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A CONCEPT OF MODULAR MECHANICS FOR SMALL SATELLITES AS A KEY DRIVER IN MODERN SATELLITE MECHANICS DEVELOPMENT

Maciej Urbanowicz*

The modern approach to mechanics design assumes constructing optimized structures and mechanisms which fulfil the given requirements concerning the overall development cost and product lifetime. Optimization is driven by economical rationales which usually imply diversity of products from a single product line. This approach allows to reduce a development cost if proper assumptions are applied, based on unification, flexibility and rationalistic design of technical requirements.

INTRODUCTION

A concept of modular mechanics presented in this paper briefly describes issues and advantages of a new approach for modern satellite mechanics development. This new approach is concerned as a paradigm for further analyses of a small satellites development, including CubeSats and other small spacecrafts.

An initial idea which had an effect on the concept of modular mechanics was a development of modular components for small satellites which would be unified and able to installed on-board another satellite. This approach comes from an automotive industry where a good practice is to use same parts for many – usually completely different – vehicles. This automotive-like approach is widely used in various industries where components, for example electric engines, are being shared between different systems. It lets to decrease an overall development cost and satisfy longer product lifetime even if main supplier does not provide spare parts. Standardization let to create unified solutions within a product line and/or class of products developed by one entity or group of entities. In parallel a product delivery time is decreased as well overall reliability of a product line can be kept on a required level.

This paper concerns on safety factor management and unification – which are key drivers in a modern satellite mechanics development.

It is important to highlight that the concept of modular mechanics for small satellites is being analyzed and this paper does not cover a development approach itself for all components of a satellite (such as electronic components, software). This concept is introduced to a new satellite platform from SSBV Polska: PanelSAT^{nano}, the next generation of small satellite platforms that will be a mission-enabler for CubeSat form-factor satellites to be used for In-Orbit-Demonstration, as well as operational missions. SSBV Polska Sp. z o.o. is developing a new design approach which is to

* Operations Manager, SSBV Polska Sp. z o.o., ul. Innowacyjna 1 lok. 309, 16-400 Suwalki, Poland

become a key driver in modern satellite development. The PanelSAT^{nano} introduces a new system design approach which allows better performance and reliability, thanks to the innovative solutions introduced and improved time of development.

SAFETY FACTOR MANAGEMENT

Safety factor management is the most important element of a concept of the modern approach to mechanics design. It concerns on providing requirements for designers who develop parts that meet technical requirements. A safety factor itself is defined as:

$$k = \frac{Maximum\ allowed\ loads}{Maximum\ applied\ loads} \quad (1)$$

Factor *k* takes various values due to obtained conditions and requirements. It is always greater than 1 (*k>1*) and depending on concerned system it often takes values of natural number such as 2, 3, … .

Definition of maximum allowed loads directly depends on material properties, its reliability (as a function of quality of a raw material given by relevant certificates, etc.) and another factors which should be obtained if necessary. For space applications the most common used materials for mechanical structures and components are: aluminum alloy (various alloys, mostly used 7075, 6063) and steel alloys.

[1]To define a safety factor it is necessary to assume a reference point for a maximum allowed load applied to a part. To describe various reference points' definition an example should be described. Figure 1 presents a chart of tension of a steel road in a function of $\sigma = f(\varepsilon)$. Up to the σ_{prop} (point *A* on chart) a ratio between σ and ε is linear, so the Hook's law applies. Which is defined as:

$$\sigma = E\varepsilon \quad (2)$$

where σ – a tension [MPa], E – Young's module, ε – extension coefficient.

Above this value a relation is not linear and a value of σ increases slower than below point *A*. A second characteristic point is a point *B*, where ε increases where σ is constant and equals R_e. This is a critical point of plasticity. For σ=const we experience a slip of material. Very interesting point is a point *A'* where there are irreversible deformations, only existed up to σ_{spr}. It is also a critical point of elasticity.

For the purpose of a *k* factor definition point *A* and *A'* should be considered as points of reference. If a component is exposed to external loads during a short period of time (which can be described in seconds or minutes, and it is not frequent), then *A'* should be a reference (or even *B*, depending on requirements and characteristic of purpose of mechanism). Thus σ_{spr} should be put to a numerator of an equation (1). It is higher than σ_{prop} which applies for components which are loaded in more frequent existed loads as well for a longer period of time.

Difference between σ_{prop} and σ_{spr} is important and implies technical issues for designers, especially if low *k* was assumed (*k=1.2*, *k=2* …). A proper σ should be chosen regarding to an environmental and working conditions of a component.

Fortunately for steel alloys it is a quite simply choice. Steel alloys are more predictable than aluminum alloys and selection of a proper σ is easier. It usually concerns on an external loads and its frequency. Thus calculations can be more accurate.

