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Abstract: Airborne dust monitoring is crucial to characterize Martian atmosphere' thermal structure, balance and dynamics. In order to achieve this objective, the MicroMED instrument has been selected to join the Dust Suite payload within the ExoMars 2020 mission. The particle analyzer is mainly developed to characterize the dust on Mars but, the instrument is suitable to be mounted on different landers or rovers thanks to the limited mass budget and size. In this study, design of the instrument has been reported as long as preliminary testing in representative environment of a mockup of the pumping system.

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COVER LETTER

Subject: Submission of "*MicroMED, design of a particle analyzer for Mars*" for the Special Issue 4th IEEE International Workshop on Metrology for Aerospace.

Dear Editor,

On the behalf of all the co-authors I am enclosing herewith the manuscript entitled "*MicroMED, design of a particle analyzer for Mars*", extended version of the paper "Thermo-mechanical design of a particle analyzer for Mars", published in 2017 at the 4th IEEE International Workshop on Metrology for Aerospace. The manuscript has been extended with optical layout design, description of the instrument pumping system and preliminary testing activity.

With the submission of this manuscript I would like to undertake that the above mentioned manuscript has not been published elsewhere, accepted for publication elsewhere or under editorial review for publication elsewhere; and that our Institute (Politecnico di Milano) representative is fully aware of this submission.

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My best regards,

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MicroMED, design of a particle analyzer for Mars

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Abstract

Airborne dust monitoring is crucial to characterize Martian atmosphere' thermal structure, balance and dynamics. In order to achieve this objective, the MicroMED instrument has been selected to join the Dust Suite payload within the ExoMars 2020 mission. The particle analyzer is mainly developed to characterize the dust on Mars but, the instrument is suitable to be mounted on different landers or rovers thanks to the limited mass budget and size. In this study, design of the instrument has been reported as long as preliminary testing in representative environment of a mockup of the pumping system.

Keywords

MicroMED; ExoMars 2020 mission, particle analyzer, Mars, dust.

Introduction

Airborne dust monitoring is very important for planetary climatology. Dust absorbs and scatter solar and thermal radiation, strongly modifying atmospheric thermal structure and balance. Moreover, blowing of sand and dust causes planetary surfaces shaping through the formation of sand dunes,

ripples, erosion of rocks and transport of soil particles. Martian atmosphere is characterized by regional and global dust storms that cause absorption of the incoming sunlight and consequently an intense atmospheric heating. Airborne dust is therefore a crucial climate component to be monitored. Beside dust and size distribution, knowledge of surface flux and granulometry would allow improvements of the existing Mars climate models. These are actually different observations of the dust haze from orbit but, the primary airborne dust size measurement (i.e. the one lifted from ground) has not been performed yet. This is the primary objective of MicroMED (Micro MEDUSA), miniaturized version of the instrument MEDUSA (Martian Environmental Dust Systematic Analyzer), developed for the Humboldt payload of the ExoMars mission [1]. MicroMED would allow measurement of the abundance and size distribution of dust, not in the atmospheric column, but close to the surface, where dust is lifted, allowing monitoring of the dust injection into the atmosphere. The MicroMED has been selected to be mounted on the Dust Suite onboard the ExoMars 2020, suite of five sensors devoted to the study of Aeolian processes on Mars. Beside the MicroMED, Conductivity Sensor, Impact Sensor, Electric Probes and EM-sensor are present. The MicroMED is an optical particle counter that analyzes the light scattered from single dust particles to measure their size and abundance. A proper fluid-dynamic collector [2], including a pump [3] and a sampling head, allows the sampling of Martian atmosphere with embedded dust. Captured dust grains are detected by an optical system and then ejected into the atmosphere. The work undertaken for the preliminary design of the optical bench of the instrument is described in this paper as long as the instrument pumping system. In particular, finite element models of the instrument main components have been developed to allow mass fulfillment of the design budget and provide mechanical resistance against expected mechanical environment. Finally, testing activity of a mockup of the pumping system has been reported as proof of the proposed concept in low pressure environment.

