ULTRA-LIGHTWEIGHT DEPLOYABLE SPACE STRUCTURES

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ABSTRACT

The ultra-lightweight construction of large, deployable space structures is a fundamental prerequisite for the realization of Solar Sail propulsion concepts. In addition to the functionality of the deployment technique and the development of control concepts, lightweight aspects and their technical implementation play a key role in future Solar Sail missions. A further development of the set-up and successful ground demonstration of an ESA-DLR breadboard model in 1999/2000 will be the goal of a demonstrative mission in Earth orbit. The DLR Institute of Structural Mechanics is involved in the follow-up project by the development, verification, and construction of ultra-light, deployable booms made of Carbon-Fibre Reinforced Plastics (CFRP) and extremely thin sail segments. Kayser Threde GmbH, Germany has been commissioned as system responsible for the implementation of this project.

KEYWORDS

Deployable Space Structures, Solar Sail, Deployable Booms, Probabilistic Buckling Analysis, Membrane Wrinkling

INTRODUCTION

The innovative propulsion concept of the impulse transfer of solar photons onto a reflecting surface is used in Solar Sail concepts. Since the source of the propulsion does not have to be carried on board as is the case with conventional methods but is available in almost unlimited quantities in space, Solar Sails provide an interesting alternative to chemical propulsion methods especially for long-term missions that have a high demand for energy. The available thrust, however, is extremely small due to the very low mass of the reflected photons. A significant change in velocity can only be reached after a certain duration of the mission as a result of the continuous effect of acceleration or deceleration, respectively. Because of the tremendous engineering challenges they have faced up to now, Solar Sail concepts have not yet advanced beyond theoretical design studies and a few functional models. Extreme lightweight construction, the development and verification of safe deployment concepts for large Gossamer Space Structures, the realization of the long-term stability of the applied materials in the