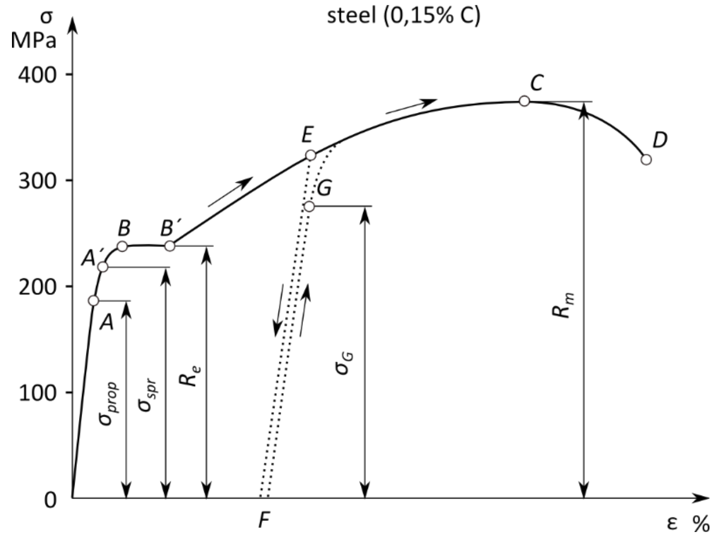

Figure 1. Tension of a steel rod

Another behavior is presented on a Figure 2 which presents an aluminum alloy AL-Cu4. Tensile force applied to a rod causes an extension which up to point *A* is reversible. But if a rod is being loaded by almost 2 times bigger force, the extension is increased over 0,2% (point *B*). It means that there is not visible critical point of plasticity. Thus a choice of a proper σ or R is difficult for aluminum alloys.

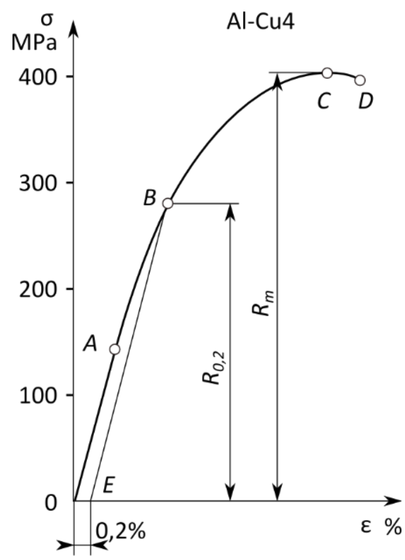

Figure 2. Tension of an aluminum rod

It implies a need to concern on technical requirements for a component, then choice of a proper maximum allowed loads for each type of material in reference to a condition of work.

Thus the safety factor management is becoming more important in a development process. It is intended to help to choose a proper reference allowed loads and develop a proper design requirements list. To give an overview on the idea it is necessary to present it on an example.

Table 1 presents what happens if various *k* are considered in reference to different maximum allowed loads. The reference values are in a row 1 (220, 190 and 205 MPa; *k=1*). They are taken from a Figure 1 (average value was calculated). This step shows that σ varies depending on a reference point. Thus assumed *k* values implies different values for σ as a maximum allowed load.

k	Max [MPa]	Min [MPa]	Average [MPa]
1	220	190	205
1,5	146,7	126,7	136,7
2	110	95	102,5
2,5	88	76	82
3	73,3	63,3	68,3
3,5	62,9	54,3	58,6
4	55	47,5	51,25
4,5	48,9	42,2	45,6

Table 1 . Loads versus k

It is shown that *k* decreases maximum allowed loads which can be applied to a component. Depending on a value of *k*, a component might be more or less exposed to a risk of a malfunction due to unpredicted internal material errors and design errors.

Furthermore a choice of a reference value is important. Depending on working conditions, it should be carefully chosen, because as it is shown in Table 1 and Figure 3 for each *k* there are different values of allowed maximum loads which can be applied.

