DEVELOPMENT AND TEST OF DEPLOYABLE ULTRA-LIGHTWEIGHT CFRP-BOOMS FOR A SOLAR SAIL

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Abstract: *The Institute of Structural Mechanics of the German Aerospace Center is developing ultra lightweight, deployable boom structures made of carbon fibre-reinforced plastics (CFRP booms). Although the concept of CFRP booms can be universally applied to a number of tasks, its application in the development of a Solar Sail demonstrator and the results are presented in this report. The CFRP booms have high bending and torsion stiffness and, additionally, the folding concept enables transportation within a very tight volume. Towards the end of 1999, it was possible to prove the use of the booms, by means of a 20x20* m^2 *demonstrator, as an essential structurally mechanical part of a solar sail. The goal in the next phase of the project is the realisation of a 40x40* m^2 *flyable version in 2004–2005.*

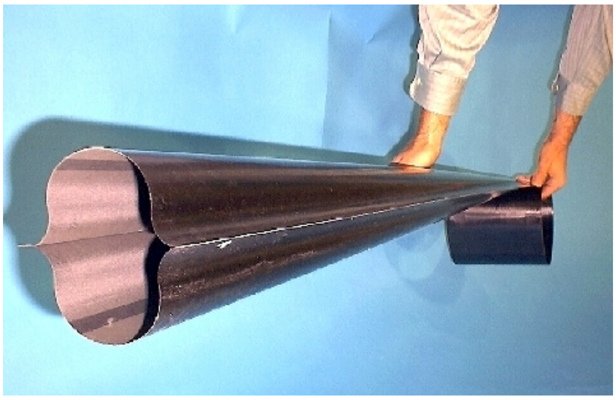

Figure 1: DLR's deployable CFRP boom.

1 Solar Sail

Since the beginnings of quantum physics it is common knowledge that photons are more than just pure light. Photons have particle characteristics and, therefore, a mass, even if it is a very low one. The idea to make use of the $E = mc^2$ energy stored in a photon as propulsion for a spacecraft was already thought of in the 1920s. When photons hit a reflecting surface, they transfer their impulse in the form of radiation pressure. The solar radiation pressure in space can be used for continuous thrust and, compared to conventional forms of propulsion, has the advantage that the original source of propulsion is available in space which means that heavy propellants do not have to be transported on board. Because of the photon's low mass, this idea can be practically implemented only if it is feasible to combine a large reflecting surface with a comparably low weight. A solar sail surface of 100x100 m^2 at a total weight of 200 kg is an order of magnitude which already provides possibilities for a number of missions. The extreme challenges which come as a result of these requirements are the subject of development work on a Solar Sail demonstrator. In co-operation with INVENT GmbH and ESA a concept for the realisation of a square sail is being developed. In order to guarantee good impulse transfer and manoeuvrability, it is necessary to put the sail surface under tension via a mechanism. The supporting structure of the Solar Sail is made up of four ultra lightweight booms which are developed at the Institute of Structural Mechanics of the German Aerospace Center in Brunswick.

2 CFRP Booms

Significant progress in lightweight deployable structures, using advanced materials and processing methods, opens new perspectives concerning the realization of a solar sail structure in orbit. Carbon fibre reinforced plastics (CFRPs) have matured within the last decades so that they are now potential candidates to be utilized for solar sails. A visible milestone toward this goal is the design and analysis, development, manufacturing, and successful test of four CFRP booms with a length of 14m each. These deployable CFRP booms, developed by the DLR Institute of Structural Mechanics under DLR funding, combine high strength and stiffness with extremely low density and can be stored within a very tight volume. Because of the very tight volume constraint, e. g. prescribed by the Ariane 5 Microsat Piggy-Back ASAP-5 start option (60x60x80 cm^3), it is necessary that the supporting structure of the Solar Sail is made to be deployable. When

Figure 2: The CFRP booms confirmed their capabilities during the on-ground verification of the Solar Sail project. End of 1999, DLR site Cologne.

considering the enormous size of the solar sail compared with the available transportation volume, the deployment concept must be capable of making very stiff structures readily available but, on the other hand, it must be possible to compress these structures to a very small size without damaging them.

