EE9 FORUM INTERFEROMETER MECHANISM ASSEMBLY: DESIGN AND TESTING OF A FLIGHT-LIKE ENGINEERING MODEL

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ABSTRACT

This paper presents the design and test results of the flight-like Engineering Model (EM) of the Interferometer Mechanism Assembly (IMA) developed by OHB System AG in the frame of the FORUM (Far-infrared Outgoing Radiation Understanding and Monitoring) mission. FORUM is an ESA Earth Explorer mission aiming at measuring Earth's long-wave infrared radiation. The IMA plays a crucial role in generating interferograms, contributing significantly to the instrument's spectral performance. The paper focuses on the results of the IMA EM test campaign, covering functional, optical, micro-vibration and vibration tests.

1 INTRODUCTION

FORUM (Far-infrared Outgoing Radiation Understanding and Monitoring) is the ninth ESA Earth Explorer mission, whose main goal is to measure the long-wave infrared radiation emitted by Earth [1]. These measurements will improve the understanding of the climate system by supplying, for the first time, spectral observations of the far-infrared contribution to the Earth radiation budget.

The Interferometer Mechanism Assembly (IMA) is a key element for the mission success as it provides a major contribution to the instrument spectral performance. The main function of the IMA is to create the interferograms by splitting and recombining the incident beams, and varying the optical path difference. The FORUM IMA combines the Michelson and Mach-Zehnder interferometer designs with a dual-port double-pendulum concept. The double pendulum interferometer was invented by former Kayser-Threde (now OHB System AG) and achieved space heritage with ACE on SCISAT and GOSAT [2, 3, 4].

In the B1 phase of the project, multiple breadboarding and testing activities were carried out to raise the Technology Readiness Level (TRL) and to prove the IMA technology. With this purpose, a flight-like engineering model (EM) of the IMA was developed and tested by OHB System AG. This paper presents the design of the FORUM IMA EM, and the results of the tests which are relevant to verify the mechanism design.

2 DESIGN DESCRIPTION

The main function of the IMA is to create interferograms. This is achieved by splitting and recombining the incident beams. The optical path difference (OPD) between the beams is varied to scan the interferogram. The interfering beams are directed to two output ports: named balanced and unbalanced.

The interferometer concept is a combination of a Michelson and a Mach-Zehnder interferometer. It benefits from the compact and simple design of a Michelson interferometer and from separated and accessible 4 beam splitter ports of a Mach-Zehnder design. It is implemented as double pendulum, where the simultaneous motion of the corner cubes allows for a mechanically compact design while maintaining the required OPD.

The IMA accomplishes its functions together with other sub-systems which are part of the interferometer top level assembly:

- the Metrology System (MS) which together with the optical components of the IMA is responsible for the position measurement. The MS itself consists of the Laser Unit (LAU), which is creating the laser beam for the position measurement, and the Receiver Unit (REU), which senses the interfered metrology laser beam and forwards this signal to the Interferometer Control Electronics for the control of the pendulum.
- The Interferometer Control Electronics (ICE), which is responsible for controlling the power provision of the complete interferometer assembly.

The IMA provides the main structure to the interferometer assembly and accommodates all the parts needed to perform the movement and generate the interferometry. The IMA and its main components are shown in Figure 2-1

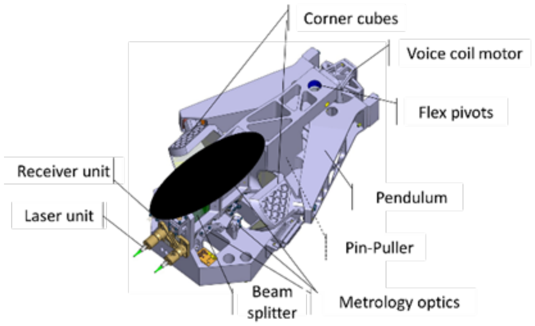


Figure 2-1 IMA with its main components.