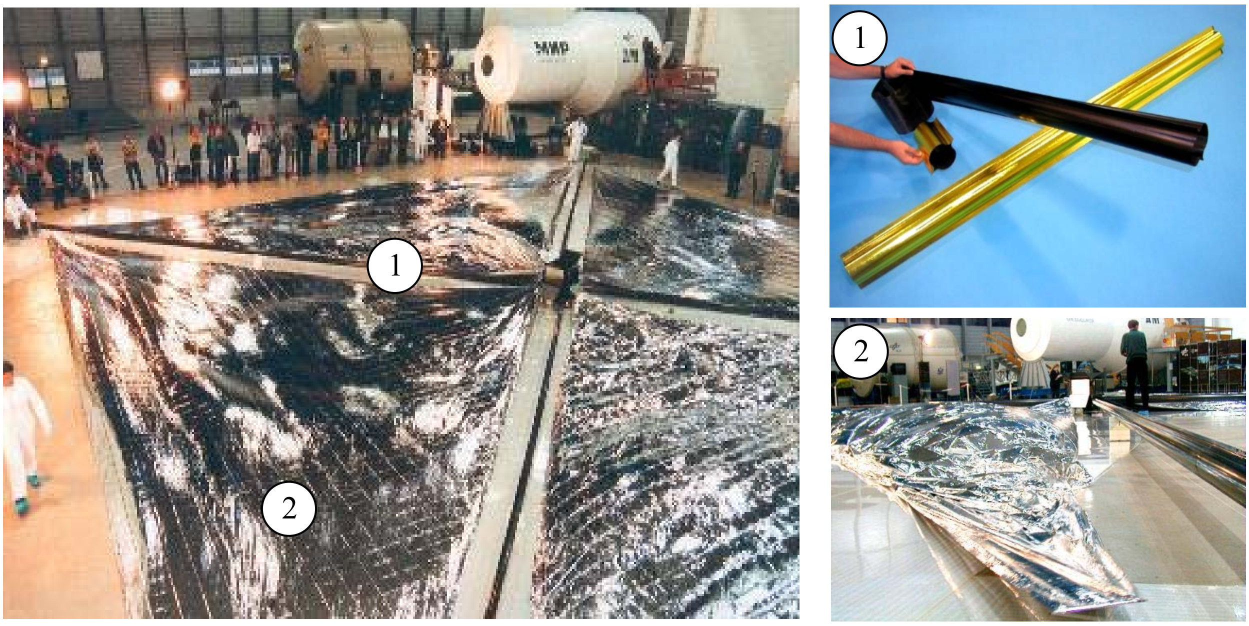

Figure 1: ESA-DLR Solar Sail breadboard model 1999/2000; DLR-SM hardware contributions thin-walled ‘deployable CFRP booms’ and ‘ultra-thin sail segments’.

space environment, and, finally, the development of control concepts and mission analysis are important tasks that must be taken on in preparation of a first Solar Sail mission.

The extreme demands on Solar Sail technologies are comparable to the requirements of a number of possible spin-off applications in the area of lightweight deployable space structures. The development of Solar Sail technologies therefore takes on a key position, e.g. for the realization of future, deployable solar arrays, sun shades, antennae and reflectors, or longer, extendable masts. Initial design studies have shown, for example, that the boom deployment technology is potentially suitable for future Synthetic Aperture Radar (SAR) Earth observation missions.

REQUIREMENTS AND DESIGN

The acceleration of a Solar Sail results from the efficiency of the sail η, radiation pressure p_S, and the ratio of the entire mass of the spacecraft and the reflecting surface σ according to

$$a = \eta\, p_S/\sigma\,.$$

The entire Solar Sail loading σ therefore has to be very small for an optimal acceleration. The degree of effectiveness η essentially depends on the optical properties of the sail and its homogenous tension and orientation. Too much tension in the sail, however, can lead to an excessive formation of wrinkles on the sail's surface and therefore has a negative influence on the degree of effectiveness. In addition, high tension forces require correspondingly massive support structures whose contribution to the mass budget, however, can have a negative influence on the acceleration. Analyses on mid-term Solar Sail missions balance the necessary, entire assembly loading to at least σ = 10-20g/m² and sail sizes up to 125m x 125m, Leipold et al. (2001). These values clearly show the enormous challenges that engineers are faced with: new types of technologies have to be developed that facilitate the safe deployment of Gossamer Structures in space; at the same time, the deployment structure has to be extremely light and transportable within a very small volume on conventional launchers. In addition, the applied ultra-light structures have to prove their long-term stability in extremely different environments. A further challenge is the realization of a control concept that is able to safely manoeuvre large, flexible Solar Sails with little energy expenditure and over long periods of time.

The Solar Sail concept that was developed in a cooperation between ESA and DLR entails a square sail that is mounted by four deployable CFRP booms (Figure 1). The thin-walled masts, which only have a specific mass of 100g/m, are axially loaded in the deployed configuration by the sail tension forces. A central deployment module, which is also made by use of CFRP technologies, contains the booms and the four triangular sail segments in a stowed configuration. Even though only a 20m x 20m version was constructed during the ground demonstration, the design and layout are based on the assumptions of a 40m x 40m sail. Sail films with different wall thickness were successfully tested: 12µm Mylar, 7.5µm Kapton, and 3µm PEN (polyethylennaphtalat).

ANALYSES

Wrinkling Analysis and thermal Aspects of thin Sail Membranes in Space

A homogenous tension of the sail film is of utmost importance for the efficiency of the Solar Sail propulsion concept. Wrinkles inevitably develop in very thin films as a result of transverse contraction with more or less uniaxial tension stresses. Such loading conditions occur with the ESA-DLR concept, for example, at the load introduction into the corners of the individual sail film segments. Wrinkled areas of the sail membranes cannot only have an effect on the quality of the reflection and therefore the degree of effectiveness of the sail. A more detailed analysis of the wrinkled areas is necessary for thermal reasons since the possibility of geometric patterns developing as the result of wrinkle formation must be taken into consideration as these can lead to a local overheating of the material ('hot spots'). A calculation of the complex, highly non-linear processes during the formation of local wrinkle patterns in the sail film is hardly possible for the entire sail. For this reason, a simplified wrinkling theory is applied that iteratively changes the stiffness by varying the element properties until no negative minor principal stress σ_2 occurs in the sail membrane. The result of this iterative process is shown in Figure 2 for a 7.5µm Kapton film applied to a 40m x 40m Solar Sail model. Assuming an isotropic sail film material, the principal stresses and their trajectories are analysed. Depending on the sign of the minor principal stress, a case decision between a 'completely taut' ($\sigma_1, \sigma_2>0$) and 'wrinkled' ($\sigma_1>0, \sigma_2<0$) condition is made afterwards for each individual element. Modified material laws are then ap-