The booms consist of two laminated sheets which are bonded at the edges to form a tubular shape. In the deployment concept of the CFRP boom, the cross-sectional geometry is set up in such a manner that the booms are pressed flat and rolled up on a central hub for storage (Figure 1). After the launch, the booms are uncoiled from the central hub and reach their full stiffness by means of the cross-sectional shape. Once free of the deployment module, the booms resume their original tubular characteristic with high bending stiffness. With regard to the deployment sequence the wall thickness of the structure must therefore be low enough to avoid strength problems with the local bending constraint which are necessary to press the booms flat. On the other hand, the walls of the structure should not be too thin since the buckling loads would then be too small.

The cross-sectional geometry of the booms is shown in Figure 3. The profile consists of two half cross-sections which are connected to each other on the adhesive surfaces. The entire cross-section, except for the adhesive flanges, consists of curved areas. The resulting membrane stiffness is to a great extent responsible for the buckling stiffness of the profile. The wall thickness is not distributed homogeneously across the cross-section. Since the very tight volume does not allow for cross-sectional forms of every height or width, great bending stiffness occur due to increased wall thickness in the areas which show maximum eccentricity from the neutral axis of the boom*.

*With regard to the global stiffness the optimum comes to an infinitesimally thin-walled pipe with an infinite large radius with moments of inertia of $I_x = I_y = \pi r^3 t$ and $J_z = 2\pi r^3 t$. However, this statement does not consider buckling problems!

present CFRP boom properties			
stiffness [Nm^2]	EI_x	EI_y	GJ_z
analytical solution	4886	5599	2627
linear FEA	5210	5575	2728
non-linear FEA	5113	5559	2539
crit. buckling moments [Nm]	M_x	M_y	M_z
linear FEA	252.2	26.3	26.3
non-linear FEA	69.6	46.9	23.5
factor non-linear/linear FEA	0.28	1.78	0.90
unit mass m/l [g/m]		101	
length l [m]		14	

Table 1: Stiffness and buckling moments of the present CFRP boom design. Non-linear analysis considers a maximum geometrical imperfection of $u^* = 0.2$ mm.

Unidirectional carbon fiber prepregs are used as the material. The stacking sequence is made up of a combination of 0°- and ±45° plies. The choice of the ply angle orientation does not only make it possible to realize a high bending and torsional stiffness; the stacking sequence also has approximate thermal neutrality in longitudinal direction ($\alpha_1 \approx 0$) so that the expected differences in temperature between the "dark" and "light" sides result in only a very low overall thermal deflection which has a positive effect on the stress and manoeuvrability of the Solar Sail.

The results of the stiffness calculations are shown in Table 1 together with the critical buckling moments. The unit weight of the booms in relation to the boom length results in $m/l \approx 101$ g/m based on the geometry shown in Figure 3. It is important to note that the booms were sized according to worst-case assumptions for load cases of a 40x40 m^2 sail structure. That means an approximate boom length of 28 m! Bending moments resulting from pre-tensioning of the sail segments considers pre-deflections of the boom tips due to manufacturing inac-

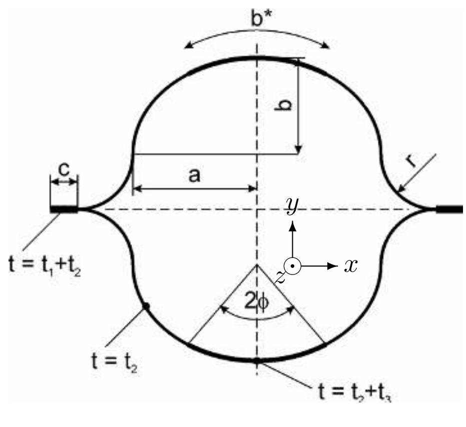

Figure 3: Cross-section of the present CFRP boom design.

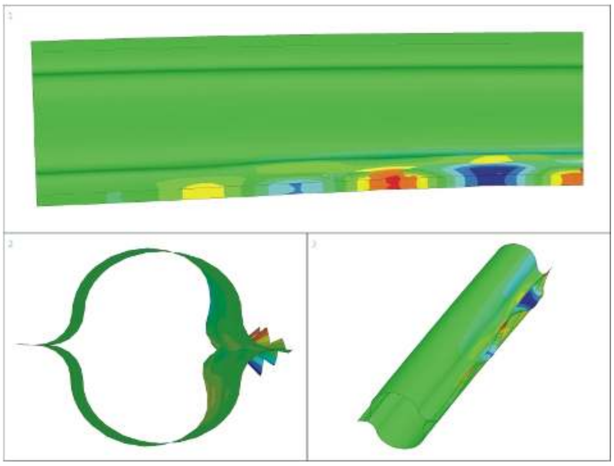

Figure 4: Buckling caused by out-of-plane bending (about y).

curacies, creep, as well as misalignments at the fixture of the booms to the deployment module.

