FUNCTIONAL MEMBRANES – A BASIS FOR SATELLITE ARCHITECTURES OF THE FUTURE

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Very thin shells, shell-membrane and membrane structures offer high actuator authority for controlling their behaviour. On the other side, special care has to be taken for proper material and structural characterisation and its interaction with the actuators. In the paper different types of actuators are discussed in the context of precision shell-membrane space reflectors. For actuation, emphasis is given on piezo-ceramics and electro-active polymers. Special integration, modelling and testing techniques for smart fibre reinforced shell-membranes and membranes are addressed. A possible long term impact on some satellite architectures is also addressed.

1. INTRODUCTION

Membrane space structures – being either „small“ or „large“ – get increasing attention for future satellite missions. Reasons for this are both programmatic and technical, as can be seen from the list of current and future applications:

- tensioned membranes as the carrier material and structure for solar arrays with flexible solar cells
- solar sails (“slightly” tensioned)
- (large) communication, radar and even optical reflectors with different stiffening techniques such as tensioned meshes, or membrane mirrors tensioned by (low) internal pressure, space rigidizable materials, or the use of so called shell-membranes with slight bending stiffness just large enough to deliver double curved shells in orbit without any further pre-tensioning
- habitats on Moon or Mars
- Martian balloons or other types of UAVs for planets with an atmosphere

Without going into details at this stage of discussion, these concepts contain quite promising aspects and advantages such as:

- small stowage volume for launch
- low sensitivity to dynamic and acoustic launch loads
- well tailorable to in-orbit functional requirements, with less needed focus on launch requirements
- large in-orbit surfaces achievable
- low mass density
- good if not high shape accuracy under proper design and material concepts, eventually to be combined with proper active control measures

On the other side, proper deployment and static as well (thermo-elastic) dynamic shape stabilisation generate new challenges for research and development. Moreover, in some cases either global or local reconfiguration of the structural shape shall be possible such as for communication antennas with possible reconfiguration for the data downlink.

In the following, some activities in these areas as carried out at the Institute of Lightweight structures (LLB) at Technische Universitaet Muenchen (TUM) are addressed. While chapter 2 addresses some aspects quite briefly, the smart shell-membrane reflector SAFIRS is discussed in more detail in chapter 3 together with Carbon Fibre Reinforced Silicone (CFRS) as the structural base material and different smart materials for actuating and sensing. Specific challenges for materials testing and characterisation as well as for meso- and macromechanical membrane analysis are discussed in chapter 4. In chapter 5 an outlook is given which stretches the horizon of membrane structures beyond those of these components and subsystems already mentioned.

2. LARGE MEMBRANE STRUCTURES ACTIVITIES

In general, large membrane, shell-membrane or space rigidizing structures require proper deployment into final shape, usually to be followed by high dimensional stability of the required shape. This then means proper deployment (or inflation) technology, followed by either passive or active shape control. While the latter should be preferably achieved by a combination of design concepts, thermal control and material selection, active shape control techniques are in order for highly stringent static and dynamic in-orbit accuracy requirements.

2.1. Inflatable booms and structures

For the consideration of deployment stability, inflatable structures should deploy with a relatively slow inflation speed. However, dynamic deployment simulations often employ explicit integration algorithms that require small time steps. Depending on the complexity of the structure and on the total time required for the deployment, this could lead to an order of a million time integration steps. Increasing the mass flow rate of the inflating gas shortens the deployment analysis time, or also special integration time step algorithms. However, it is still open whether the fast inflation analysis results can be extrapolated to predict the structural deployment behaviours at slow inflation rates. Furthermore, for high stiffness and rigidization requirement, space inflatable/rigidizible tubes are considered made by carbon/epoxy fabric prepregs to be cured after being fully deployed. However, pneumatic or pressurized fabric tube structures differ fundamentally from “conventional” structural materials.

