Millimetron microvibration analysis at low frequency range

A P Kravchunovsky

1Spacecraft Structure Strength Analysis and Dynamics Department, JSC Academician M F Reshetnev Information Satellite Systems, 52 Lenin Street, 662972, Zheleznogorsk, Krasnoyarsk region, Russian Federation
2Institute of Informatics and Telecommunications, Reshetnev Siberian State University of Science and Technology, 31 Krasnoyarsky Rabochy Avenue, 660037, Krasnoyarsk, Russian Federation

E-mail: kravchunovskiyap@iss-reshetnev.ru

Abstract. This paper presents the results of Millimetron microvibration analysis at low frequencies. Millimetron telescope structure behavior was studied in order to predict its central mirror response from microvibration disturbance caused by mechanical cryocoolers. The results contain the most significant values of acceleration which appeared on the mirror surface as well as rotational deflections which affect the telescope optical axis stability. To make it possible the microvibration analysis technique was derived from the theoretical aspects and other researches results. This technique was adapted to Millimetron microvibration analysis using its finite-element model and taking into account several assumptions which were also discussed at this paper.

1. Introduction

Microvibration effects and problem of their correct estimation are the key issues of modern space missions. Moreover, the microvibration problem can be actual for avia-sector if high-pointing stability is also important.

Nowadays, spacecrafts are equipped with high accuracy pointing payloads. In spite of the fact that microvibration levels have no influence on a structural stability of a spacecraft, they may cause severe disturbances of pointing performances of its sensitive payload instrument [1].

The problem of microvibration assessing, as well as almost any other technical problem, can be solved using a computational method or an experimental one, or a combination of both. The last method is the most effective one due to the opportunity to correlate the results [2]. However, the main purpose of the current research was to consider a possibility of computational microvibration analysis applying on practice. Within the scope of the underlined purpose, the microvibration analysis technique was derived from the theoretical aspects and adapted to the practical task performing. This task was to determine the line-of-sight jitter of Millimetron telescope in its flight configuration influenced by the microvibration sources - cryocoolers, within interested frequency band and to determine the main assumptions of the technique used.

The microvibration prediction has become a rather actual issue in modern science. A lot of scientists and engineers present their developments, approaches and methods in order to solve the microvibration problem and study, how it can be analyzed. For instance, the authors [3] present the methodology of microvibration prediction with a technique named in this paper as the Craig-Bampton stochastic method.
Another author [4] provides the readers with rather volume knowledge of how to account for dynamic variability in microvibration analysis of satellites.

All these materials, as well as many others [5-7], were analyzed in order to derive the technique that can be used at the specific task of the microvibration analysis for Millimetron telescope.

The latest papers [8,9] are dedicated to the analysis of complex models at high frequencies. The authors suggest methods, which require to make considerable changes in existing model or even create a new one with more suitable properties. Besides, special software is usually necessary. These papers have an idea, that element-based methods are limited in use to the low-frequency range. However, there is no detailed explanation of such limitations there. So, the main motive to start the research was how the finite-element model can be used for the microvibration analysis and what assumptions should be done.

Microvibrations are the low-level vibrations occurring during on-orbit operations of mobile or vibratory parts [1]. The acceleration magnitude of such vibrations is about $10^{-6}$–$10^{-3}$ g. These perturbations are transmitted to sensitive payload equipment through the spacecraft structure. As a result, microvibrations might cause severe disturbances of instrument pointing performances. It is strong limitation for normal functioning of such sensitive payloads as telescopes, space cameras and other equipment with high pointing stability requirements.

Considering even such a brief description of the problem, it becomes clear that assessing the microvibration levels is the actual task. This task can be implemented by carrying out an experiment or analyzing a mathematical model. In general, a combination of both is used to predict the microvibration effects. The accuracy of the test results mostly depends on the test conditions that are rather difficult to provide. When applying analytical method based on the mathematical model using, it is necessary to consider a wide spectrum of model parameters that make it a correct one.

The main feature of every mathematical model is the frequency range, on which the model provides acceptable representation. On this evidence, such methods as finite-element analysis (FEA) or statistical energy analysis (SEA) and their variations are used. These two methods are widely used to predict dynamic responses [3]. Each of them has their assumptions. At low frequency, up to several hundred Hertz, where a dense mesh is not required, the finite-element approach is representative enough [1]. At mid- and high frequency ranges it is recommended to use the energy approach because the behavior of real structures assumes more nondeterministic characteristics [3]. In this case, the modal density is sufficient to justify the using of SEA methods [1].

For such finite-element models (FEM) as Millimetron space observatory the modal density of which is high enough, it should apply the SEA method. However, if the analysis of such a spacecraft is required to perform at low frequency band, the using of FEA method is also feasible. Moreover, it seems to be a rational approach not to create a new model for the separate microvibration analysis, but to use the model that was created on the earlier steps of the spacecraft constructing. In this case, it is important to examine this finite-element model in order to make sure that it is valid in terms of the microvibration propagating conditions. One more considerable step is to determine assumptions of the method used.