1 MicroMED feasibility design

1.1 Instrument optical layout

MicroMED instrument performs the measurement of the size of single dust grains and dust size distribution. A particle flux is created by a pumping system through a sampling volume, and laser beam light is focused in center of the sampling volume by means of an optical collimator. A collecting mirror conveys to a photodiode detector light scattered by particles flux. In order to reach the sampling volume with the laser, an optical fiber is used. This allows moving the diode laser source outside the sampling volume, and moreover, eases the instrument optical alignment. Thus, the optical system can be divided in three different sections:

- Diode laser source that feeds the optical fiber; and
- Focusing system of the light beam at the exit of the optical fiber, into a sampling volume; and
- Parabolic mirror, collecting and focusing the light, scattered by particles, onto the detector.

Moreover, in order to monitor laser diode performance that may change due to aging or exposure to radiation, an additional detector measures the signal derived from the light trap. Zemax NSC model of the instrument optical layout is shown in Figure 2.

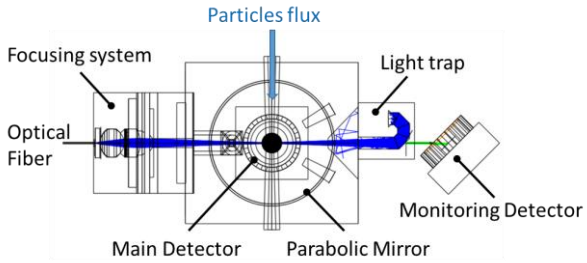

Figure 1 MicroMED optical layout (Zemax NSC model)

The optical design is suitable for 780÷940 nm band, using fused silica glasses. Ray tracing analyses have been performed to derive the efficiency of the focusing system and obtain the optical density

in the sampling volume. For the optical density computation, conservative assumption has been made, i.e. minimum fiber output power was set to 128 mW (85% of laser power).

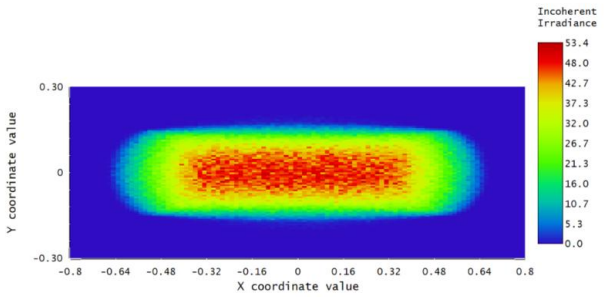

Figure 2 Beam spot onto a detector with size 1.6 mm x 600 µm, in the center of the sample volume, with efficiency of 88% , 10^6 fired rays

Figure 2 shows the shape of the spot obtained in a rectangular detector (1.6 mm x 600 µm), placed on the center of the sample volume, along the optical axis. More than the 88% of the rays emitted by the fiber are collected by the instrument detector, as preliminary validation of the optical design layout.

The design is still ongoing activity aiming to the definition of the opto-mechanical manufacturing tolerances, highlighting (if present) the influence of working temperature and pressure conditions. Moreover, analysis of the straight-light sensitivity of the MicroMED will be performed as well.

1.2 Thermo-mechanical design

1.2.1 Thermal analysis

Instruments mounted on the Dust Complex suite are expected to work within controlled temperature range between -20 °C and 40 °C [4]. Storage temperature range is between -40 °C and 50 °C. The thermal requirements are not critical for the intended application. Anyway, a thermal model of the MicroMED envelope has been developed to assess if the highest interface temperature would lead to critical temperatures on the instrument internal components, electronics in particular.

TABLE 1: MATERIALS AND OPTICAL PROPERTIES

Material	Thermal Conductivity [W/(mK)]	Emissivity
Al7075t6 (Alodine coating)	130	0.3
FR4/Cu electronics	36.6	1*

Model comprises the MicroMED envelope, the optical stage and the preliminary electronics board layout. Materials and optical properties are summarized in Table 1. Temperature constraint at 40 °C is set at the instrument base, whereas expected dissipated power is added to the instrument electronic board. Thermal resistances have been computed at the joined interfaces. Steady state analyses have been performed with radiative environment at 40 °C and 1 W dissipated power by electronics. Computed temperature distribution is provided in Figure 3.

