**
As shown in configuration, the filter wheel mass is coming at the top of the 75 mm long shaft and will vibrate in the cantilever mode. Due to this, it is also important to reduce mass of the wheel to improve stiffness. Aluminum with its density of 2.7 $g/cc^3$ is the lighter most as compared to kovar and invar with 8.13 $g/cc^3$ and titanium with 4.4 $g/cc^3$. Table 1 gives comparison of filter wheel mass if made from different materials. Here, filter mass of 0.7 kg is included in the total mass.

Table 1

| Filter wheel material | Mass of Filter Wheel |
|---|---|
| Aluminium | 1.2 kg |
| Titanium | 1.5 kg |
| Invar | 2.1 kg |
| Kovar | 2.1 kg |

**Conductivity comparison:**
Filter wheel material is required to have better thermal conductivity, due to its low temperature operation, in controlled manner. Aluminum is having conductivity of 160 W/m–K which is 22 times better compared to titanium (K= 7.3 W/m-K) and 16 times better as compared to kovar and invar (K= 10 W/m-K).

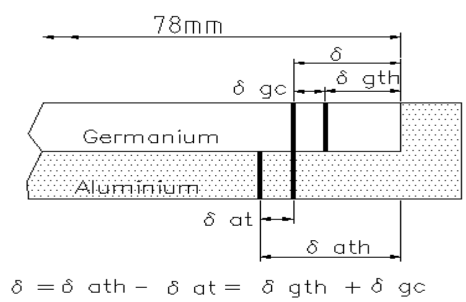
**Space Heritage:**
Aluminium and invar have demonstrated very good long term dimensional stability in all the ISRO meteorological and remote sensing missions, whereas kovar and titanium are not used in EOMs. Aluminium 6061-T651 is the most commonly used material for its long term dimensional stability in optical sensors.

Considering the above analysis, Aluminum was selected as the filter wheel material.

## 4. FORCE ANALYSIS OF MOUNT

Filter mount design is governed by three forces as explained below.

**Thermal Force:**
Due to large CTE difference between aluminium wheel and germanium filter, it will not be possible to mount the filters directly on to the wheel. As per analysis shown in Fig.3, the worst case bimetallic stresses that can come due to direct mounting are worked out as shown here.




$\delta_{gth}$ = *Thermal Contraction of Germanium in free condition*
$\delta_{ath}$ = *Thermal Contraction of Aluminium in free condition*
$\delta_{gc}$ = *Germanium compression under force P*
$\delta_{at}$ = *Aluminium expansion under force P*

Fig. 3 Behaviour under bimetallic force

Filter from the outer most ring is considered for analysis being the longest among three types.

- Its longer dimension is taken linearly as L = 78 mm
- $\Delta t$ = Temperature range of 100K
- P = Static force acting on the interface
- A = Resisting area of filter =135mm$^2$
- $E_g$= Germanium Modulus of Elasticity = 8300 kg/ mm$^2$
- $E_a$ = Aluminium Modulus of Elasticity = 7000 kg/ mm$^2$

Germanium contraction being less than aluminum as shown in Eqs. 1-2, germanium will experience compressive force and aluminium will come under tension.

- $\delta_{gth} = \alpha * L * \Delta t = = 0.046$ mm (1)
- $\delta_{ath} = \alpha * L * \Delta t = = 0.179$mm (2)

Since both materials are not free in actual condition, and resultant change in length is δ, germanium will compress by amount $\delta_{gc}$ and aluminium will expand by $\delta_{at}$ causing compressive stress in germanium and tensile stress in aluminium. This static deformation will be equal to PL/AE for each material.

From above $\delta = \delta_{ath} - \delta_{at} = \delta_{gth} + \delta_{gc}$ [1] (3)
Static force on interface is P = 3521 kg
So Stress = P/A = 3521/135 = 26 kg/ mm$^2$

Compressive stress of 26 kg/mm$^2$ is more than 5 kg/mm$^2$ - yield strength of germanium. Hence direct mounting on the aluminium wheel is not possible. It is required to mount filter through filter mounts due to this. Fig. 4 shows the Finite Element Analysis (FEA) results of filter.