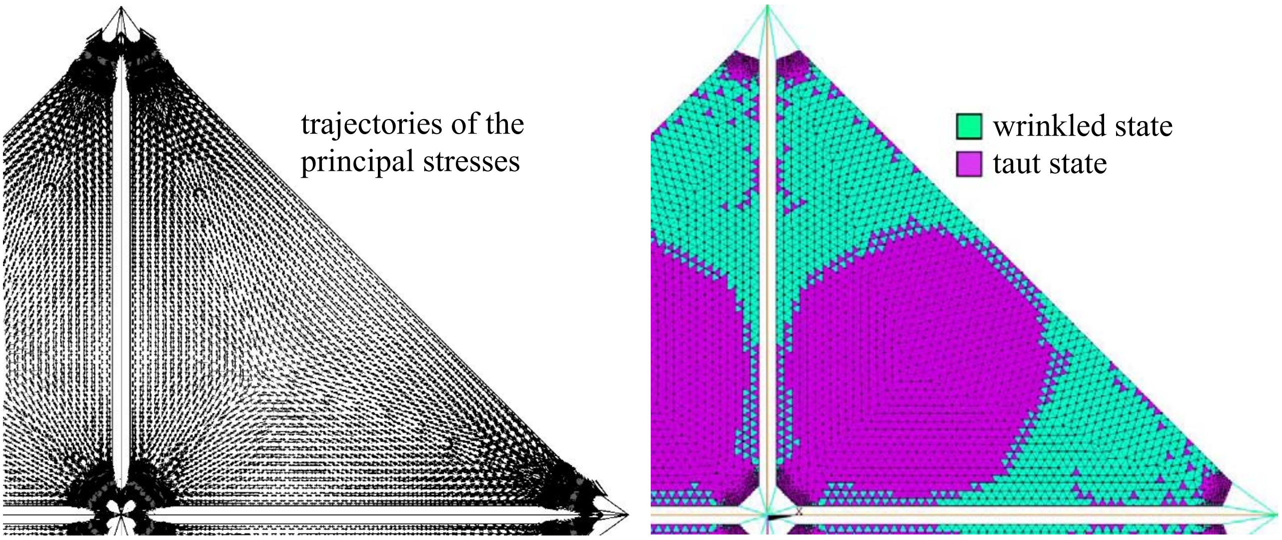

Figure 2: Ultra-thin sail membranes: analysis of the principal stresses and the trajectories; taut and wrinkled sail areas.

plied accordingly. A disadvantage is here that a convergence is not always given. For example, 42 iterations were necessary for the depicted result. Due to this simplified calculation, reliable statements on the amplitudes and wavelengths of the wrinkle patterns and therefore on the efficiency of the reflection are not available to the required extent and have to be examined in a detailed, local analysis. The evaluation of the calculation leads to a ratio of 56.1% between the fully taut and nominal sail surface. As can be seen in Figure 2, the taut area is approximately located in the circle inscribed within the triangular segment of each sail segment, and the wrinkled areas mainly develop from the sail edges up to the boom tips.