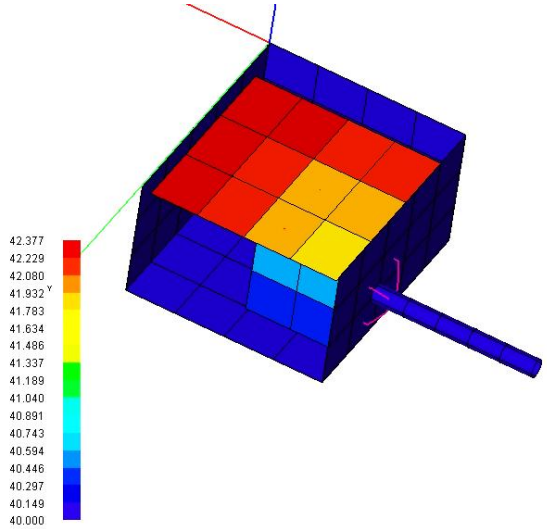

Figure 3 Temperature distribution computed with the hot case analysis. Measurement units are Celsius.

Temperature increase with respect the environment is limited to few degree Celsius. Thus, no criticalities are foreseen both for the instrument and the electronics.

1.2.2 Mechanical requirements

Several requirements must be considered within the design of the MicroMED optical bench, mainly coming from the accelerations during launch and landing operations [4]. Quasi-static acceleration

105 defined for the entry phase is somehow low, i.e. about 100 m/s^2. However, for the initial design
106 phase, a quasi-static acceleration 10 times larger was considered. This was done on the basis of
107 previous designed instruments [5-7], judged to be more conservative for the intended application.
108 Mission dynamic requirement limits the resonance frequencies to be considered in the design phase
109 at 150 Hz, value that allows a safety margin with respect to the strong sine excitation (ranging up to
110 80 Hz) during the takeoff. Size of the instrument has been locked by preliminary interaction with
111 the Roscosmos team which is manufacturing a structural model of the Exomars lander. Interface
112 drawing is shown in Figure 4. Mass budget of the MicroMED is about 500g considering a maturity
113 margin of 20%. The available mass for the optical bench (OB) and cover is 110g, including the
114 supports of the main instrument components and fasteners.

115 1.2.3 Optical bench and cover optimization

116 In order to satisfy the requirements described above, the design of the OB has been based on a
117 ribbed geometry. Geometry and OB parameters are shown in Figure 5. w_{OBv} and w_{OBh} are widths of
118 the vertical and horizontal ribs respectively, whereas th_{OB} is the OB thickness.

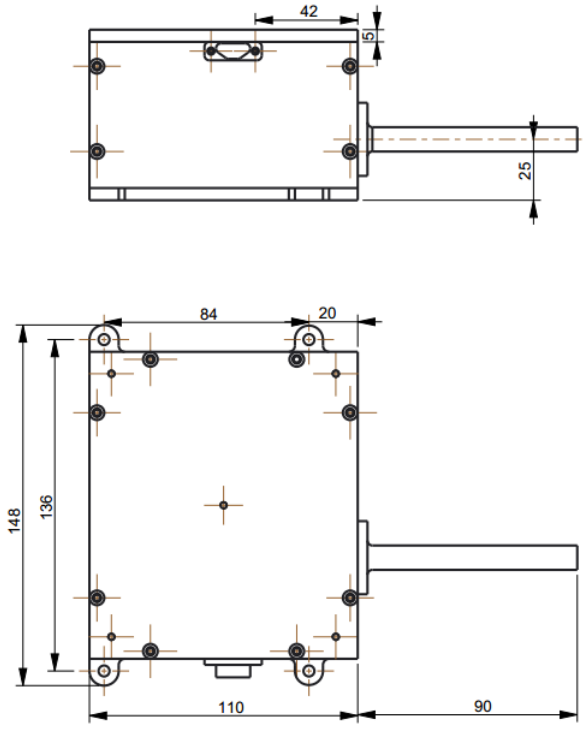

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Figure 4 MicroMED interface drawings.