The IMA consists of the following main parts:

- **IMA structure:**
  It accommodates all IMA parts and provides the connection to the FORUM optical bench. It is also responsible for the fixation and translational movement of the beam splitter during alignment.
- **Interferometer arm (pendulum)**
  The pendulum has the main task to hold the corner cubes and to move them in the needed range. In addition, during launch the pendulum provides an interface to the pin of the pin puller. The pendulum is equipped with End Stop interfaces to limit its range of motion.
- **Two corner cubes (CCs)**
  They are retroreflectors consisting of three mutually perpendicular, intersecting flat surfaces, which reflects waves back directly towards the source, but translated. They are mounted to the interferometer arm.
- **Voice coil motor (VCM)**
  The VCM has the task to provide the rotation needed for the movement of the corner cubes which creates the needed OPD.
- **Flex pivots**
  The flex pivots are acting like a bearing and provide the rotational degree of freedom for the movement of the pendulum/corner cubes. Two of them are used to give the pendulum enough stability.
- **Beam splitter (BS) assembly with two beam splitters**
  It includes the optical components used to split and recombine the optical beams (science beam and metrology beam) and the mechanical features used to fix and align them.
- **Metrology optics**
  It consists of the metrology mirrors which reflect the laser beam along the metrology path towards the receiver unit where it is processed to derive the measurement of the pendulum position which is feedbacked in the mechanism control electronics.
- **Pin puller (Launch Lock)**
  The pin puller has the function to lock the mechanism during the launch phase and release it during the commissioning phase for the start of operation of the instrument. For ground operations, the reset of the pin puller is performed manually.

In the B1 phase of the project, a flight-like EM of the IMA has been developed and tested to raise the TRL and to prove the IMA technology. The EM of the IMA is representative in form, fit and function of the mechanism flight design. The IMA EM was equipped and tested with COTS parts representative of the functionalities of the other parts of the interferometer assembly, namely the LAU, the REU and the ICE.
The purpose of the IMA EM was to implement the lessons learnt from a previous breadboarding phase regarding the design and the integration of the IMA, as well as the way to perform some tests such as optical performance test and functional test.
The charts in Figure 2-2 and Figure 2-3 show the general assembly, integration and test (AIT) flow of the IMA EM. All AIT activities were carried out in ISO8 environmental conditions. After its testing campaign, the IMA EM will be integrated into the Instrument Development Model (IDEM) to perform performance and synchronization tests with the main components of the instrument assembled.

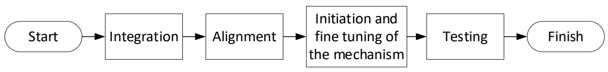


Figure 2-2 : IMA EM general AIT flow.

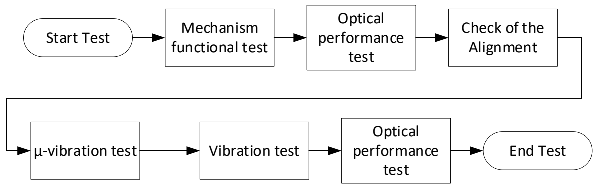


Figure 2-3 IMA EM test flow.

The test performed on the IMA EM are the following:

- Mechanism functional test
- Optical performance test
- Micro-vibration test
- Vibration test

The test flow also includes the alignment check which consists in a characterization with a coordinate measuring machine (CMM) of the following components:

- Corner Cubes
- Beam Splitter
- Metrology Components

Such measurements are performed the first time at the end of the integration phase, and are assumed to be the basis for the comparison of future alignment checks.

3 TEST RESULTS

The following sections describe the tests performed during the IMA EM testing phase and present the results achieved. The focus is on the tests whose results are important to prove the mechanism design and performance. For this reason, the verification of the mechanism results contributing to the optical performance are presented, but the optical test is left out of the scope of this paper.

3.1 Functional Test

The functional test aimed at assessing and verifying the functionality of the mechanism. The mechanism was powered up and the following parameters were checked:

- Pendulum Movement
- Hysteresis of flex pivots
- Travel Range
- Speed Stability

The speed stability is the main mechanism performance requirement of the IMA. It is a key parameter for the optical functions of the interferometer.
The requirements to be verified during the functional test are outlined in Figure 3-1.