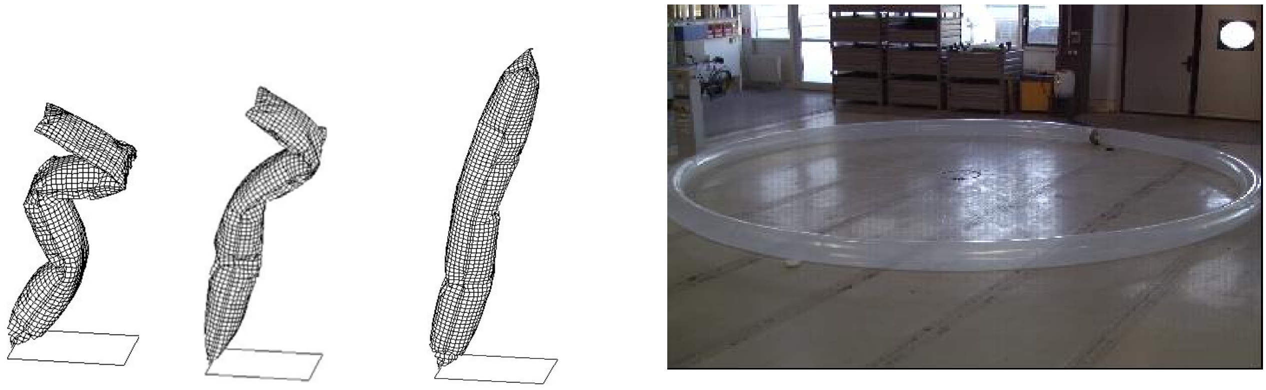

FIG. 1 Simulation and tests for inflatable booms and planar structures

Fabric materials in their non-rigidized state do not behave as a continuum, but rather as a discrete assemblage of individual tows, whose effective material properties depend on the internal pressure of the boom, its weave geometry and the contact area of interacting tows, and others.
Some results from simulation as well as from laboratory tests for inflatable and rigidizing booms are shown in figure 1.

2.2. Shape control and reshaping of reflectors

Like in other application areas, it is desirable also for space reflectors not to provide only shape control which usually requires only small strokes, but also to have the option of highly adaptive or morphing shapes for reconfiguring the antenna's radiation pattern. For example, the focus of a parabolic reflector has to be modified by actuators attached to or integrated at its backside. After this refocusing or change of parabolic curvature, the modified shape shall be again as close as possible to the new theoretical paraboloid, i.e. the rms deviation shall be minimum. Design parameters to achieve this are the number and positions of the actuators but also the thickness or stiffness distribution of the parabolic shell. The achievable minimum rms shape deviation not only depends on the number and positioning of actuators or actuator rings, but also significantly depends on the shell's thickness distribution. When allowing for variable thickness distribution in radial direction, the achievable rms-deviation gets about 5 times smaller than in the case of constant shell thickness. From this the high interaction of structural design with its actuating and control parts becomes obvious again.
The challenges get even higher in case of large precision reflectors which have to be stowed for launch. Since then often very thin shells or shell-membranes are considered, the use of smart materials for actuating gets more natural as discussed in the following.

3. THE SMART REFLECTOR SAFIRS

The need of active or smart reflectors increases with the ratio of diameter vs. required shape accuracy, the latter often specified as rms deviation of the real from ideal shape. Moreover, larger reflectors have to be stowed for launch and deployed in orbit. A new concept called SAFIRS (Structurally Adaptive Fiber Reinforced Silicone Surface) based on thin (0.12mm) shell-membranes is described in the following as a representative case of smart fabrics and membranes. Before discussing the aspects of thermo-elastic and eventually also dynamic shape control, the reflector in its passive version is briefly presented together with the structural materials envisaged and investigated.