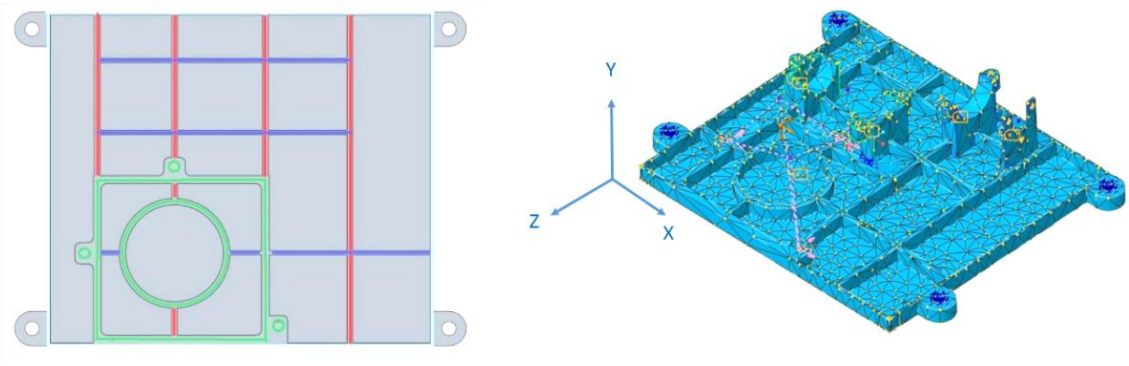

Figure 5 (Left) Configuration of the OB ribs from a top view; horizontal ribs (dark blue), vertical ribs (red), optical stage basement (green), diagonal rib (yellow), peripheral rib (light blue); (Right) OB meshed finite element model.

The largest thickness of the OB has been set to 5 mm. The ribs configuration assures both for stiffening the OB and for holding the MicroMED subassemblies, as shown in Fig. 3. Al 7075 alloy has been selected for the OB development. Mechanical properties accounted in the model are 71700 MPa (elastic modulus), 0.33 (Poisson ratio) and 2810 kg/m^3 (density).

Optimization was performed minimizing the OB mass and considering as constraints, either first natural frequency larger than 150 Hz and safety margin of 1.5 with respect the tensile yield strength (503 MPa) with quasi-static analyses.

The Finite Element (FE) model comprises 6676 solid tetrahedrons elements and 2246 nodes. OB mesh is shown in Figure 5. Table 2 summarizes range of variability of the OB parameters and optimal results.

TABLE 2: OB OPTIMIZATION PARAMETERS AND RESULTS.

Parameter	**Minimum [mm]**	**Maximum [mm]**	**Optimal [mm]**
w_{OBv}	0.5	2	0.56
w_{OBh}	0.5	2	0.95
th_{OB}	0.1	0.4	0.21

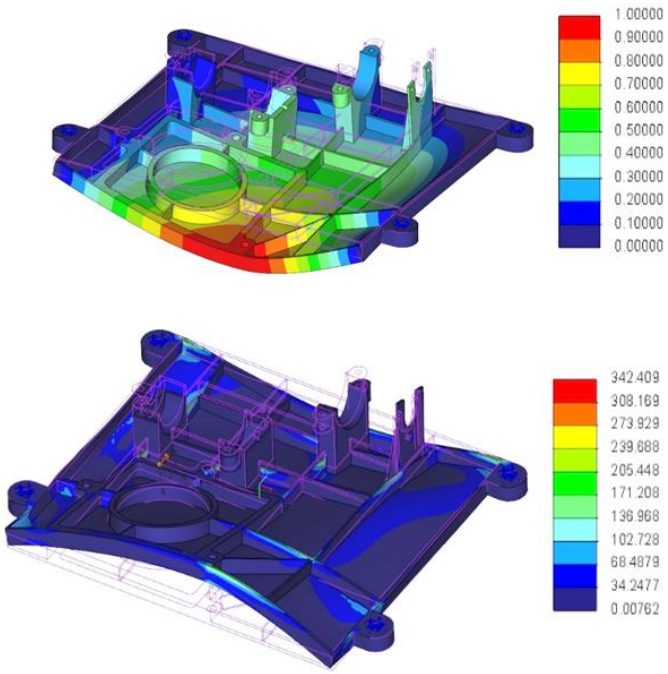

Figure 6 First mode of vibration (top) and Von Mises stress for static analysis (bottom) with optimized OB. Stress units are MPa.