ID	Req. Summary
[MV-REQ1]	The moving range of the corner cubes shall be bigger than ± 4.8 mm from the mechanical neutral position of the pendulum.
[MV -REQ2]	After a pendulum deflection to any allowed position, the mechanism shall return to the neutral position within an accuracy of ±0.02mm. (Flex-Pivot Hysteresis).
[MV -REQ3]	The nominal speed-stabilized, quasi-linear movement of the double pendulum shall be ±3.5 mm from its ZPD position.
[MV -REQ4]	The nominal speed-stabilized, quasi-linear movement shall be covered within 14.0 seconds.
[MV -REQ5]	The movement direction shall be changed within 0.8 seconds.
[MV -REQ6]	Speed variation during the speed stabilized quasi-linear movement shall be lower than 2% RMS of the nominal speed.
[MV -REQ7]	Speed variation during the speed stabilized quasi-linear movement shall be lower than 4.8% RMS of the nominal speed during the micro-vibration test.

Figure 3-1 Requirements to be verified during the functional test of the IMA EM.

The functional test was performed also directly before, during or after other tests (e.g. optical test, micro-vibration test, vibration test). In this case, the parameters to be checked during the functional test were limited depending on the goal of the test. This section addresses the results achieved in the first functional test (FT1), where all parameters were verified.

3.1.1 Pendulum movement and speed stability

The capability of the pendulum to follow the required motion profile and the achieved speed stability were verified in a combined test run in which the pendulum was commanded to move of ± 3.5 mm across the zero-path-difference (ZPD) position following the planned speed profile (Figure 3-2).

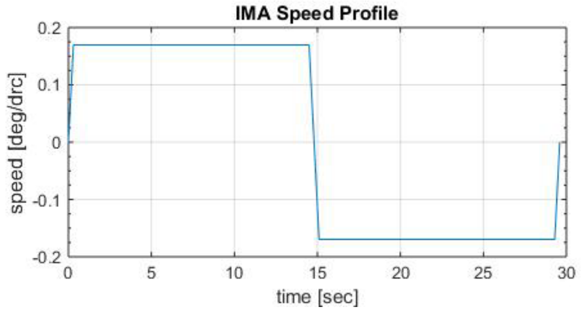


Figure 3-2 Planned speed profile of the IMA EM.

The commanded position profile of the pendulum consists of the following steps:

Initialization

The pendulum is commanded to move to the ZPD position which is then set as null position for the controller and then to one extreme position from which the pendulum cycling can start.

Pendulum cycling

The cycling motion of the pendulum as per nominal IMA speed profile is executed. During the test two full pendulum cycles (CW and CCW) were commanded and driven.

Switch-off

After the last cycle, the pendulum is commanded to move back to the ZPD and motor is switched-off.

The motion profile commanded and driven during the functional test is shown in Figure 3-3. As it can be seen in the figure, the actual pendulum position overlaps the reference position over the complete commanded motion. The offset occurring before the start of the test and after switch-off can be explained as follows:

- The offset between reference and actual position before the start of the test is removed after controller initialization.
- At the end of the motion profile the pendulum is commanded to move to the set null position for the controller, which is the ZPD. After switch-off, the pendulum moves back to and oscillates around the mechanical neutral position.

During the test the pendulum moved over a distance of ±37417 counts (3,63mm) which includes the distance travelled in the speed stabilized travel range of ±36127 counts (± 3.5 mm) and the distance travelled during the change of motion direction. This proves the verification of FUN-REQ3.

The metrology signal of the IMA was recorded during the test with a dedicated EGSE. The analysis of the metrology signal provides the information of the speed of the pendulum during the FT1. The speed of the pendulum during the FT1 is shown in Figure 3-4 .

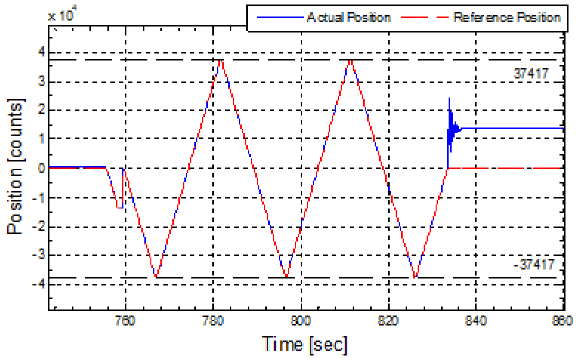


Figure 3-3 Motion profile driven during the test (pendulum angular position).