3.1. Passive reflector concept

The reference configuration is based on an originally passive deployable shell-membrane reflector. Design goals are:

- usage in L to Ku band frequencies
- reflector aperture >3 m up to very large diameters (say 20-25 m)
- circular, 2D-elliptical, 3D-elliptical apertures
- shape accuracy 1 mm to 0.5 mm RMS shape deviation and even better for lower diameters
- symmetric and offset configurations
- mean aerial density (everything included) not larger than 0.5 kg/m2
- high design flexibility and adaptability to a range of different requirements and configurations
- easy integration of enabling technologies such as shape control

In-orbit temperatures varying from -150 to +150 °C in time and typically 80 °C over the reflector area and 20 °C over reflector thickness have to be observed. Dynamic acceleration acting at the satellite boom, the reflector is attached to, are to be considered. The RF requirements (electrical damping, phase shift etc.) are such that performance shall be the same or even better than that of standard CFRP sandwich reflector antennas.
The reflector's mechanical concept consists of two major building blocks(2,3) :

- foldable and finally tensioned membranes as the backside structure
- foldable-deployable and highly accurate double curved flexible shell-membrane reflecting surface joined tension free to the rear structure and thus having no pillow effect in contrast to tensioned mesh surfaces

A scaled down laboratory model, as well as some membrane components, are shown in figure 2.
For simplicity in a first step, the laboratory model's backside stiffeners are composed of sandwich beams with CFRP-hinges at their roots. For the space model, membranes as shown on the upper right of figure 2 and

tensioned by the deployment booms or pantographs will be used instead. As the baseline material, triaxially woven Carbon fiber reinforced silicone (CFRS) is developed and investigated. Main relevant properties of this composite material are briefly given in the following.

Carbon fibre reinforced silicone CFRS as base material

CFRS is composed of triaxially woven (0°, +/-60 °) carbon fibre fabric reinforcing a space qualified silicone matrix as shown in enlarged scale in figure 3. The silicone matrix material has the following interesting properties:

- low outgassing, no or very low moisture diffusion effects
- resistance to UV radiation and to atomic oxygen
- wide range of service temperature even up to some hundred degrees Celsius
- low glass transition temperature (T_g) at -110°C
- room temperature curing possible
- no or very low shrinkage during curing, thus no or very little curing stresses

The composite has quite low bending stiffness above T_g and the components are thus called shell-membranes. Though foldable above T_g, it is just stiff enough to achieve a double curvature parabolic shell in orbit. Because of the low stiffness of the silicone matrix, the composite behaviour is even more determined by the C-fibers than is already the case for CFRP. This especially results into very low CTEs typically in the range of –0.4 E-6 / °K. It has a mass of roughly 100 – 140 g/m^2, depending on the density of the weave. Due to a special impregnation process, the small holes (diagonal about 1-2 mm) between the fiber bundles can be free of silicone matrix which results into an effective fiber volume content of about 55%. These holes have the advantage of reducing the mass of the structure, make it less susceptible to noise excitation, provide less solar pressure in orbit, and cannot be "seen" by most RF waves. Smaller holes can be produced, and also standard Carbon layers (without holes) can be used together with this silicone matrix.