The instrument components are accounted as lumped masses and the OB is connected to the ground with the interface feet at the holes surfaces. Optimization led to OB mass of about 38g. Resulting first mode of vibration (150 Hz) and VM stress along Z direction are shown in Figure 6.

Structural requirements for the cover design are the same of MicroMED OB previously defined. One main difference is that the first acceptable resonance of the structure was set to 250 Hz. This was defined in order to avoid coupling with the OB modes on which the cover is mounted. Another difference regards the mass budget. The available mass limit is 55g. Keeping into account the geometry of the OB and size constraints, cover was defined as an empty rectangular box (65 mm height) with 110 x 124 mm base. w_{Cf} , w_{Cl} , w_{Ct} are widths of the front, lateral and bottom surfaces, respectively. Similarly, th_{Cf} , th_{Cl} and th_{Ct} are cover' thicknesses of the front, lateral and bottom surfaces. The largest thickness of the cover was set to 2 mm. Two apertures were added to the case, to allow mounting of the cover without interference with the OB optical stage. Cover ribs and cover FE model are shown in Figure 7. Mesh comprises 18445 solid tetrahedrons elements and 6059

nodes. The geometry was constrained on four L profiles in the internal edges of the cover to serve as mountings with the cover. Cover material is aluminum alloy Al7075T6.

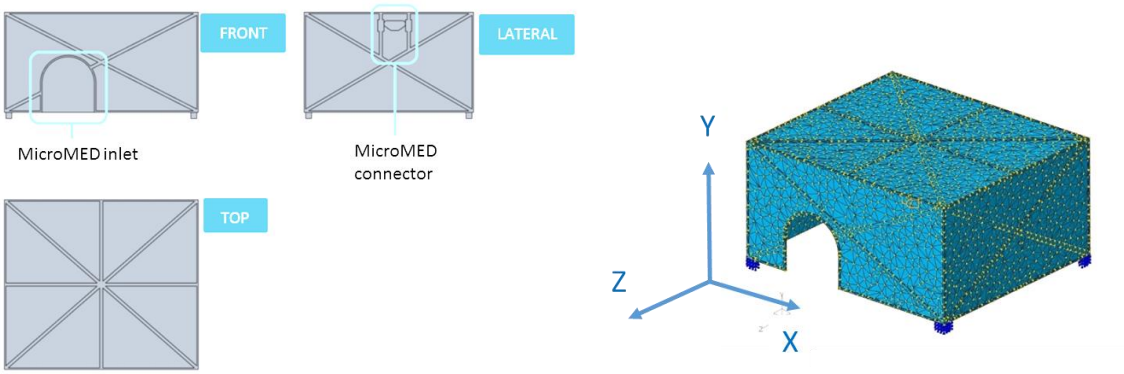

Figure 7 (Left) Configuration of the cover ribs FE model mesh and reference system; (right) cover meshed finite element model.

TABLE 3 COVER OPTIMIZATION PARAMETERS AND RESULTS.

Parameter	Minimum [mm]	Maximum [mm]	Optimal [mm]
w_{Cf}	0.5	3	1.93
w_{Ct}	0.5	3	0.66
w_{Cl}	0.5	3	2.55
th_{Cf}	0.1	1	0.2
th_{Cl}	0.1	1	0.2
th_{Ct}	0.1	1	0.2

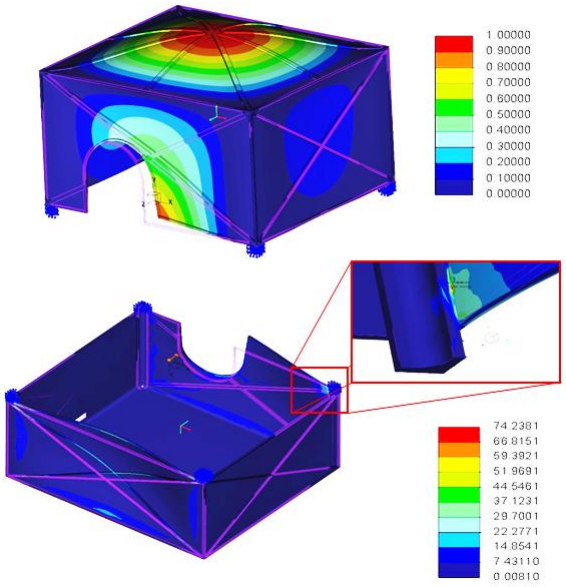

Figure 8 First mode of vibration (top) and Von Mises stress for static analysis (bottom) with optimized cover. Stress units are MPa.