So, the aim of the current research is to define the main assumptions and limitations to the FEM created on the previous steps of the spacecraft designing process and its relevance for the microvibration analysis.

2. Initial data
Designing of every spacecraft is a complex process which includes several stages of development. Static and dynamic analyses of the spacecraft structure have an important significance in this process. They are performed in different interpretations to solve the tasks, which deal with the structure behavior under mechanical loads. Usually, such analyses are implemented by numerical methods. Finite-element approach is the most known and widely used one for this purpose [10-12]. So, finite-element model creating is an essential part of each spacecraft designing.

According to the above mentioned, the finite-element model of Millimetron spacecraft that was created earlier, was applied for the microvibration analysis. The spacecraft consists of payload module and service module. The finite-element models of both are presented on figure 1 and figure 2.
respectively. The central mirror is the part of Millimetron spacecraft payload that requires a high pointing stability, influenced by onboard microvibration sources.

There are different types of sources that can be mounted on the spacecraft structure. The most rational way to protect a sensitive payload from the microvibration disturbances is to divide the operating time of the sources and the payload equipment. Sometimes there is no opportunity to do this, as it is for Millimetron spacecraft. The system of its mirrors must operate under cryogenic temperature conditions. So the special cooling system is needed to operate during sensitive instrument operating. The microvibration disturbance, in this case, is produced by the mechanical cryocooler.

![Figure 1. Millimetron FEM.](image1)

![Figure 2. Service module FEM.](image2)
3. Microvibration analysis technique

The first issue that should be taken into consideration before the microvibration analysis starting is the disturbance characterization. The microvibration disturbance is produced by mechanical, electric or other onboard instruments called sources. The disturbance excitations can be classified by the physical nature, the duration and the disturber physics [1]. Besides, these excitations might be also classified with respect to whether they are constant frequency periodic (harmonic) or transient in nature [1]. This parameter determines what type of analysis is more applicable for the response computation under the current conditions whether frequency or time domain.

It is supposed that Millimetron cooling system will be consisted of a set of Stirling cryocoolers. The disturbance produced by them is caused by periodic reciprocating motion of the cryocooler pistons. Taking into account the nature of disturbance of the mechanical cryocooler, it will be right to consider this perturbation as a periodic function. So the harmonic response analysis in frequency domain is more applicable in this case.

The disturbance amplitude must be defined as a function of frequency or time as input data for the microvibration analysis. This function can be found by analytical method, experimental approach or mixture of the two [2]. The experimental approach allows to get the most realistic results, but it has got one feature that was researched and presented at [3,13]. The feature is that test configuration must take into account the coupling of the instrument and its base in order to simulate real conditions.

Moreover, the problem of vibration reducing is actual nowadays among the cryocoolers developers. So they try to solve this problem by improving a functioning scheme of their products. Some results of the application of active pistons amplitude and phase control are presented at [14]. The resulting force function of frequency was measured by the test of cryocooler with active control. The similar function was applied as the input disturbance function (figure 3) at this paper for the microvibration analysis.

![Figure 3. Input disturbance of cryocooler.](image)

In general, cryocoolers operate with a fixed drive frequency at the range of 30 to 60 Hz [1]. The other disturbance excitations are generated at that frequency and its multiples. It means that the load induced by the mechanical (or pulse tube) cryocooler is a complex of harmonic signals with the main frequency and its multiple harmonics. So the drive frequency can be chosen for analysis as having the most significant amplitude. The other types of vibration may also be noticed in the cryocooler disturbance spectrum, but they have no such a considerable effect as the harmonic vibration on the fundamental drive frequency. Taking into account this fact, the first assumption of the microvibration analysis should be made: the effects with the exception of the harmonic component are neglected. It should be noticed that the worst case approach was used in order to choose the analysis assumptions.

After defining disturbance function, its applying conditions should be determined. Under conditions in this paper, the disturbance summation rules and the cases of its applying are meant. The main information of them is described at [1]. Considering the worst case summation rule or the amplitude
summation in other words, it is supposed that all of cryocoolers operates in-phase and simultaneously. Such an approach is most fit one when no information on the phases is available. It is the second point for the current analysis to assume.

The analysis of Millimetron finite-element model was realized by NASTRAN software. The cryocoolers were modeled as the MASS type finite elements. The cryocoolers placing as well as their models are shown at figure 4 and figure 5 respectively. In the frame of the worst case analysis, using at this paper, cryocoolers were assumed to have a rigid coupling with the spacecraft structure. It is such a condition when the disturbance is fully transferred to its foundation. The source coupling neglecting is the third assumption of the current analysis.

![Figure 4. The cryocoolers placed on the structure panel.](image1)

![Figure 5. The cryocoolers finite-element models.](image2)

In order to more accurately assess the microvibration effects it is necessary at first to estimate a higher bound of the response. To do this a modal analysis of the FEM of spacecraft structure was performed. The FEM was built as a linear model. The modal analysis was implemented by the Lanczos method. The coincidences of frequencies of the disturbance harmonics and the resonant modes may cause the most significant perturbations of the telescope optical axis. The modal analysis of the FEM was performed up to 100 Hz. Such a limitation have been chosen because, as it was described above, the main frequency of disturbance excitation is from 30 to 60 Hz.