The deployment concept is based on a feasibility study which the German Aerospace Research Establishment e.V. (DFVLR), as it was called back then, had already proposed in the early 1970s [6].

3 Buckling Behaviour

Due to the sail tension forces, the booms are primarily stressed by axial compression forces. Since the Solar Sail is a structure capable of comparatively large deflections in relation to its dimensions, it does not suffice to regard the system as ideally linear. Instead, due to e. g. manufacturing inaccuracies, vibrations, or particularly due to structural or thermal stresses itself, the appearance of more or less large deformations which contribute to a displacement of the point of load application at the boom tips can be expected[†]. Bending stresses, which have a decisive effect on the dimensioning, are the result for the axially stressed and geometrically "imperfect" boom. In addition to the dimensioning bending stresses, torsion occurs in connection with the deformations of the relatively flexible structure. Detailed Finite Element (FE) computations, however, have shown that because of the high $\pm 45°$ share on the stacking sequence, the torsional stiffness are so great that the critical buckling moments are considerably higher than the expected torsion loads [1].

The detailed computation of the stability behaviour of the boom is carried out via Finite Element Analysis (FEA). Linear as well as non-linear computations of the buckling limits are made while taking geometrical imperfections into consideration. The eigenvalue computation of the linear stability analysis is a means of getting an idea of the expected buckling loads so that reasonable ranges of the non-linear calculation can be defined based on the results. On the other hand, the linear results are of great significance with regard on the application of the geometrical imperfections. The eigenforms are scaled with a specific imperfection amplitude and are applied as a worst case pre-deformation in the preliminary non-linear computation. Since the bending moment is primarily responsible for the dimensioning, the buckling behaviour is depicted in the following in relation to the moments about the x and y axes. The transverse forces are so low that their influence on the buckling behaviour can be neglected here. The compression forces do not significantly directly contribute to the buckling behaviour either[‡]. Since the transverse forces are low, it follows that the gradients of the bending moments are small. If the expected buckling wave lengths are taken into consideration, a constant bending moment can be approximately assumed for the analysis. Thus, for reasons of efficiency, only a section of a boom is modelled under constant bending stress.

3.1 out-of-plane bending

The classical buckling limit in plane, thin-walled components does not necessarily pose restrictions on the design. Rather, a stable post-buckling area can appear beyond the bifurcation point which allows for further load increase with a synchronous formation of a buckling deformation. However, a loss in stiffness above the buckling limit must be expected.

The buckling pattern of the last converging load step under a constant out-of-plane bending stress is depicted in Figure 4. As expected, the flange which has little support is prone to buckling. If the load is increased, the shell increasingly contributes to the buckling deformation which is apparent in the changed cross-section shape. After a certain point it is no longer possible to find converging solutions to the stress-controlled calculation. It must

[†]On a 40x40 m^2 Solar Sail, different load models indicate deformations of up to several meters at the tips of the booms.

[‡]Compression forces, however, are of great significance to the buckling behaviour since they are responsible for the development of bending moments when combined with global geometric deformations.

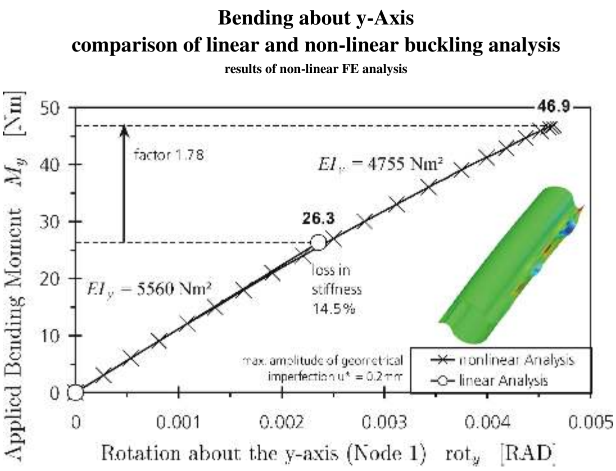

Figure 5: Global load-deflection behaviour due to out-of-plane bending.