Optimization was performed minimizing the cover mass and considering results of the modal and static analyses as constraints. Table 3 provides parameters range and optimization results. Cover mass after minimization was found to be 39.4g. Figure 8 shows results of the FE modal (first mode at 250 Hz) and static analysis (loading case along Z direction).

Summarizing the results of the feasibility design it can be noticed that horizontal ribs are the ones most affecting the mass reduction and modal behavior of the OB, as demonstrated by the first mode of vibration shown in Figure 6, where bending of the OB is involving the stiffness of the horizontal ribs.

A similar result was found for the cover; lateral and front ribs are the ones most affecting the modes of vibration of the cover.

The overall mass is about 78g, providing mass saving of 30% with respect to the mass budget, validating the feasibility design.

1.2.4 Pumping system

In order to achieve the dust flux through the optical head, pumping system has been designed. Gardner Denver Thomas G 6/04 EB was used as a reference for the design of the pump for Mars. Pump mass budget is constrained to 30g. The geometry and the size of the compression chamber, inlet and outlet ports maintained the same geometry of the commercial pump, but only space qualified materials have been used. Thus, the commercial pump underwent to a process of reverse engineering that allowed identifying the criticalities for space usage. These were mainly related to the outgassing of the materials, resistance against the expected mechanical loading and compliance with the thermal environment. Main changes applied to the pump scheme are shown in Figure 9 and are summarized hereafter:

- Pump rotor and shaft (5) are made of Aluminum alloy (Al7075T6) instead of the combination of steel and plastic used in the commercial pump; and

- Stator (2) is made in aluminum alloy as well; inner surface of the compression chamber is anodized to limit friction between stator and rotor and avoid soldering between stator and rotor during the lunch (due to high loading); and
- Vanes and palettes are made of Vespel SP1, which limit outgassing and provides self-lubrication; and
- Two radial bearings (4) are mounted in back to back configuration and preloaded to take out the quasi-static loading at the landing, both in axial and radial directions, to avoid the hammering due to vibration at launch, and to assure proper working during the pump activity; in the commercial pump only one radial ball bearing was present to accomplish the latter task.

Selected materials would provide the sealing of the pumping chamber at every temperature since CT allows to recover the CTE difference between the rotor, vanes, sealing elements and aluminum pump case (1).

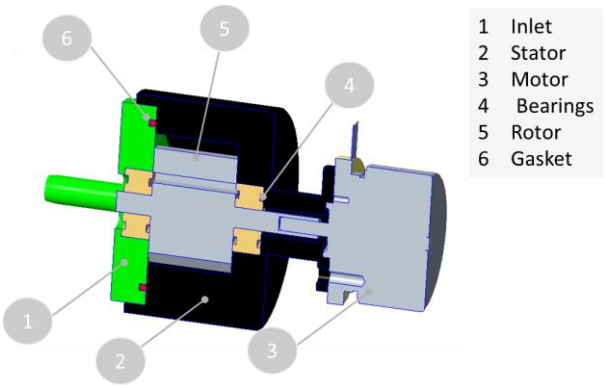

Figure 9 MicroMED pump design concept.

The final configuration is based on a Maxon EC 20 brushless motor, not qualified but similar model has been used in previous mission driller. Motor mass is 22 g mass without control electronics. The motor provides about 31 Nmm stall torque and 8.3 Nmm torque in continuous working and maximum continuous power provided by the motor 5W.