4. Results and discussion

The results of the modal analysis are presented in table 1. The sum of the effective masses of the first N modes is the cumulative modal effective mass. Millimetron FEM analyzed up to 100 Hz has the cumulative mass that is upper than 95% of the total mass on each of six degrees of freedom (DOFs). It
means that the most significant perturbations of the sensitive instrument are excited on the resonant mode frequencies derived from the foregoing modal analysis up to 100 Hz.

The FEM influenced by loads reflects the dynamic behavior of the structure and depends on its boundary conditions. As it is recommended at [1], the free-free boundary conditions were used for the microvibration analysis. Free-free means that all six DOFs are free.

**Table 1.** Results of the modal analysis of Millimetron FEM up to 100 Hz. The table contains the rows with the values of modal effective mass not lower than 1.5%.

| Mode | Frequency, Hz | Modal effective mass, % |
|------|---------------|-------------------------|
|      |               | X | Y | Z | RX | RY | RZ |
| …^a^ | …            | … | … | … | … | … | … |
| 99   | 5.44         | — | — | — | 4.24 | — | — |
| 100  | 5.47         | — | — | — | 37.17 | — | — |
| …   | …           | … | … | … | … | … | … |
| 182  | 8.78         | 2.11 | 17.75 | — | 5.69 | — | — |
| 183  | 8.93         | 1.60 | 8.22 | — | 2.92 | — | — |
| …   | …           | … | … | … | … | … | … |
| 195  | 9.63         | 35.73 | 5.57 | — | 1.48 | 9.40 | — |
| …   | …           | … | … | … | … | … | … |
| 424  | 25.52        | — | 9.39 | — | 22.16 | — | — |
| …   | …           | … | … | … | … | … | … |
| 426  | 25.82        | 3.93 | 6.76 | — | — | — | 15.17 |
| …   | …           | … | … | … | … | … | … |
| 499  | 33.40        | 11.99 | — | — | — | — | — |
| …   | …           | … | … | … | … | … | … |
| 1001 | 67.56        | 4.67 | — | — | — | — | — |

^a^Means the missed rows in which all values are less than 1.5%.

^b^Means the value less than 1.5% for the row in which other values more than 1.5% are presented.

After all analysis parameters are set, the estimation of the response can be performed for Millimetron central mirror. The mirror is mounted on the base by legs. Besides the optical axis deflection estimating, eight control points were chosen at the mirror surface (on its inner and outer edges) in order to predict the acceleration levels (figure 6). The results of the harmonic response analysis were obtained by NASTRAN solver (figures 7 and 8).

![Figure 6. The FEM of Millimetron central mirror.](image)
Figure 7. Harmonic response of the central mirror loading by one cryocooler: (a) acceleration evaluated at control points; (b) optical axis deflection.

Figure 8. Harmonic response of the central mirror loading by set of cryocoolers: (a) acceleration evaluated at control points; (b) optical axis deflection.

The results show that the most significant response is calculated at lateral directions in case of loading at these directions:
- maximum acceleration response from one cryocooler is \(7.86 \times 10^{-5}\) g;
- maximum acceleration response from a set of cryocoolers is \(3.53 \times 10^{-3}\) g;
- maximum rotational deflection \(R_y\) from one cryocooler is \(1.95 \times 10^{-9}\) rad;
- maximum rotational deflection \(R_y\) from a set of cryocoolers is of \(3.31 \times 10^{-9}\) rad.

The value of maximum \(R_y\) calculated at frequency of 47.63 Hz from one cryocooler loading was compared with the same value computed by the authors [2]. They also used the FEM of the space camera for microvibration analysis in their paper. Their results relate to the space camera loaded by the mechanical cryocooler. The resulting value of rotational deflection is derived at frequency of 50 Hz and equal to \(10^{-11} - 10^{-10}\) rad.

If to take into account the fact that the authors [2] dealt with the test results and were able to use the real construction properties, while as at this paper the worst case conditions were applied, the results can be considered as close. Thus, the derived technique allows to obtain rather adequate results using the FEM that was created at previous steps of spacecraft constructing.
5. Conclusion

The research results more relate to constructing of the spacecrafts, but also can be useful for other technical spheres, where the microvibration analysis problem requires the solution. In this article the microvibration analysis technique was applied for Millimetron spacecraft. Thus, the FEM that was created on previous steps of the spacecraft constructing is applicable for the microvibration analysis with several assumptions. They relate to the frequency band, the mesh quality, the analysis approach, the source modeling and described above in more detailed way. The main assumptions were made for an approximate low-frequency response evaluation by the finite-element model. Consequently, if to consider all the analysis parameters correctly, it will be possible to use the existing model and save designing time.

A finite-element harmonic analysis was performed to assess the influence of the cryocoolers disturbance on the sensitive payload instrument within low-frequency band. Such an instrument in this case was Millimetron central mirror. The optical axis deflection was also calculated.

The results can be used as the starting point for more detailed assessing of the microvibration effects on Millimetron spacecraft as well as others, which have the sensitive payload on board.

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