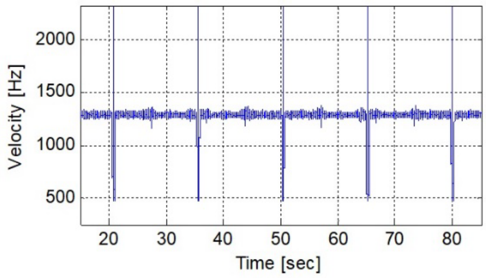
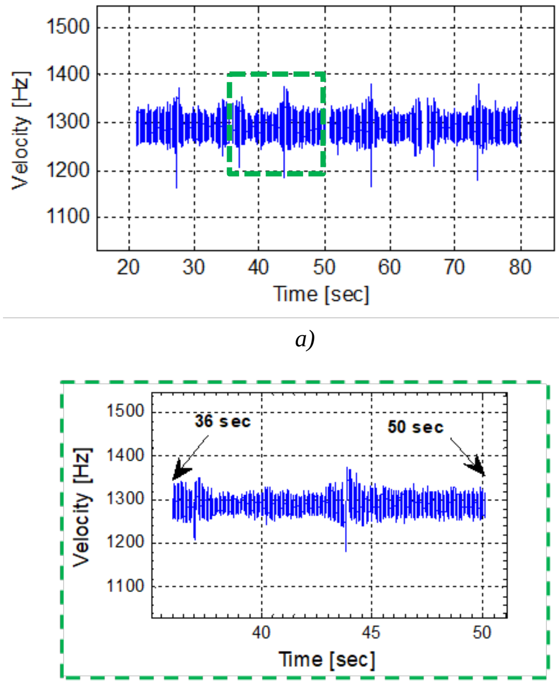


Figure 3-4 Speed of the pendulum derived from the metrology signal during FT1.

Two main pendulum motion phases can be distinguished in the speed profile:

- Speed stabilized ranges (Figure 3-5): in those phases the pendulum moves with constant speed for 14 sec. This verifies FUN-REQ4.
- Change of direction (Figure 3-6): in those phases the direction of the pendulum motion changes in < 0.8 sec. This verifies FUN-REQ5.



b)

Figure 3-5 Speed stabilized ranges of the pendulum motion during the FT1 (a). In b) the duration of one speed stabilized range is shown.

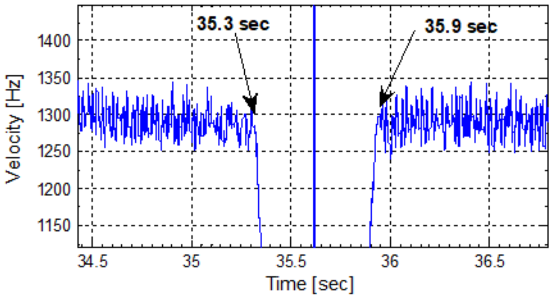


Figure 3-6 Change of direction of the pendulum motion.

The analysis of the speed during the speed stabilized ranges provides an estimation of the speed stability. During the FT1 four speed stabilized ranges were driven and analyzed. The standard deviation of the speed for each stabilized range was computed and proved to be lower than 2% as sown in Figure 3-7. The maximum standard value is 1.35%, while the average value is 1.33%. This verifies the FUN-REQ6.

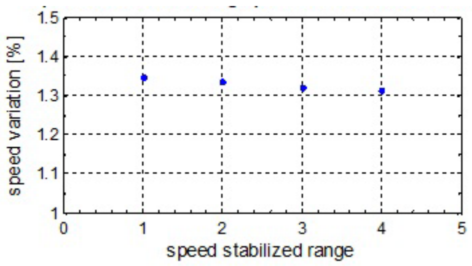


Figure 3-7: Speed variation during speed stabilized ranges.

3.1.2 Motion range and flex-pivot hysteresis test results

The verification of the motion range and of the flex-pivot hysteresis was verified in a combined test. The test setup is shown in Figure 3-8.
The measurement device for the motion range of the IMA EM pendulum is the sensor KEYENCE IL-030 (Repeatability 1 µm).