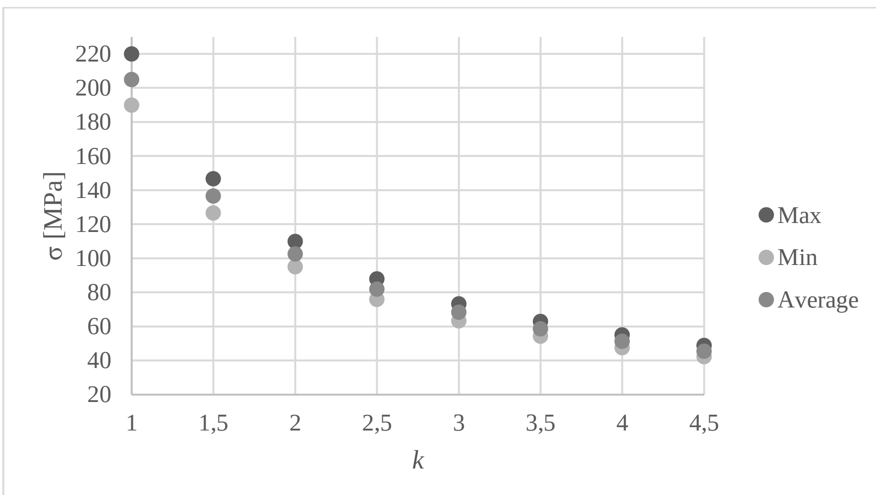

Figure 3 . σ=f(k)

It causes a serious issue especially for low *k* values, because it is a higher risk to get closer to maximum allowed loads in case of unpredicted internal material errors or design errors. Finally a choice of *k* and reference σ has a huge impact on a total mass of a component. Depending on design it might vary even by 20-30% (for each *k*).

The safety factor management is a complex topic which was introduced. This topic, as well unification provide a guideline for decision makers to select the best possible solution for solving a technical problem in a small satellite development. It forces solutions to decrease an overall budget as well fulfil requirements for mechanical components of a system.

UNIFICATION

Unification allows to develop set of parts, components, elements designed for specific purpose, but with various properties (such as dimensions, etc.) for specific use. Unification goes along with safety factor management, thus a component might be used for various missions when different load forces apply. Thanks to unification cost reduction applies to an overall budget for development and it simplifies the design and maintains high quality (due to the reliability of well tested parts of the code).

The unification might be realized by adding a module to existing system or replacing parts with similar ones which differ by size (for example one dimension). A good example is a difference between an aircraft B767-100 and B767-200 where two segments have been added and engines have been changed to get more seats for passengers (190 versus 210 seats). Thus there is no need to redesign an entire project. The load capacity has increased. The unification in this case let to cut costs, and it was an optimal solution from the economical point of view. Of course from the engineering point of view it was not an optimal solution, but stayed in designed safety factor boundaries.

For small satellite mechanics the unification should be applied for any kind of mechanical components where a standardized part can be used. A good example of this approach is a mechanical structure for a CubeSat which can be developed in different sizes (1U-3U) and still keep similar mechanical properties. An example of mechanical structure for a CubeSat – 1U – is presented in the
Figure 4. The structure consists of three elements: main frame + two side frames. Main frame is the same for any kind of sizes of structures when side frames are interchangeable. Safety factors for compression forces along Z axis is k~15[*], thus it is possible to increase a height of structure, keeping the same cross section of elements and adding only a support bar for the side frames. No other elements of frames have to be changed due to earlier designed mechanical interfaces.

[*] Factor value calculated for a 1U CubeSat – the PW-Sat which was launched on the Vega Maiden Flight (VVO1).

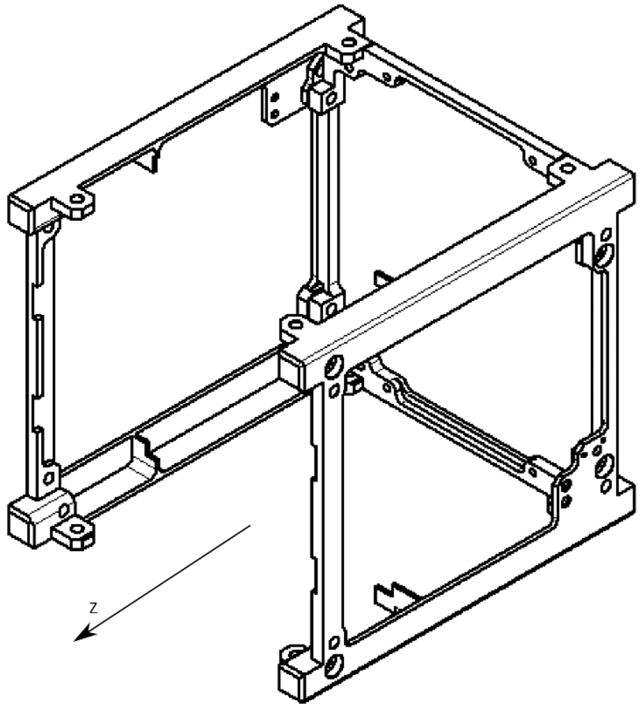

Figure 4. 1U mechanical structure for a CubeSat (credit: M. Urbanowicz)

Similar behavior is presented by a modified structure which is presented in the Figure 5. The only two changes have been made – extension of a height of the side panels and adding a support bar in the middle of frames. As mentioned above, all mechanical interfaces stayed the same.