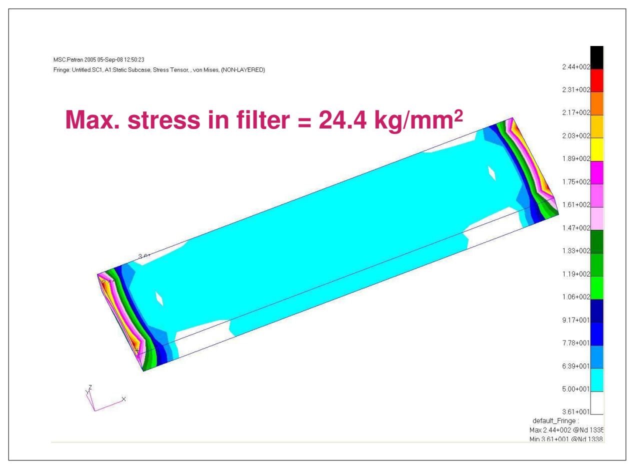



Fig. 4 FEA results of bimetallic stress on the Filter

**Centrifugal Force ($F_c$):**
Here also longest filter weighing 51 gram has been considered for centrifugal force on each filter. Weight of this filter is more than the other two types.

$$\text{Centrifugal force } F_c = \frac{W * \omega^2 * r_c}{g} \quad (4)$$

= **2.27 kg**

**Vibration Force ($F_v$):**

Dummy filter wheel was subjected to vibration to understand the behavior of the wheel. Maximum amplification near the filter was found to be 37 at resonance. Response analysis was showing amplification of 25.

Maximum g force during random vibration will be

$$3 * \sqrt{\pi/2 * fn * PSD * Q} \quad [2] \qquad (5)$$

where fn is resonance frequency.

= 5.28 kg (on each filter)

## 5. MOUNT DESIGN

Considering above force conditions, two types of mount designs were worked out.

Option:1 Soft Mount
Option:2 Flexure Mount

**Option: 1 Soft Mount**

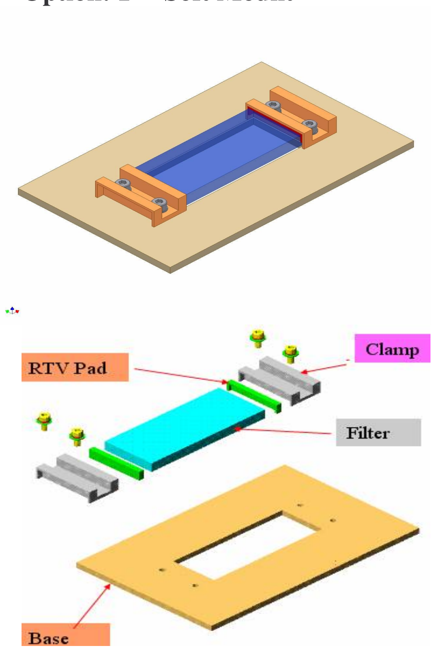



Fig.5 Assembly and Exploded Views of Soft Mount

Fig. 5 shows design of soft mount with straight filter element which was used for qualification for thermal and vibration tests. Soft mount was designed with Room Temperature Vulcaniser (RTV) pads between aluminum clamps and filters. Each filter will have two aluminum clamps with RTV pads between them, on two ends. One clamp will be shared by adjacent edges of the two consecutive filters. Aluminium clamps will be fixed to the filter wheel with two M3 screws. Fig. shows aluminium base plate, which simulates the wheel for testing purpose. Thermal mismatch will be absorbed by the RTV pads equally on both sides.

**RTV Pad design:**

A unique approach of making RTV pads by curing RTV in specially designed mould was adopted, instead of gluing with the RTV. This approach has advantage of keeping the filters free from RTV. This allows filters to be interchangeable in case of damage or under performance of the filters. Both ends of filter will be covered by the RTV pad from four sides. One side of filter will butt against the wheel, to ensure proper alignment of filters. This way effect of aluminium contraction on the filter will greatly be alleviated under thermal changes. The load–deflection curve for RTV in compression is non-linear. However non-linearity can be ignored for strains up to 10%. [3] Objective of using RTV is to absorb the differential thermal contraction between aluminium and germanium which is of the order of 0.13mm. Considering this, and area restrictions on the wheel, 1 mm thickness was planned for RTV pads.