The demand for an ultra-light Solar Sail Gossamer Structure inevitably leads to very thin-walled structures that have extremely large surfaces in relation to their volumes and, as a result, have an intensive exchange of radiation with their environment. Good degrees of reflection can be achieved with aluminium coatings which, however, strongly heat up the sail film as a result of the unfavourable ratio between the absorptivity and emissivity $\alpha/\varepsilon > 1$. Minimum and maximum temperatures, thermal gradients, and transient jitter events such as the shade-light passages therefore have to be particularly taken into consideration during the design and material selection process. In order to determine the sail equilibrium temperature, the infrared earth shine and the albedo must be taken into consideration in addition to the solar constant (= 1360W/m^2). A sail film coated with aluminium on both sides (manufacturer information: $\alpha = 0.12$, $\varepsilon = 0.05$) develops equilibrium temperatures of at least 183°C when the sails are completely unfurled along the incident radiation, which the sail materials must be able to withstand. Because of the square inherent law of the solar radiation intensity, the thermal design of the sail is highly important, particularly when they come close to the sun down to 0.2 - 0.3AU. Solar Sail missions therefore require that the backside of the sail has a surface with, e.g., a chrome coating that has a good emissivity and low absorptivity for cooling purposes. Because of its significance for the thermal household and manoeuvrability, the long-term stability and degradation of the thermo-optical properties must be additionally examined under space conditions before a Solar Sail mission takes place.

Probabilistic Lightweight Design of Deployable Solar Sail CFRP Booms

In the design of deployable masts, the booms are pressed down flatly and are rolled up in such a manner that they can be stored and transported within a very small volume (see Figure 1). Ultra-thin prepregs made of carbon-fibre reinforced plastics (CFRP) are used for the manufacture of the booms. They are cured to two half cross-sections by means of a conventional autoclave process. In the end, the two half cross-sections are bonded together at the bonding flanges. The laminate set-up is made up of a combination of 0°- and +-45°-layers. In addition to a favourable influence on the buckling behaviour of the very thin-walled structure, the choice of the stacking sequence is essentially based on the requirement to minimize the bending that takes place during single-sided thermal loading. For this reason, very low coefficients of thermal expansion in the boom longitudinal direction are an important prerequisite ($CTE_l = 0$ 1/K). Just as in the case of the sail film, thermal loading and the long-term stability of the material play an important role in CFRP booms. Coating measures that positively influence the thermal household of the thin-walled CFRP structure and that also provide protection against additional space environment conditions such as atomic oxygen have already been examined in development tests (see Figure 1), Sickinger et al. (2003).

The structural boom design is based on requirements that were determined during a Solar Sail ground demonstration, Herbeck et al. (2000). Although only 14-meter long booms were built during this demonstration phase, the design was worked out for a length of 28 meters. The cross-section geometry definition results from a mass optimisation while fulfilling a certain minimum bending stiffness requirement. It is important to note that the boom geometry is restricted in the stowed configuration due to very tight volume constraints. Therefore, the current specific mass of approx. 100g/m can be reduced even more with free optimisation and a revised cross-section design.