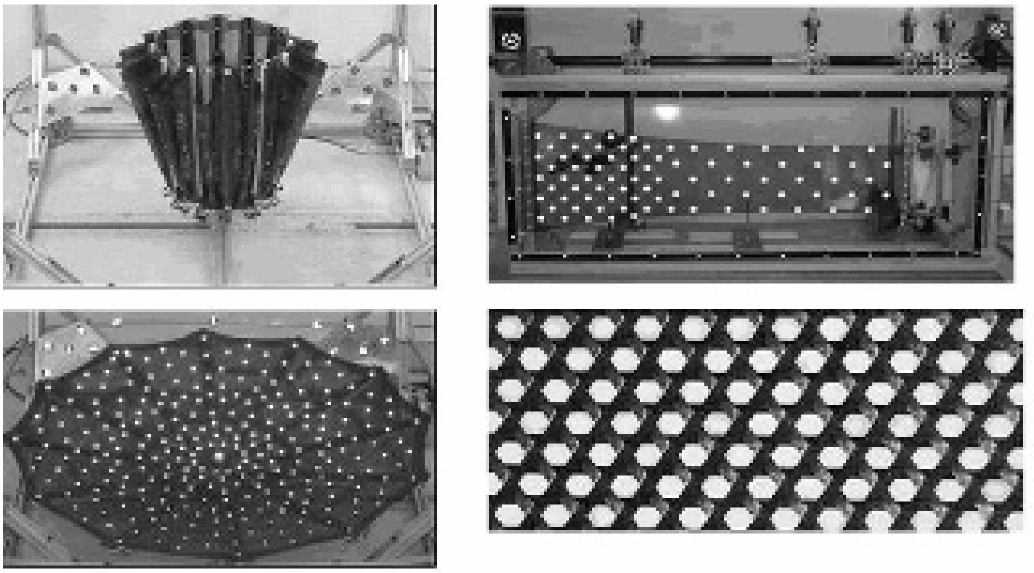

FIG. 2 SAFIRS scaled Reflector in deployed (left up) and folded (left down) positions; stiffening membrane for backside structures (right up) and upscaled foto of CFRS (right down)

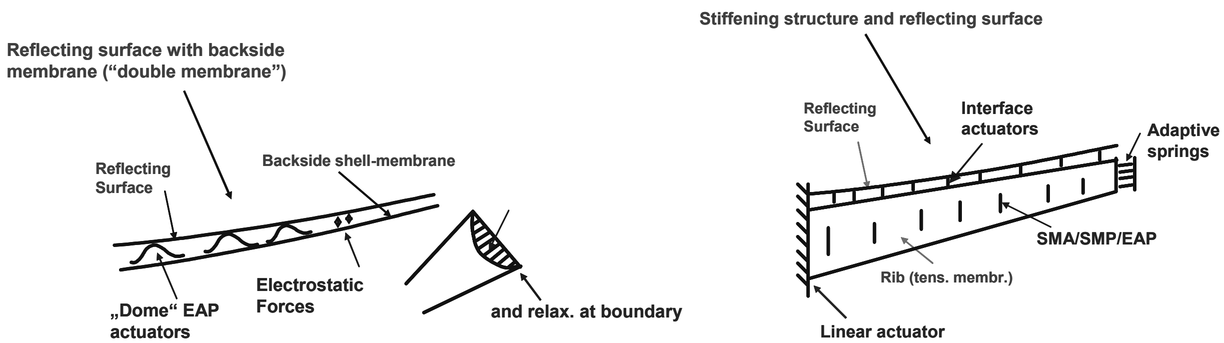

FIG. 3 Shape control options using smart materials in SAFIRS

3.2. Shape controlled reflector

For the shape controlled and adaptive version of this shell membrane reflector, proper actuators, their positioning and integration are the main technical keys. As outlined in figure 3, options for actuating positions are at the backside (tensioned) membrane structure, at the interface between this backside stiffening structure and the reflecting surface, and at the (non tensioned!) reflecting surface itself. At the tensioned rear membranes, linear actuators at the support points can influence the overall rigid and elastic body behaviour, while adaptive springs at the outer edges allow the variation of the membrane's pre-tension and thus also of the structural resonance frequencies. Actuators at the interface between the stiffening structure and the reflecting surface induce lateral forces and bending deformations in the reflecting surface. Because of its low bending stiffness, these deformations decay much faster from the load introduction point as compared to a bending stiff shell, thus allowing also for better local control. Eventual geometrically nonlinear effects due to membrane stiffening might have to be taken into account. For compensation of very local errors, the reflecting surface can be complemented by a further shell-membrane thus establishing a "double membrane". Within this double membrane, "dome type" actuators can be integrated for providing very local shape control, as outlined in figure 3.
A global shape control strategy can be established by solving

$$\text{Minimize } f = \sum_i (d_i - \sum_j u_{ij} x_j)^2 \qquad (1)$$
$$i = 1,...m, j = 1,...n$$