RTV having its usability in temperature range of 93K to 473K, was selected. This has been used in various Indian space missions.

**Clamping force considerations:**

Continuous mechanical loading is required under various forces. This was achieved by fixing each clamp with two M3 screws. Here, adequate torque was required for dynamic loads to avoid loosening and filter chattering as the clamps are fixed only at the ends. At the same time, this torque should not squeeze the RTV also to a non-acceptable limit. High compression of RTV can transfer force to the filter under thermal contraction of the mount. RTV should have margin to absorb the mount contraction. But, trials showed that, there is a large RTV compression at just torque of 11.5 kg-mm. Considering the apprehension that screws can get loosened in the random vibration, if torque is reduced further, it was decided to carry out assembly by controlling deformation instead of controlling torque, where the gap was modified from 0.5 to 0.15mm, as shown in Fig.6. This way RTV compression was controlled to 0.15mm and the torque was increased to 57.5kg-mm. RTV compression beyond 0.15mm was prevented by this method. Any type of optical deformation was not observed under this clamping force. This way higher clamping force was achieved without squeezing the pad.

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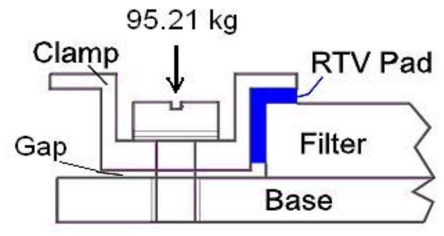


Fig.6 Soft Mount Assembly with gap

Force per screw will be, $W = T/k.D$ (6)
k= friction factor = 0.2
D = Screw diameter in mm = 3mm
W= = 96.21 kg.
This offers high margin for vibration loads.

**Option: 2 Flexure Mount**

Generally flexure mounts are used to reduce mounting and thermal stresses. [4] Flexures have advantage of flexing more and there by reducing the force on filter. It is a single piece mount having blades for filter interface and three lugs for the filter wheel interface, connected by thin frame, as shown in Fig. 7. Flexure positions are optimized on the frame, for minimum stress on filter. Here, the force P acting on filter will have relationship of, $P \alpha E I y / h^3$. E is Modulus of Elasticity, I am Moment of Inertia, y is thickness of the blade and h is the height of the blade.

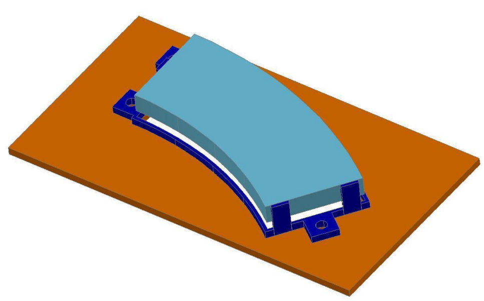

Fig. 7 Flexure Mount

Results of FEA thermal analysis for 100K temperature difference and blade height h of 15mm, are shown in Table 2. Fig. No. 8 and 9 show FEA results for aluminium mount.

Table 2

| Flexure Mount material | Stress in the mount | Stress in the filter |
|---|---|---|
| Aluminium | 25.2 $kg/mm^2$ | 20.4 $kg/mm^2$ |
| Invar | 9.46 $kg/mm^2$ | 5.76 $kg/mm^2$ |