1.2.5 MicroMED envelope detailed design

Review of fundamental geometries and dimensions of the MicroMED OB and cover was performed in order to overcome technological limits related to the ribs manufacturing. Ribs layout of the MicroMED optimal model is kept as reference but the parameters were modified as show in Table 4. Change of the ribs led to mass increase of about 24% and 7.5% for the OB and cover, respectively. A FE model of the instrument was made. Meshed geometry comprises 68913 solid tetrahedrons elements and 22253 nodes.

TABLE 4 MICROMED DETAILED DESIGN.

Parameter	Detailed design value [mm]
w_{OBv}, w_{OBh}	2
th_{OB}	0.2
th_{Cf}, th_{Cl}, th_{Ct}	0.2
w_{Cf}, w_{Cl}	2
w_{Ct}	3

Modal analyses were performed on the detailed instrument model. Results are shown in Figure 10. First three modes of vibration are located on the MicroMED cover at 260, 325 and 388 Hz, respectively.

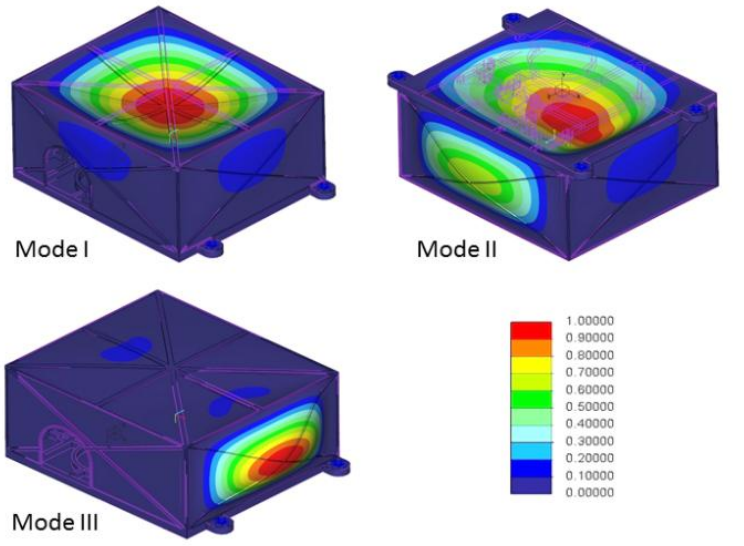

Figure 10 Results of modal analyses, with detailed MicroMED model.

Obtained stiffening is due to the increase of the ribs' width that compensate the compliance of the cover constraint, connected to the OB rather than to ground (as for optimization). Quasi static analyses were performed as well. Positive MOSs (Margin Of Safety) were obtained, thus validating the performed mechanical design for the detailed model as well.

2 Flow rate testing in low pressure condition

Testing of the pumping system in low pressure condition is required to verify the pumping performances in working condition. The pump characterization is of primary interest, because the generated flow rate affects the instrument measurement range, i.e. particle size and collecting efficiency. Preliminary fluid dynamic analyses evidenced flow rate requirement between 1.5 and 1.2 L/min with 3 mbar pressure difference to be overcome by the pumping system, with Martian atmosphere temperature between 150 and 300 K. The 3 mbar pressure difference has been identified as the best working condition to sample the particles ranging between 0.5 and 20 μm.

However, the measurement of the flow rate in low pressure condition is not an easy task since the commercially available sensors are not directly applicable to low pressure environment and must be calibrated. Thus, we designed a setup based on a bellow which acts as collecting volume of the flux at the pump outlet. Details of the setup design and validation are described in authors' manuscript under review. Sketch of the measurement setup is shown in Figure 11. A differential pressure sensor is mounted as well to measure the pressure difference change during the bellow displacement (measured by mean of laser transducer, ILD 1400 Micro-Optronic, 100 mm range). Pressure in the chamber was monitored by means of vacuum gauge (Varian PCG-750). Testing was performed with the commercial pump Gardner Denver Thomas G 6/04 EB at ambient temperature and 10 mbar pressure condition. Figure 12 shows measurement results.