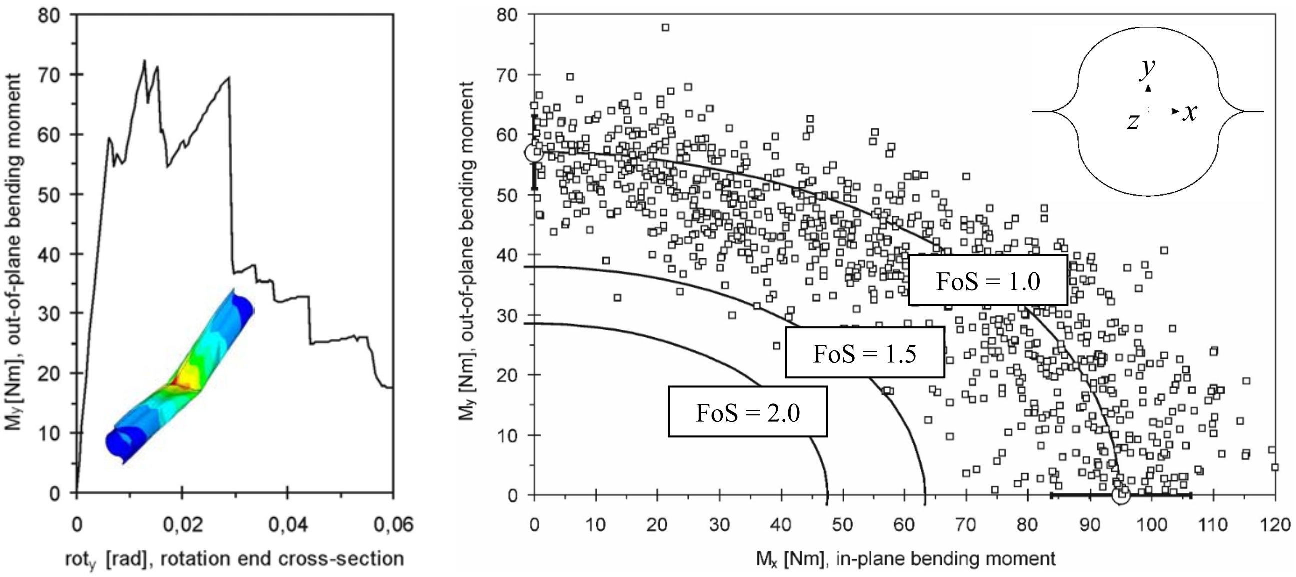

Figure 3: deterministic non-linear buckling and post-buckling analysis of a thin-walled CFRP boom shell structure due to out-of-plane bending M_y and development of a failure mode envelope based on probabilistic boom buckling analyses.

Because of the role it plays in the entire concept, the structural calculation of the booms is very significant. Stiffness restrictions, such as those in the form of minimum bending stiffness requirements, as well as strength requirements are usually defined. From a global point of view, the booms can be described by defining the beam stiffness EI_x, EI_y, GJ_z and EA with a uniaxial beam model. The loading limit, on the other hand, is characterized in the thin-walled profile only by the buckling stability that, as an essential part of the structural description, has to be analysed in detail. A recording of the buckling behaviour that is accurate as possible is of central importance, also due to the lightweight philosophy of the design.

Implicit and explicit finite element methods (FE) are applied for the analysis of the boom stability behaviour (ANSYS/LS-DYNA). The computation of any member force condition is basically possible, however, the antimetric transverse forces F_x and F_y as well as torsion behaviour due to M_z play a subordinate role in the comparatively long booms. Although the booms are loaded by an axial compression force F_z as a result of the sail tension forces, primarily the bending moments M_x and M_y play an important role for the cross-section design. The bending moments do not necessarily arise from out-of-plane loading only. Even the axial tension forces F_z create 'internal' bending moments during large geometrical deformations of the sail structure combined with sail and boom eccentricities, which must be taken into consideration in the design. Based on the reasoning that the transverse forces are 'small', it follows that the gradients of the bending moments are 'small' as well. The computation can therefore be made within a good approximation of a boom section in which constant member forces and moments F_z, M_x, M_y are assumed for each section. In order to introduce the forces and moments properly, a rigid bulkhead is modelled on one the side of the section being examined. Symmetric boundary conditions are formulated on the other side. The utilization of symmetries during the treatment of buckling problems is generally not possible without additional effort since unsymmetrical buckling patterns can fall in an energetic minimum also. However, this is still done for reasons of efficiency and because several computed examples have not show any significant differences.

First, a computation of the static solution is made after the result of any type of load combination M_x, M_y, F_z. The nominal beam stiffness EI_x, EI_y and EA can be derived from the results in a simple manner and a linear eigenvalue buckling analysis is performed afterwards. The computation of the eigenvalues and eigenvectors are used to define reasonable load ranges for the subsequent non-linear computation. The eigenvectors are additionally used to define the geometrical imperfections that are necessary to initiate the non-linear solution. In this case the first two eigenforms are analysed and applied with a maximum imperfection amplitude to the size of the maximum wall thickness of the profile. The geometrically imperfect structure is then conducted to the bifurcation point by means of a non-linear implicit FE calculation. The bifurcation point characterizes the load that the system reacts unstably to and switches to an energetically better position of large deformations while forming a buckling pattern. The determination of the post-buckling behaviour has two essential targets: first, only a qualitative interpretation of the post-buckling area together with the definition of a buckling criterion enables a statement to be made on the sensitivity of the structure in relation to the buckling phenomena; second, stable deformation patterns can occur even beyond the bifurcation point that do not yet lead to a local transgression of the strength limit, making it possible to include these areas in the dimensioning, as is often done in over-critical lightweight constructions.