where d_i is his shape error at reference point i of in total m reference points, and u_{ij} is the deformation at this reference point i due to a unit stroke at actuator position j of in total n actuators. The solutions x_j then are the actual actuator strokes to be applied. In case of a linear structure, the solution results from solving then a linear least squares problem. In nonlinear cases, the influence matrix $\overline{u}_{ij}$ might have to be updated stepwise. In the linear case, the condition values of the pseudo-inverse related to the least square problem also gives an indication of proper or improper selection of actuator positions.
Active damping might be less relevant for the reflector itself because of the relatively high inherent damping of CFRS material and the small effective masses involved. It is of more interest for the reflector interface to the satellite bus, being either a mounting structure or a (eventually lengthy) boom. One possibility to compensate for thermo-elastic distortions and also to provide active damping is the CFRP demonstrator shown in figure 4. It contains piezo-ceramic actuators and fiber optic strain sensors. The latter provide the feedback signals for a controller. Results from a PI-controller to compensate thermo-elastic effects are also shown in figure 4. Disturbances in boom length are brought back to practically zero in short time interval . For active damping, the use of a PID-controller results into typical damping values of 3 % to 12 % in the first 2 modes, the eigenfrequencies of which are determined by the boom's stiffness and the rigid body inertias of the reflector.

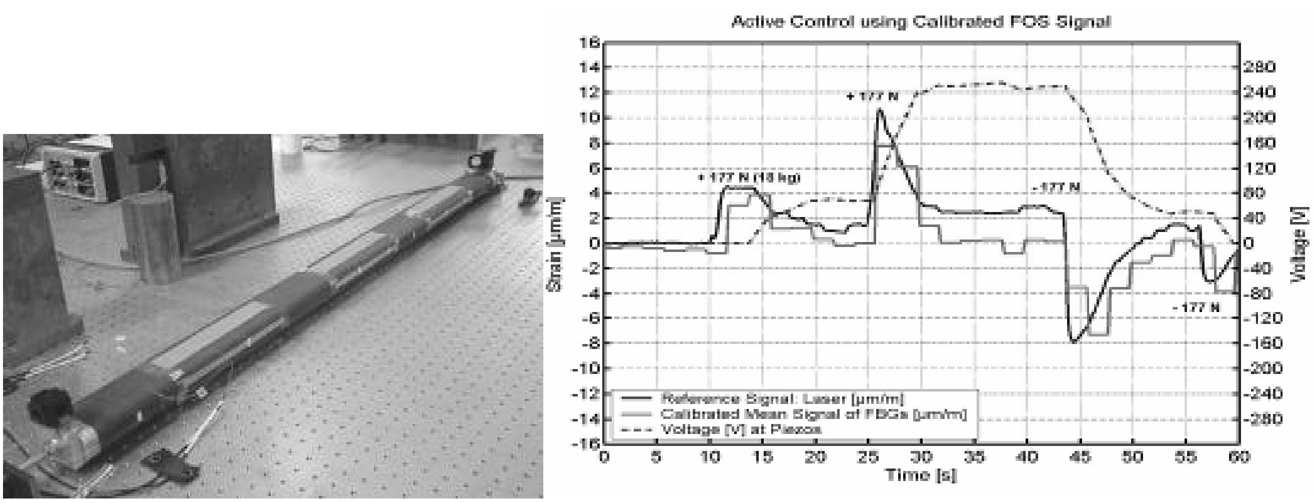

FIG. 4 Smart boom with integrated piezo-ceramics and FOS for deformation compensation