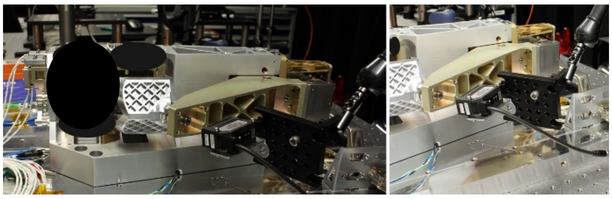


Figure 3-8: Test setup of motion range analysis

The sequence of steps performed during the test was:

1. the laser sensor was zeroed before the start of the test;
2. the pendulum was driven to a certain commanded position with the voice coil actuator;
3. the position of the pendulum at the commanded position was recorded;
4. the VCM was switched off;
5. the position of the pendulum was recorded.

The test results are presented in Figure 3-9 and confirm compliance to FUN-REQ1 and FUN-REQ2.

Commanded Distance [mm]	Direction	Measured Distance [mm]	Position after Switch-off [mm]	Position Stability [µm]
-1,800	CW	-1,789	0,000	±1
+3,000	CCW	3,019	0,001	±1
-5,000	CW	-4,973	0,000	±1
+5,000	CCW	5,021	0,002	±1

Figure 3-9 Commanded and measured distance of the IA EM pendulum.

3.2 Micro-vibration test

The micro-vibration test was performed to characterize the micro-vibration performance of the IMA in terms of:

- beam splitter tilt;
- corner cubes vertical relative displacements;
- speed stability under micro-vibration.

The requirements to be verified with the micro-vibration test are listed in Figure 3-10.

ID	Req. Summary
MV-REQ 1	Vertical relative displacement (vs frequency) of corner cubes shall be according to Figure 3-11.
MV- REQ 2	Tilt (vs frequency) of beam splitters shall be according to Figure 3-11.
MV- REQ 3	Speed stability requirement under MV as per FUN-REQ7 (Figure 3-1).

Figure 3-10 Requirements to be verified during the micro-vibration test of the IMA EM.

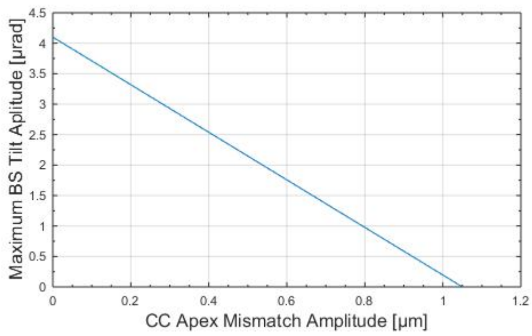


Figure 3-11: Maximum BS tilt allowed for a given CC vertical relative displacement. BS tilt and CC vertical displacement shall not breach the highlighted blue threshold.

The micro-vibration test configuration is shown in Figure 3-12. During the test, the test article was mounted on the micro-vibration test adapter, which was attached to the isolation system, which was mounted on the optical table. The external input loads were applied at the excitation points through mini shakers.

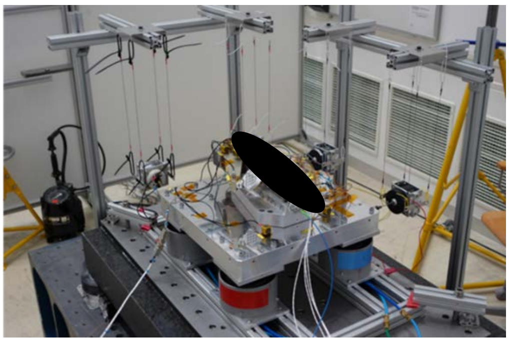
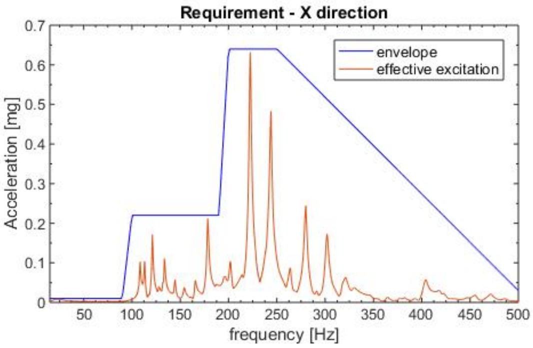
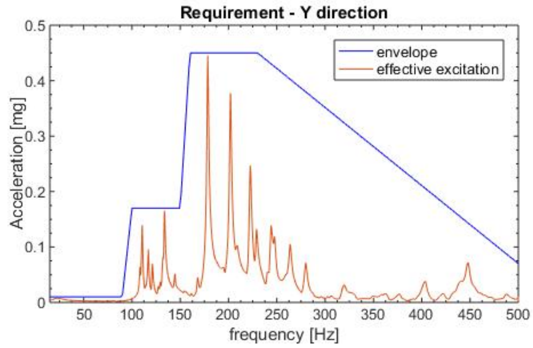