When the structural behaviour is significantly influenced by scattered input parameters, a deterministic dimensioning combined with safety factors can lead to dissatisfying results. Probabilistic analysis procedures therefore offer further saving potential in addition to conventional structural optimisation in order to achieve the global goal of realizing a design that is as light as possible. The detailed calculation of the boom buckling behaviour has shown, for example, that the results react very sensitively to parameter variations. Taking a constant safety factor into consideration can therefore lead to very conservative restrictions but also to an underestimation of the phenomenon. For this reason, probabilistic methods at Solar Sail system and deployable boom sub-system level are considered during the dimensioning of the booms by defining significant structural parameters under the assumption of certain probabilistic distribution functions, Sickinger et al. (2003). The following parameters are taken into consideration for the determination of the probabilistic boom stiffness and buckling limits:

- varying shell wall thickness as the result of a variation of the prepreg fibre areal weight,
- CFRP material data depending on the prepreg lay-up accuracy during the manufacture,
- geometrical manufacturing tolerances of the boom cross-section,
- geometrical imperfection amplitudes for the nonlinear calculation of the buckling load,
- load eccentricities as the result of a cross-section distortion due to the nominal loading.

The probabilistic simulations are carried out via a Monte Carlo Method with Latin Hypercube Sampling and the ANSYS probabilistic module. The evaluation of the analysis for both bending load cases including the derivation of A-values is shown in Table 1. It is important to mention that the statistic formulation of the probabilistic input parameters are directly connected to the quality requirements for the structure and initially lead to a relatively conservative assumption during the design phase. In this manner deviations in the areal weight of the CF prepregs, for example, can be taken into consideration within the detailed design and, at the same time, defined as a release criteria for a material incoming inspection.

TABLE 1
PROBABILISTIC ANALYSIS RESULTS OF THIN-WALLED DEPLOYABLE SOLAR SAIL CFRP BOOMS:

beam parameters		*unit*	*mean value* σ_M	*standard deviation s*	*A-value*
nominal bending stiffness	$EI_{x,nom}$	[Nm^2]	5073	430	4236
	$EI_{y,nom}$		5318	442	4380
secant stiffness	$EI_{x,Sec}$		4989	426	4185
	$EI_{y,Sec}$		4742	390	3908
buckling moments	$M^*_{x,cr}$	[Nm]	95.0	11.3	70.5
	$M^*_{y,cr}$		57.0	6.1	40.3

The probabilistic computations at a boom sub-system level also are very important as input for a system analysis levelled higher than the booms. From the system side, it is not very efficient to model the booms in detail with shell elements. On the other hand, it is not possible to simply make a statement on the boom failure under any system loads or to carry out system optimisations when the local buckling behaviour of the booms is not considered within a simplified uniaxial beam formulation. The detailed probabilistic boom computations can therefore be used to establish a boom failure mode envelope based on the uniaxial beam load at boom sub-system level. This criterion is then made available for a Solar Sail system analysis and allows for the computation of the safety margins at a general load. Figure 3 shows the result of a probabilistic implicit buckling analysis in the virtual M_x,M_y-space of the boom. The elliptic lines characterize a simple failure criterion that can be determined by using the uniaxial, probabilistic mean values $M^*_{x,cr}$, $M^*_{y,cr}$ and a factor of safety (FoS). The computation of the margin of safety (MoS) can be determined at an early stage in the design based on the uniaxial results of a theoretical probabilistic analysis (Table 1) or during the detailed design by means of development tests, Sickinger et al. (2003):

$$MoS_{Boom} = \frac{\sqrt{M^{*2}_{x,cr}\, M_x^2 + M^{*2}_{y,cr}\, M_y^2}}{FoS\left(M_x^2 + M_y^2\right)} - 1$$