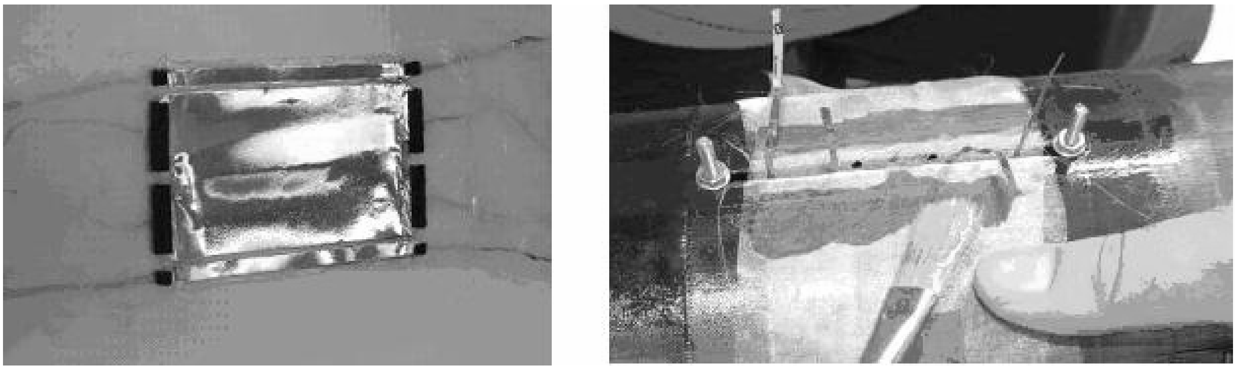

FIG. 5 An electro-active polymer actuator (left) during integration into a fibre composite part (right)

3.3. Actuating smart materials

Apart from the "standard" requirements for the actuators such as low mass, volume and (lower and higher) temperature resistance, the actuators also have to induce their strokes into the structure very smoothly e.g. in order to avoid wrinkling. Because of their low bandwidth and not well controllable behaviour in more extreme temperature environment, shape memory materials are not considered as a serious option in such applications. So piezo materials and electro active polymers (EAP) come into play[4].

Piezo-electric fibre actuators have reached a certain stage of maturity, and for this type of applications often also provide sufficient stroke. Electro-active polymers with a silicone elastomer sandwiched between compliant thin electrodes seem to be even a more natural choice for such shell membranes, since they suggest better integrateability and smoother actuator force introduction into the structure. Compared to piezo-ceramic (fibre) actuators, they also have higher energy density and coupling efficiency with the structure. Their high expansion rate is also relevant, and results into lower actuator masses. Obstacles to overcome are the still relatively high electric fields and voltages needed, and also limited possibility to generate push and pull effects. In addition, thermal expansion has to be properly tuned to that of the structural material. This avoids that parts of the actuating effects would have to be used for compensating such spurious negative properties of the actuators.

3.4. Integration and mounting of actuators and sensors

While for actuators and sensors their integration is envisaged for reasons of improved robustness and eventually also performance, integration is not a design goal per se and has to be traded off with mounting at (external) surfaces. The latter has the advantage of being more flexible with respect to positioning up to the last manufacturing phase, and repair or substitution is easier as well.

When integrating piezoceramic actuators into CFRP laminates, generation of local fibre bending and local resin concentration is hard to avoid. So in addition to likely thermo-elastic mismatch between the piezoceramic actuators and the CFRP base material, these disturbance might lead to further "hot spots" both for temperature or strain in an otherwise highly precise and dimensionally stable structure. This gets even more severe for thin shell and membrane type structures, where for example wrinkling e.g. due to thermal stresses or improper introduction of actuating forces is to be avoided. An actuator based on EAP(5) and shown in figure 5 can be relatively easily attached or integrated in a laminate layup, and can be bonded on a CFRS shell-membrane.

For strain or temperature sensing, fibre optic sensors (FOS) are an interesting option. Typically, about 20-60 Bragg sensors for strain (or temperature) measurement can be included in a single optical fibre, which depends on the electronic equipment for sensor data processing. So in principle a network of such sensors can be relatively easily established as compared to standard strain and temperature gauges with their high amount of required wiring. Moreover, FOS have found to be quite robust with low drift.

Figure 6 shows some investigated options for mounting via bonding or integrating FOS into CFRP laminates, with some results also listed. Bonding requires careful selection of glue and bonding process, while integration shows best correlation to otherwise measured strain data[6].