Figure 3-12 Test setup for the micro-vibration test performed at IABG (X and Y axes).

Before any test or measurement was conducted the air condition system was switched-off, the background noise was checked, and the speed stability of the IMA EM recorded.
The characterization of the performance under micro-vibration was done at three different levels applied during the test (i.e. sine-sweeps at 0.5 mg, 1 mg, 10mg). The three levels were applied to prove linearity of the transfer function. During the test, the speed stability test was also performed.
The results obtained during the sine-sweeps tests were used to derive analytically the performance under applicable micro-vibration spectra (Figure 3-13).



a)



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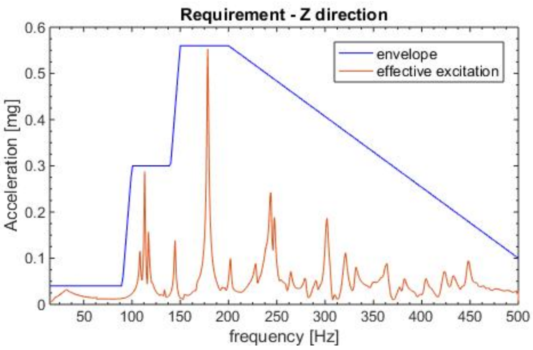
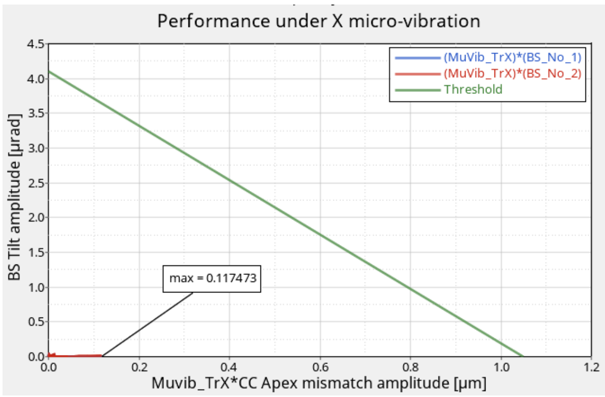


c)

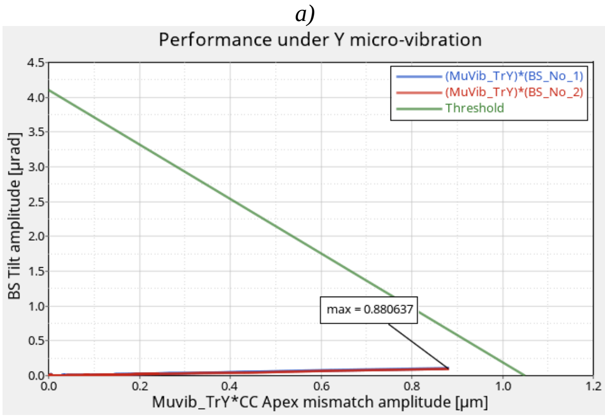
Figure 3-13 Micro-vibration spectra applicable to the IMA in x (a), y (b) and z (c) directions. The in-plane directions are x and y.