Thus safety factor for compression forces stays similar due to the fact that such forces do not make higher tenses inside a material. So it can be assumed that these loads stays the same due to the same external loads. Of course a deformation of buckling must be considered due to change of dimensions. An axial load exhibits the characteristic deformation of buckling which depends also on a shape of a part.

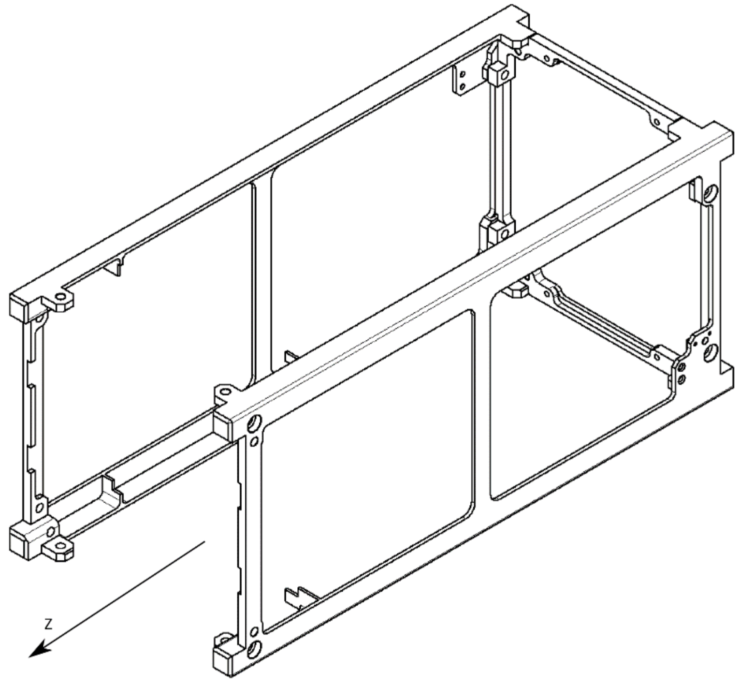

Figure 5. 2U mechanical structure for a CubeSat (credit: M. Urbanowicz)

These two structures present the idea of unification. Thus a development time can be decreased and an overall development cost can be kept on a reasonable level.

Furthermore above mentioned examples are based on a modular design which advantage is a flexibility of configuration. Thanks to a concept of modular mechanics and unification mechanical parts can be interchangeable between missions and thus the overall development cost (including test campaigns) is decreased.

MANUFACTURING TECHNIQUES – IMPROVEMENT OF MECHANICAL PROPERTIES

Choosing a proper manufacturing and finishing technique is an important element of development process. If proper manufacturing and finishing technique is chosen, mechanical properties can be improved and safety factors as well, thus a design can be improved to minimize a total mass of elements.

For mechanical components which are being produced in a small series (or even for individual request) usually are manufactured by two main techniques: milling and turning. These two techniques use rotary cutter to remove material. It removes layers of material and cuts an internal material structure to get a designed shape. In result a strength of material is decreased, because an internal structure on external layers is destroyed. This is a disadvantage of milling and turning manufacturing methods which imply a need to keep safety factors on higher level (depends on application it can be *k=2-3, 6* or more) in requirements.

There are several methods to enhance the fatigue strength of components. From various methods shoot peening and anodizing were selected as the most promising methods to enhance strength of components made of aluminum alloy and steel alloys.

Shoot peening increases a maximum load capability of metal components by converting a tensile residual stress into compressive residual stress. Anodizing is widely used to coat a material and then protect it against external environment as well to enhance strength. From the author's experience, shoot peening might increase a maximum load capability by 10-30% (depending on a material, characteristics of loads, etc.). From the other hand, anodizing protects a material against a harsh environment as well as can increase a load capability similar to shoot peening.

It is suggested to apply finishing methods, according to requirements and *k* to improve performance and capability of produced devices. A total mass of a device can be decreased due to applied techniques and its strength can be kept on a same level.

CONCLUSION

Modular mechanics, safety factor management and unification combined together play an important role in a modern small satellite development. Presented topics briefly introduce issues, but focus on a key point – which is an optimization.

A new approach assumes to conduct safety margins along with reasonable budget. But it focuses on flexibility, unification and improvement of performance along with minimization of a mass. The advantage of this approach is that a new component can be verified and tested than a specific designed element which cannot be shared between different projects because better new approach assumes that each component can work in various conditions. Thus a reliability can be kept on a required level or even increased due to a wider range of possible missions which each developed mechanical part could be assigned.

REFERENCES

[1] Brzoska Z., *Wytrzymalosc materialow*, Panstwowe Wydawnictwo Naukowe, Warszawa, Poland, 1983