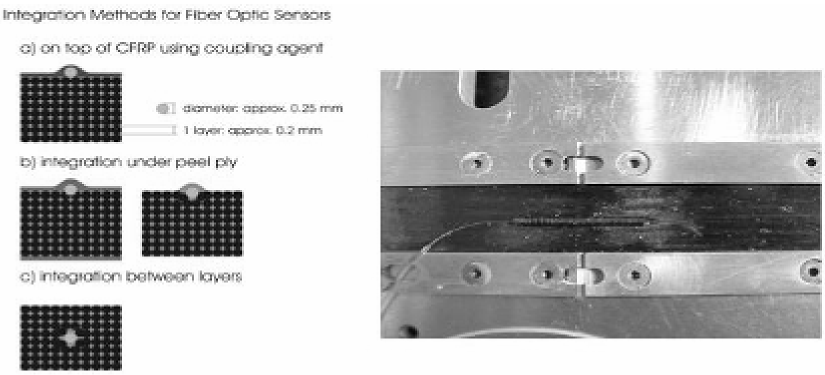

FIG. 6 Optical fibers in carbon composite materials (left) and embedded FOS temperature sensor (right)

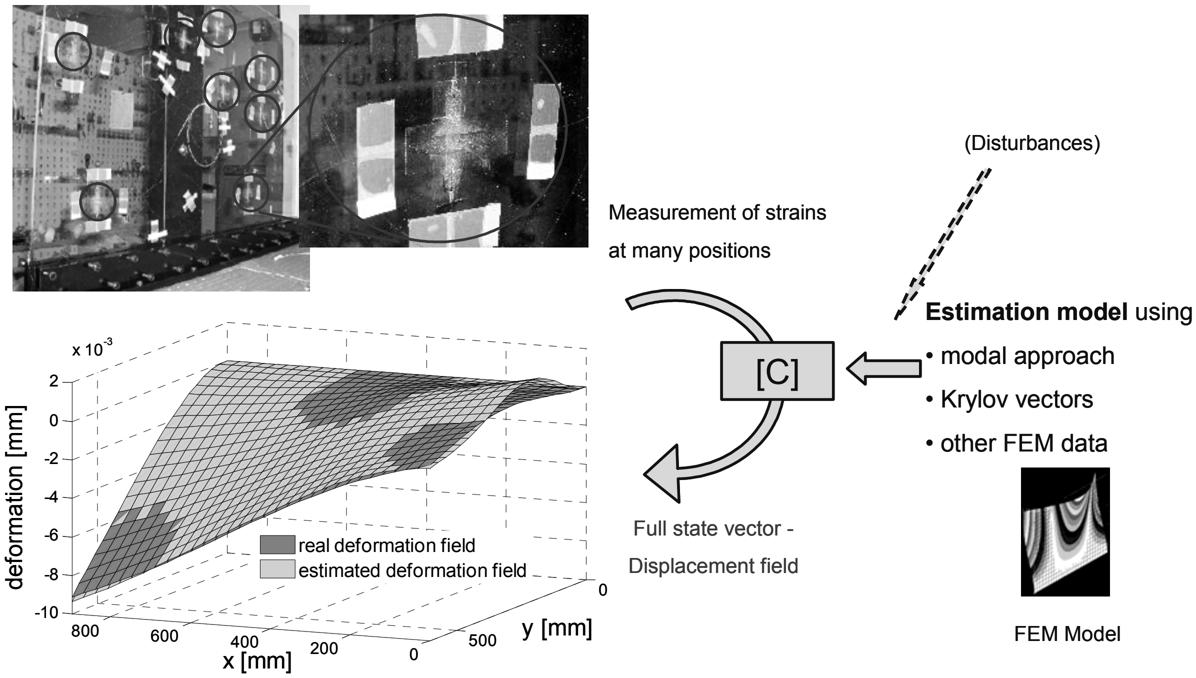

FIG. 7 Displacement field estimation process

In order to avoid possible delaminations of CFRP layers in highly stressed areas, quite thin optical fibres should be used. For CFRS, the optical fibre could be attached by local sewing and bonding, respectively.

Once a network of strain sensors is established, the displacement field or shape deviation can be derived by a process as outlined in figure 7. Such inherent displacement field (!) observation techniques might be used complementary or in redundancy to optical or RF sensing techniques for mirrors or antenna reflectors. Important elements of this process are the number and position of sensors, as well as the establishment and quality of the matrix [w] which transfers several or many strain data to the displacement vector {u} (i.e. the discretized displacement field) with its very high number of dofs. The columns of transfer matrix [w] could be established via eigen-modes, Krylov vectors, from FEM calculations, or a combination of these. Some results obtained analytically and experimentally are given in figure 7 and 8. They demonstrate the general validity of the approach.