3.2.1 Beam splitter tilt and corner cubes relative vertical displacement compared to the threshold

The CC and BS data measured during the sine-sweeps at 1 mg level were scaled to the level applicable to the IMA (Figure 3-13) to derive the performance under applicable micro-vibration spectra and verify the requirements MV-REQ1 and MV-REQ2.
The results obtained are shown in Figure 3-14. They are below the specified threshold for all axes.



a)



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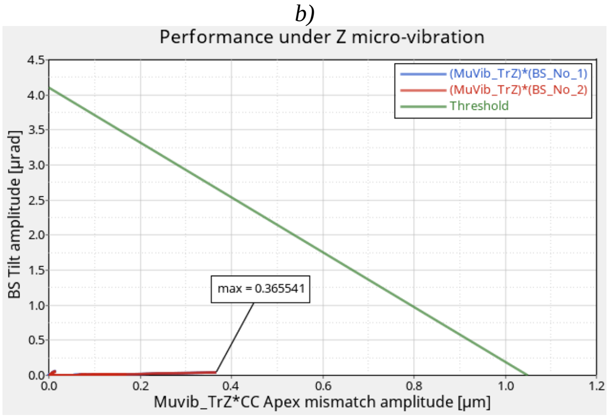
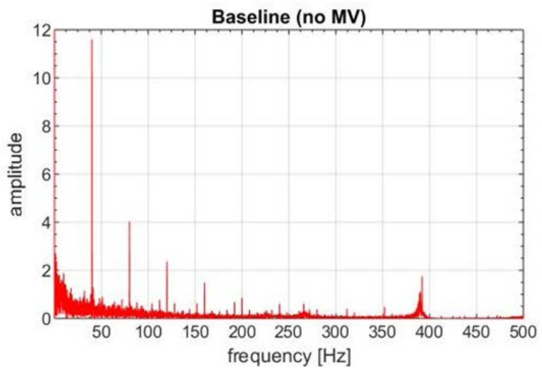


c)

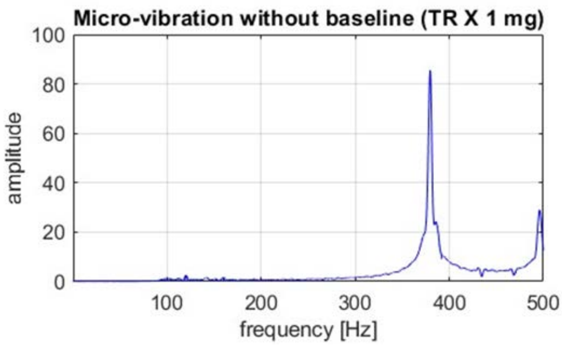
Figure 3-14 BS tilt vs CC vertical relative displacement under the applicable MV levels.

3.2.2 Speed stability under micro-vibration

To verify the speed stability performance (MV-REQ3), the spectral response of the speed fluctuations under the applicable micro-vibration spectra was reconstructed based on the results obtained during the sweep excitations at 1 mg. For this analysis the effective micro-vibration profile was considered (Figure 3-13).
The reconstructed spectral response of the speed fluctuations consists of two parts: the “baseline”, which is independent from the applied excitation, and the “MV contribution”, which is the dependent on the applied micro-vibration spectra (Figure 3-15).



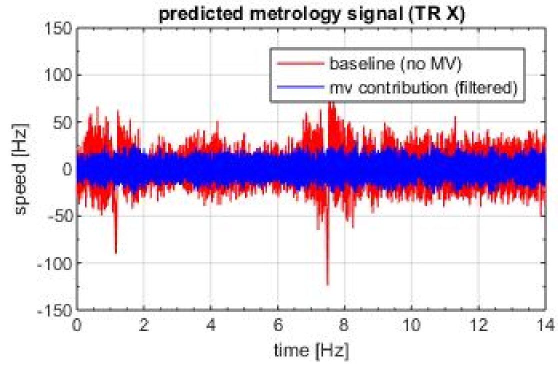
a)



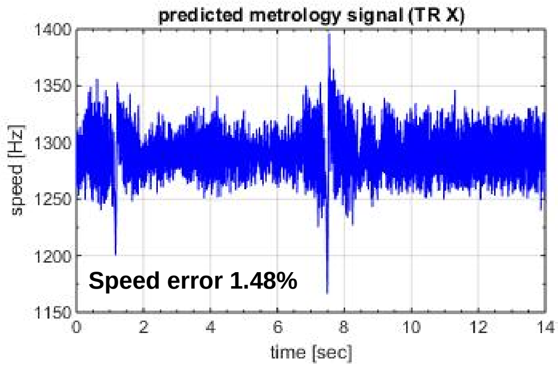
b)

Figure 3-15 The reconstructed spectral response can be seen as a combination of one part which is independent from the excitation (i.e. baseline (a)) and of one part which is dependent on the micro-vibration spectra (b). In this figure the results for the x axis only are shown.