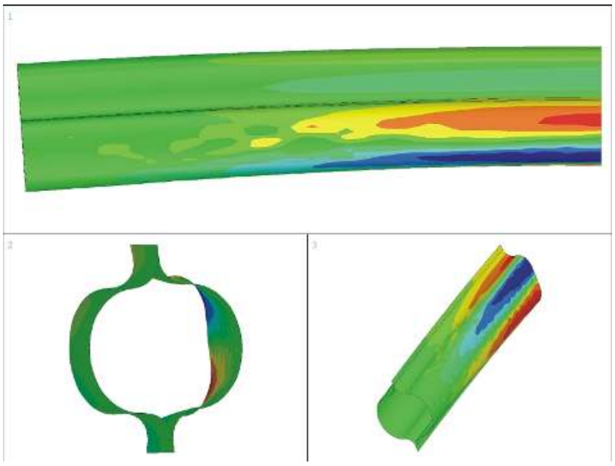

Figure 6: Buckling caused by in-plane bending (about x).

be assumed that a further increase in load will lead to a collapse of the component.

This behaviour is evident in Figure 5. The diagram shows the global deformation behaviour as a characteristic line between the rotation of the end cross-section rot_y and the applied moment M_y. The linear calculation initially leads to the expected flange buckling at a critical bending moment of $M_{y,cr} = 26.3\,\text{Nm}$. The analysis of the elementary relations provides a bending stiffness of $EI_y \approx 5575\,\text{Nm}^2$ which leads to a good agreement with an analytical calculation. After the analysis of the linear buckling deformation and scaling with an amplitude of $u^* = 0.2\,\text{mm}$, the non-linear calculation is carried out[§]. Geometrical imperfections first become evident by a slight reduction in stiffness when load is added ($EI_y \approx 5560\,\text{Nm}^2$). As opposed to a linear calculation, the non-linear calculation indicates a pronounced surpassing of the linear buckling limit due to the formation of a stable post-buckling area which reaches a critical moment of up to $M_{y,cr} = 46.9\,\text{Nm}$. Although a considerable reduction in stiffness can be anticipated (here about 14.5 %) beyond the linear buckling limit, the result is of great significance since the post-buckling behaviour can be specifically used as a safety zone and thus greatly contributes to the effectiveness of the structure. In this example a factor of 1.78 results between the critical moments of the non-linear and linear analysis.

3.2 in-plane bending

The computation of the stability behaviour of in-plane bending is completely different compared to the non-linear computation of out-of-plane bending. The computation steps are analogous to the procedure presented in section 3.1. A linear stability analysis is also carried out here first and then the eigenform is applied with an imperfection amplitude of $u^* = 0.2\,\text{mm}$ in the preliminary non-linear computation as a worst case pre-deformation. The influence of the geometric imperfection can be seen by a slight global loss in stiffness EI_x in this case as well (linear: $5210\,\text{Nm}^2$, non-linear: $5115\,\text{Nm}^2$) but it is not possible to find converging load steps of the stress-controlled calculation near the linear buckling load. Between the non-linear and linear analysis a factor of 0.28 occurs — a knock-down factor which can almost be termed as classical with regard on shell buckling problems. According to the non-linear calculation, a critical bending moment of $M_{x,cr} = 69.6\,\text{Nm}$ must be expected. The deformation figure of the last converging load step is given in Figure 6. In addition, the deformation behaviour is approximately linear up to the convergence problems which can be interpreted as an indication for the sudden snap-through phenomenon.

3.3 combined bending

For the concrete dimensioning of a boom it is necessary to analyse the structural behaviour with combined loads. The general assumption with non-linear analysis is that the loads influence each other and that the superposition principle is no longer valid. In Figure 7 a result of a non-linear buckling analysis is shown which takes into consideration both bending about x and bending about y. The relation of both applied moments is chosen in such a manner that it corresponds to the relation of the critical buckling moment at uniaxial bending. The result shows that with combined stress it is not possible to achieve the uniaxial buckling moments. In that concrete case the result is a reduction of approximately 9 % with regard to the critical buckling moments at a uniaxial stress. The sketched elliptical contour between the moments of the uniaxial stress indicates the determination of a failure criterion similar to the procedure for the strength analysis of unidirectional lamina. In this manner a number of non-linear calculation results under M_x, M_y and M_z stresses can be obtained in order to determine a three-dimensional failure mode envelope under any moment stress.