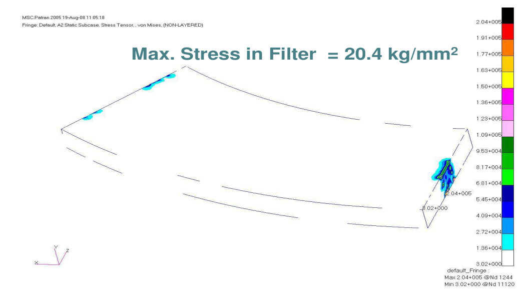


Fig. 8 FEA thermal stress results for Filter while in flexure mount

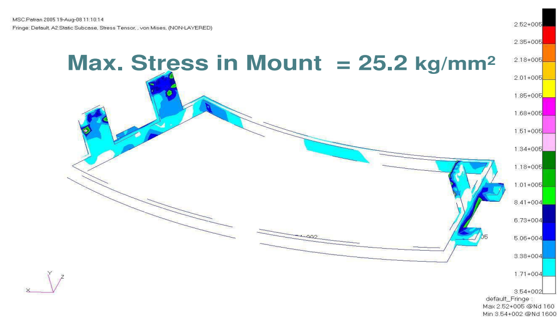


Fig. 9 FEA thermal stress results for Flexure Mount

Results show that blade height of 15mm also is not enough to lower the stresses. Further increase in height will reduce the filter stress but will increase the volume of filter wheel and casing in which wheel will rotate, causing more thermal load on the cooler attached to the casing. This in turn will need more radiator area, causing substantial cooler mass increase.

Based on these results, Soft mount was selected for mounting filters on the wheel.

## 6. FILTER WHEEL DESIGN

Filter Wheel acts as a support structure for 18 filters, and is connected to the FRP shaft. It is designed for stiffness of more than 100 Hz. This will be cooled in radiating mode by top and bottom casings, which house the wheel. Wheel should be as compact as possible to prevent thermal loss. This should not deform by more than 5 arc-minutes under thermal loads.

Eigen value analysis in Fig. 10 shows that first wheel mode with soft mount is at 134 Hz. This is bending mode for the wheel. Thermal analysis as shown in Fig. 11 gives the stress experienced by the wheel for 100K temperature range which is within the yield strength of aluminium.

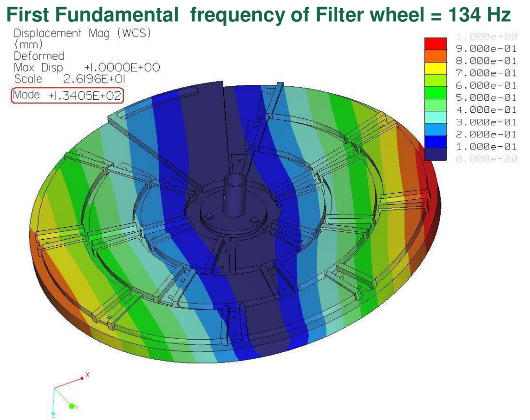


Fig. 10 Eigen value analysis of the wheel

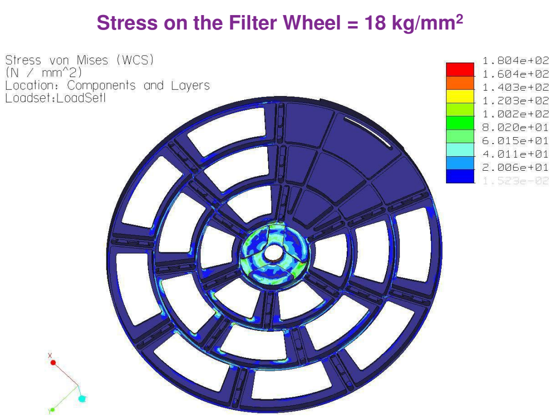


Fig. 11 Thermal stress on the wheel

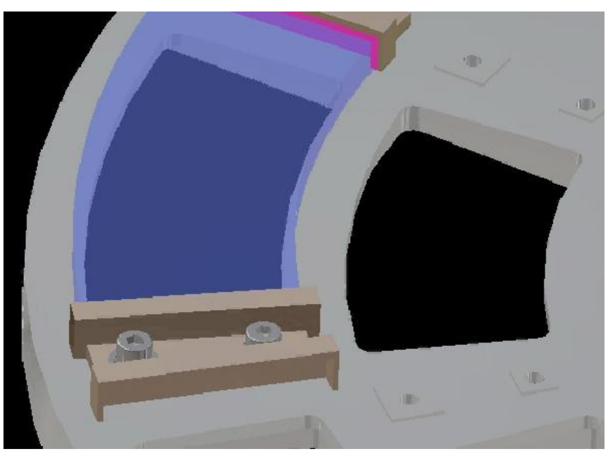

Fig. 12 Section of wheel showing buttons

## 7. REALIZATION AND QUALIFICATION

Soft mount was realized and integrated as shown in Fig.5. Component details are as under.