From the reconstructed spectral response, the resulting speed and correspondent speed fluctuations were derived (Figure 3-16). The speed fluctuations are the sum of the two contributors: the baseline, which is independent from the excitation applied, and the part dependent on the micro-vibration. The speed fluctuation of the reconstructed signal is for all axes below 4.8%, which proves compliance to the MV-REQ3.



a)



b)

Figure 3-16 Reconstructed speed variation under micro-vibration. In this figure the results for the x axis only are shown.

3.3 Vibration Test

The mechanical vibration test was performed to obtain relevant information with respect to the mechanical verification of the IMA, and to assesses the compatibility of the mechanism to the launch loads. In particular, the test objectives were:

- to confirm structural verification of the IMA EM when subjected to sine vibration;
- to confirm structural verification of the IMA EM when subjected to random vibration;
- to confirm optical stability under the aforementioned structural loads;
- to provide data that will be used for correlation of the structural mathematical model.

The requirements to be verified with the vibration test are listed in Figure 3-17.

ID	Req. Summary
[VIB-REQ1]	The IA EM shall meet all functional, performance and operational requirements following the exposure to the sine vibration qualification environment as shown in Table 3-1.
[VIB-REQ2]	The IA EM shall meet all functional, performance and operational requirements following exposure to the random vibration qualification environment as shown in Table 3-2.
[VIB-REQ3]	The Interferometer Mechanism Assembly (IMA) shall have its first natural frequency higher than or equal to 170 Hz when mounted on an infinitely rigid plate.

Figure 3-17 Requirements to be verified during the vibration test of the IMA EM.

Table 3-1: Sine vibration input load

Min. frequency [Hz]	Max. frequency [Hz]	Load
5	29,07	10 mm
29,07	155	34 g

Table 3-2: Random vibration load

Frequency [Hz]	PSD [g²/Hz]	Slope [dB/oct]
20	0,017	*
100	0,250	5
400	0,250	0
2 000	0,017	-5
1σ RMS acceleration [g_{RMS}]		13,5
3σ RMS acceleration [g_{RMS}]		40,6

During the test, the test article was mounted on the vibration test adapter, which was attached to the shaker in a position corresponding to the tested vibration axis. The vibration test was executed for each axis separately.

During test, the IMA EM was in launch configuration with the pin puller engaged. Before and after each vibration level was applied by the shaker, a resonance search was run to ensure the stability of the eigenfrequencies of the test article. Before and after the vibration test, the functional test of the mechanism was run to check the pendulum movement, the range of motion and pendulum hysteresis.

The vibration test was successful for all axis tested and in particular:

- sine vibration acceleration in CoG achieved;
- random Vibration notched on pendulum grms prediction;
- comparison of pre and post low-level runs shows negligible frequency shift (within tolerance);
- the functional test performed after the vibration test was successful.

After the vibration test, the alignment check at the CMM was repeated and the results showed that no movement of the main optical interfaces could be detected within the tolerances of the machine.

4 CONCLUSIONS

In this paper, the key aspects of the FORUM IMA EM design were introduced. Additionally, the main results achieved during the test campaign to prove the IMA technology were presented. In particular:

- The functional test was successfully performed and proved that the key mechanism performance can be achieved. Those include the capability to follow the required motion profile with a certain accuracy and repeatability, and the speed stability.
- The micro-vibration test allowed to characterize the IMA behaviour under micro-vibrations, and to demonstrate that the key mechanism performance are achieved also when disturbances are applied at the IMA interfaces.
- The vibration test proved that the mechanical design of the mechanism can survive the specified structural loads without damages and without degradation of the mechanism performance.

5 REFERENCES

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