Solar Sail System Analysis

If the structural mass of a 40m x 40m Solar Sail is assessed on the basis of a specific boom density of approx. 100g/m and the mass of a conventional 7.5µm Kapton film as the sail material, it becomes apparent that both of these components have already a mutual loading of approx. 18.7g/m² compared with the sailcraft loading requirement of σ = 10-20g/m². The necessity for an additional mass reduction becomes even more apparent when additional masses are assumed for the deployment mechanisms and the payload. Two general questions are particularly important for the dimensioning:

1. ***How great is the necessary sail tension?*** It must be big enough so that the sail surface remains even under loading and that the sail is optimally effective. However, sail tensions that are too great can negatively influence the degree of effectiveness due to the formation of wrinkles. In addition, the support structure (booms) must be dimensioned more stiffly and heavily. The additional reduction in the film thickness is very important since, under the assumption of a minimal sail tension that has to be maintained, the reduced thickness has a direct effect on the mass of the sail as well as on the design load of the support structure and therefore its mass. The determination of the optimal sail tension results from the optimisation of the Solar Sail acceleration. Since the sail tension has an influence on the degree of effectiveness as well as on the mass budget, the lightest Solar Sail design does not necessarily also mean a maximization of the acceleration.
2. ***What is the minimum eigenfrequency that must be maintained?*** Mass optimizations such as those presented here inevitably lead to very flexible thin-walled structures that border very closely on the static stability limit. As a result, the fundamental frequencies are extremely low and the amplitudes and oscillation times are very high due to low damping rates. Requirements for the system stiffness in the form of minimal eigenfrequencies that have to be maintained or tolerable, dynamic displacements like those that would have to be derived from an analysis of the manoeuvrability of suitable control concepts of a concrete design are presently not available.

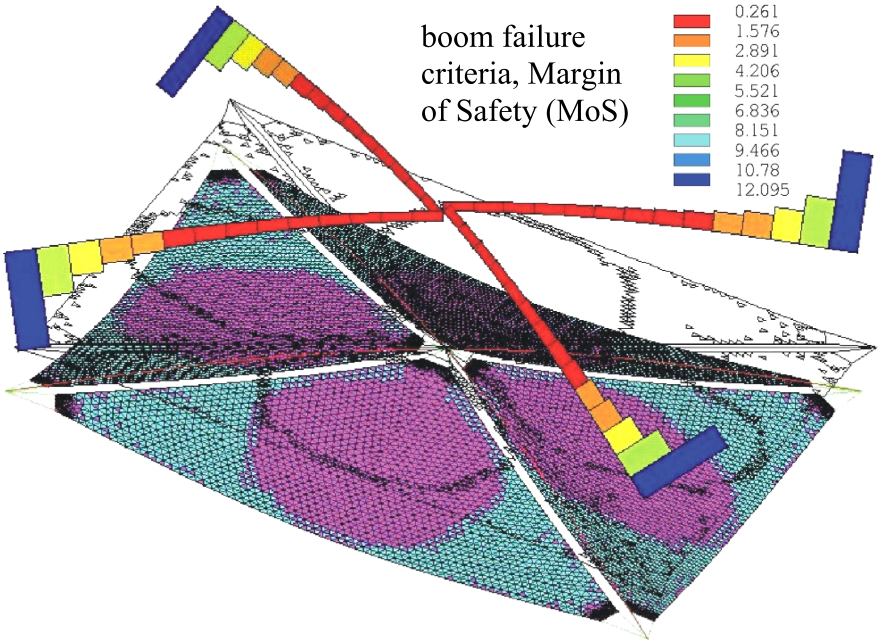

Figure 4: 40m x 40m Solar Sail, $\sigma = 60g/m^2$, load case ‚air drag', 300km Low Earth Orbit.