- 3 mm thick Aluminum 6061-T651 plate as base simulating filter wheel material
- Aluminum 6061-T651 clamps on the two ends of the germanium filter, fixed with the base
- RTV sandwiched between the filter and the clamps
- Rectangular germanium piece 80mm long x 25 mm wide x 5 mm thick.

Wheel was realized from Aluminium 6061-T651, for circular germanium filters. All 18 Filters were integrated. Wheel has 0.5 mm raised buttons coplanar within 0.05mm as interface with the mounts, as shown in Fig. 12. They ensure specified alignment of filters with reference to optical axis.

In order to validate the finalized design of Soft mount, two stage qualification was carried out, first at mount level and subsequently at wheel level. Lastly, wheel underwent qualification tests as part of integrated EOM also.

Assembly was put into the chamber and subjected to thermal excursions between 180K and 303K. Dwelling at both the extreme temperatures was done for 60 minutes. Temperature was monitored at base and filter. Five thermal cycles also were carried out. Interferometric measurements were carried out after these tests. No significant change was observed.

All 18 filters were integrated in the wheel and were also subjected to the given temperature range.

Mount was subjected to dynamic tests as per specifications given in Table 3 and 4.

Table 3

| Sine Qualification Levels for all three axis | |
|---|---|
| Frequency range in Hz | Amplitude |
| 5 - 18<br>18 - 70<br>70 - 100 | 9.2 mm DA<br>12 g<br>5 g<br>SWEEP 2 Oct/min. |

Table 4

| Random Qualification Levels for all three axis | |
|---|---|
| Frequency range in Hz | PSD |
| 20 - 100<br>100 - 700<br>700 - 2000 | +3 dB/ Oct<br>0.1 g2/hz<br>-3 dB/Oct<br>Overall grms 11.8<br>Duration 120 Secs |

Wheel as mounted in EOM shows 169 Hz as per Fig. 13. First mode of 74 Hz is shaft bending mode where filter wheel vibrates as a rigid body.

Electro Optics Module (EOM) Level Tests:

Integrated EOM was subjected to thermal vacuum tests and dynamic tests as per system level specifications, not discussed in detail here. Wheel performance at system level is verified with IR detectors and found to be satisfactory.

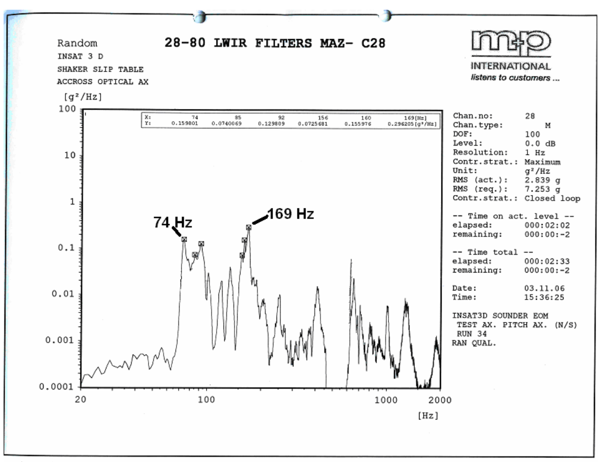


Fig. 13 Wheel modes in dynamic tests

## 8. CONCLUSIONS

- For given design objectives, Soft Mount meets all the requirements.
- No visible degradation was observed after all tests.
- No major wave front distortions are observed in interferometric measurements done after each test.
- Worst case Centrifugal force on filter will be 2.3 kg. It is not critical for the design.
- EOM level performance is validated and filter wheel has met all the design objectives.

## 9. ACKNOWLEDGEMENTS

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