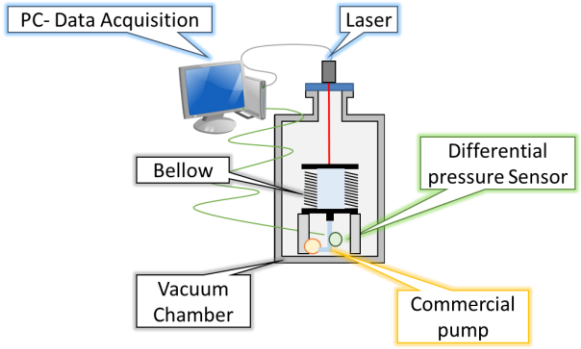

Figure 11 Scheme of the flow rate measurement setup.

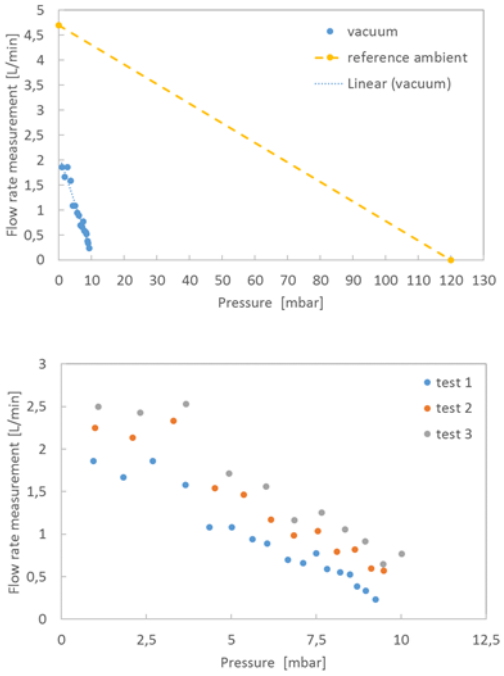

Figure 12 Flow rate measurement, commercial pump (@10mbar, ambient temperature): (Top) comparison between measured flow rate in low pressure condition and reference curve and (bottom) repeatability of the measured flow rate in low pressure condition.

The main result is that pump performances clearly worsen in low pressure condition. Measured performance provides lower flow rate and maximum working pressure is limited to 10 mbar. Repeatability assessment evidenced similar trends of the measured flow rate. Comparison of subsequent tests (number from 1 to 3) shows average increase of the flow rate. This has been endorsed to change in gas temperature (due to heating in the compression chamber) that would lead to increase of the volumetric flow rate. Anyway, the measured performance is compatible with the design requirement, validating the usage of the identified pumping system for the MicroMED development.

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3 Conclusions

The main result of this work is the assessment of the feasibility of the MicroMED instrument, a dust analyzer for Mars. The feasibility study was carried-out by means of finite element modelling, developing different FE models of the instrument' optical bench and cover. Modal and quasi-static stress analyses were performed to verify the dynamic behavior and the mechanical resistance of the main components under the design loads. The instrument geometry was optimized with the goal of minimizing the instrument overall mass. Optimization led to a mass saving of 30 % with respect to the allocated mass and the fulfilling of the design requirements about mass margins.

Beside the optimization study, a detail design of the MicroMED was performed changing ribs' dimension to values set to manufacturing limits. Modal and mechanical analyses were performed as well, comparing the results with those deriving from the optimization. An increase of the natural frequencies (lowest natural frequency is about 260 Hz) and of the overall mass was found. The latter is 1.5 % larger than the allowed maximum one (considering also the mass budget to be located for the supports of the instrument components). Thus, being the obtained overall mass within the tolerated deviation from the design requirement, the feasibility design of the MicroMED was successfully demonstrated.

Pumping system has been re-designed starting from a commercial pump preliminary selected to be used in an instrument breadboard. The re-design allows withstanding the expected mechanical loading and operate in low pressure condition. This was preliminary validated by testing of the commercial pump in representative environment. Additional testing is planned to validate the new pump design in low pressure and within expected temperature working conditions.

Figure Captions

Figure 1 MicroMED optical layout (Zemax NSC model)

Figure 2 Beam spot onto a detector with size 1.6 mm x 600 μm, in the center of the sample volume, with efficiency of 88% , 106 fired rays

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305 Figure 10 Results of modal analyses, with detailed MicroMED model.

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Table Captions

Table 1 Materials and optical properties

Table 2 OB optimization parameters and results

Table 3 Cover optimization parameters and results

Table 4 MICROMED detailed design

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