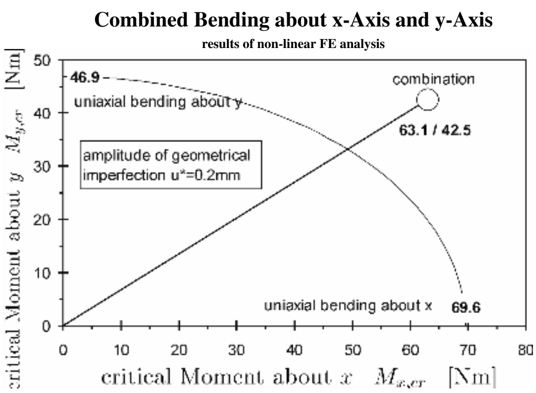

Figure 7: Non-linear buckling analysis of a boom under combined bending.

[§]The imperfection amplitude is first chosen randomly. The given value signifies a "large" amplitude.

4 Thermal Analysis

Because of the combination of a very low boom mass with a relatively large, black surface, thermal problems must generally be taken into account. For this reason, it is necessary to include the thermal behaviour in the structural dimensioning. Depending on the application case, steps must be taken which positively influence the thermal behaviour of the structure.

The result of a transient thermal analysis is depicted in Figure 8. The computation of the temperatures of the top side which faces the sun and the bottom side away from the sun takes into consideration an asymmetrical heat transfer across the surface. The radiation and length of time of the radiation from the sun are chosen according to a LEO (lower earth orbit). The goal of the investigation is to discuss the influence of coating measures, e. g. coating by use of a aluminised surface. The computation model takes into consideration heat transfer via thermal conduction within the structure as well as heat transfer via "internal radiation". The result is given in the left part of the depiction under the assumption of $\varepsilon = 0.95$ (coal) emissivity. On the right side the results for a value of $\varepsilon = 0.04$ (aluminum polished) are shown.

The results show that coating can be a particularly suitable means of positively influencing the temperature distribution on the boom which is radiated asymmetrically. On the one hand, the temperature distribution can be homogenized so that only little differences in temperature occur. On the other hand, much lower temperature maxima and minima occur which allow for an extended application area. In addition, coating acts like a type of "thermal damping". Temperature shocks can play a particularly critical role with large, flexible structures. Coating can be used to avoid such shocks.

Thus certain consequences ensue for the structural design. In order to avoid extensive thermal deformations which, together with the sail tension forces, create additional bending moments, the present boom design takes into consideration a laminate which provides approximate

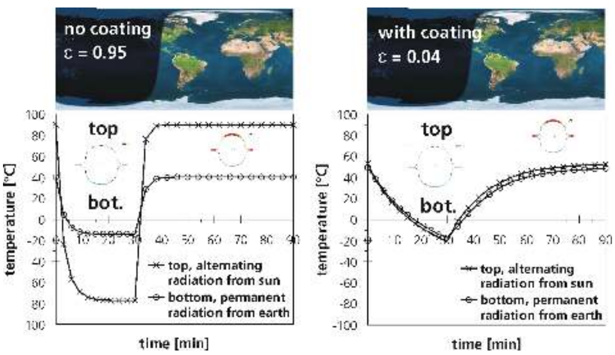

Figure 8: Transient thermal analysis of a boom section with and without coating. Data was taken from a LEO (lower earth orbit) scenario.

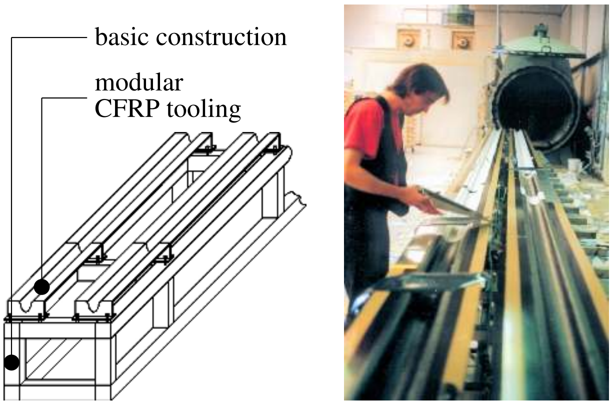

Figure 9: Manufacturing of the CFRP booms was carried out by use of ultra thin-walled CFRP prepregs via a classical prepreg/autoclave technique in conjunction with a modular CFRP tooling concept. After curing, two half-shells were bonded by use of an adhesive.

thermal neutrality in the longitudinal direction: $\alpha_1 \approx 0$. Coating measures can be taken to keep the amount of thermal deformations low even with disadvantageous combinations of layer orientation. In this manner it is possible to realise a large spectrum of possible laminates and also to determine the optimum from structural as well as thermal standpoints.