For the case study it is assumed that the sail in its nominal state is tightened by forces that create an axial compression loading of $F_z = 10N$ along the booms. The mayor principle stress in the sail membrane then reaches a minimum value of $\sigma_1 > 0.0345N/mm^2$ (= 5psi). The first eigenfrequency corresponds well with the bending mode of an axially loaded beam. It is approx. 0.067Hz for the examined structure having a sail assembly loading of $\sigma = 60g/m^2$. The Solar Sail is subjected to different load cases in this tightened condition. Drag environment factors and therefore — depending on the air density — 'air drag' forces play an important role in a demonstration mission in Low Earth Orbit. When the Solar Sail is completely unfurled at 40m x 40m, an 'air drag' force of approx. 7.4N and a pressure on the sail surface of 5.25E-03Pa can be expected (conservative estimation) at, e.g., a Low Earth Orbit of 300km altitude. The real loading from the solar radiation pressure can be almost neglected in this case. At 1AU, it is more than two orders of magnitude smaller than the 'air drag' forces at an altitude of 300km. The determination of the boom margins of safety (with FoS=1) is shown in Figure 4 based on the introduced failure criteria in Eqn. 2 for the concrete load case. The load scenario therefore characterizes the moment when the 40m x 40m sail is billowed out by the drag environment at an altitude of 300km and the boom roots nearly buckle as a result of the bending load and break off (MoS=+0.26). The bending deflection at the boom tips is approx. 2.7m, and out-of-plane bending moments of approx. 45.2Nm develop at the boom roots.

OUTLOOK

The estimated mass budget at the related sail loading of $\sigma = 60g/m^2$ clearly shows that additional mass reductions are necessary for the first Solar Sail missions. This regards the sails as well as the booms, and particularly the deployment mechanisms and payload.

A reduction in the mass of the sails can primarily be achieved by a reduction in the wall thickness. The CP1 films (clear polyimide) developed at NASA and distributed by SRS Technologies are available at thickness down to 5μm and further reductions are being pursued. Verifying the long-term stability of the coating is one of the main tasks during the development of the sail. In addition to the use of stiffer fibre systems and types of laminate, it is expected that mass reductions can be achieved in the deployable booms by means of a tapered design over the boom length. The assessment of the margins of safety depicted in Figure 4 makes it clear that the load is not homogenously distributed over the boom lengths. The bending moments that are particularly important for the design become increasingly smaller the closer they get to the boom tips. A modular tooling concept and the definition of different boom classes make a reaction to the different requirements possible, Herbeck et al. (2000). As far as the potential payload is concerned, miniaturization trends can contribute to a further reduction in the mass of a Solar Sail spacecraft. 'Picosatellites' that weigh less than 1kg are based on technological developments in the field of microelectronics and micromechanics. The greatest saving potential, however, can be expected in the deployment module technology. A patented alternative deployment concept involves the stowage of the drums at the boom tips instead at the boom root was recently developed for mass saving purposes by DLR, Breitbach et al (2002). The jettison of unnecessary parts and mechanisms after deployment is a very effective method of saving mass. However, the risk of collision must be very closely analysed at the start out of Earth orbit. Finally the rigging of the booms with a system made of tethers in accordance with classical lightweight philosophy standards is very effective since, in the ideal case, the supporting structure only has to carry tension and compression loads, and bending moments are avoided. However, rigging concepts entail a great deal of risks during deployment at zero gravity, making their use for automatic deployment difficult.

From an engineering point of view, the requirement for an overall Solar Sail loading of σ=10-20g/m² still poses enormous challenges. Yet, based on the design concepts available today as well as trends that have already been introduced, the development of an ultra-light deployment technology as a necessary prerequisite for a Solar Sail propulsion concept can be viewed as positive even if a number of necessary development work still needs to be carried out. The next concrete step currently being planned by ESA and DLR is the demonstration of the Solar Sail deployment technology in Earth orbit in the space environment. Kayser Threde GmbH, Germany was commissioned as system responsible to carry out the project. At the same time, the development of key technologies at the DLR institute will be continued in preparation of the first Solar Sail mission.

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