5 Boom Manufacturing

The manufacturing of the CFRP booms is based on ultra thin-walled CFRP prepregs. These materials have a thickness of only a few 1/100 millimeters and are, therefore, extremely useful to design booms with high bending stiffness by use of an inhomogeneous distribution of the material around the cross-section. Two separate CFRP shells are manufactured via a classical prepreg autoclave cycle (Figure 9). To avoid a thermal distortion of the laminates while curing, the manufacturing tools (form shells) are arranged by use of multi-axial warp-knits having the same laminate configuration as the prepreg shells. A special DLR-developed RI-method (resin injection), the so-called Single Line Injection technique (SLI), offers the technology to impregnate the dry textile preforms with resin and to manufacture the CFRP tools with constantly good qualities. Finally, after curing, the CFRP booms take their typical shape by bonding both shells at their edges with an adhesive.

6 Verification On-Ground

During on-ground deployment the CFRP booms are highly endangered to collapse under their own weight. Therefore, a special method for gravity compensation was developed by DLR, Institute of Structural Mechanics to simulate zero-g conditions. Helium-filled balloons are used to support the deployed booms. Due to the change

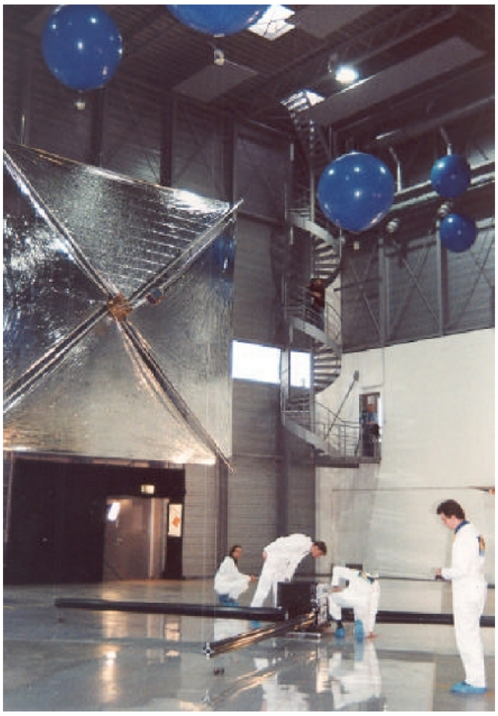

Figure 10: DLR developed a special method of gravity compensation by use of remotely controlled helium ballons.

of deployed boom mass during the unwinding process, the balloons must be designed to allow for an adjustable lift. To resolve this problem, the lift of the Helium balloons can be adjusted actively by using remotely controlled pumps draining water from small tanks below the balloons. These balloons are attached to the boom tips. Figure 10 shows the booms in a partially deployed status with the attached He-balloons moving at about 8 m height above the floor to minimize the effects of inertia. At 7 m deployed boom length additional He-balloons were attached to the CFRP booms to support the middle against gravity. Finally, another four balloons were attached to the booms near the deployment module just prior to their full deployment and latching. All in all the booms can be deployed with a speed of approximately one metre a minute.

7 Conclusions

It was shown that deployable ultra lightweight booms and extremely thin sail film materials can be handled and used to manufacture large solar sail structures. In a ground demonstration, within the joint DLR/ESA effort to pre-develop solar sail technology, the functionality of the deployment concept and associated mechanisms was demonstrated in simulated zero-g and ambient environmental conditions. Based on the successful completion of the pre-development project phase a low-cost flight-validation of solar sail technology in earth orbit is the proposed next step. Once verified in orbit, a number of challenging deep-space science missions could benefit from this advanced propulsion concept as a low-cost delivery system with basically unlimited Δv capability. Solar sail technology holds the promise of significantly enhancing, or even enabling, space exploration missions in the new millennium, by exploiting the space-pervading resource of solar radiation pressure.

Acknowledgements

The authors would like to thank the DLR-ESA-INVENT Team for their contribution to the design and ground demonstration effort.

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