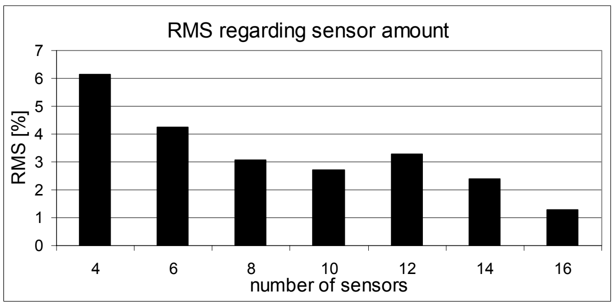

FIG. 8 Estimation error regarding sensor amount

Finally, it should be mentioned that strain data per se might be used also as feedback signals for (shape) control of space membrane structures. For example, homogenous distribution of strain in certain components could be such a control criterion. This also includes a preferable “zero-strain-state” as for the reflecting surface of SAFIRS.

4. SOME COMMENTS ON ANALYSIS AND TESTS

4.1. Analysis and simulation

For the static, thermo-elastic and also dynamic finite element models proper material data for CFRS have to be used. While in the undisturbed regions from some distance of boundaries or edges homogenisation of the behaviour on a macro-scale is relatively straightforward, more care has to be used close to boundaries. The reason is that fibre bundles are not necessarily fixed at the edges, and the behaviour may locally be more flexible and more anisotropic than in the inner parts. This becomes obvious also from the micro-geometrical model and some deformation field shown in figure 7. There is also good correlation to test results. In cases of relatively large control strokes compared to the shell-membranes’s thickness (i.e.being in the range of the thickness or larger), the behaviour becomes geometrically nonlinear. So the overall simulation of the (nonlinear) structure together with its actuators may put considerable computational burden for determining the actuator effects and also for simulating the control loop behaviour.

For dynamic excitation with many eigenmodes involved, model reduction might have to be carried out for simulation with the control loop. Automatic methods are

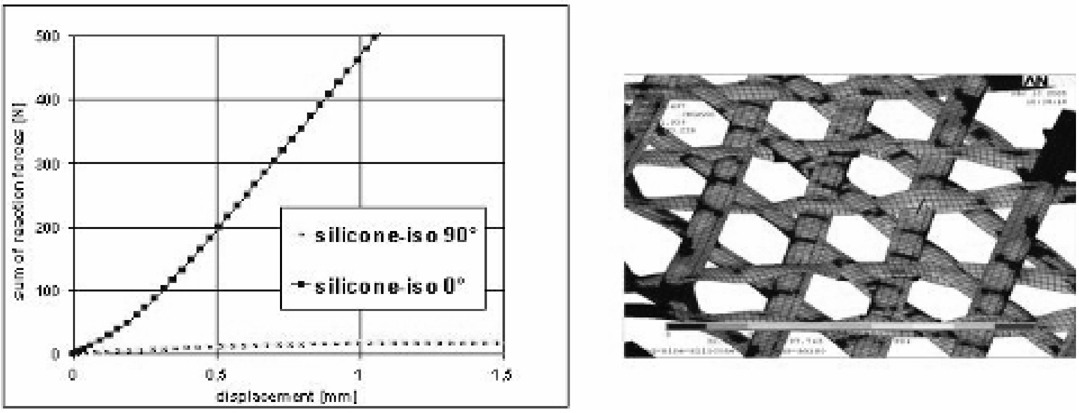

FIG. 9 Computed stiffness for triax CFRS and related micro-mechanical model

based on effective modal mass tables, controllability/observability and balanced truncating. A system is called balanced if controllability and observability Gramians are equal and diagonal. For a balanced system the new state vectors are ranked according to their contribution to the Hankel singular values. This then allows to reduce states with little or no influence on observability and controllability. In order to take into account the expected frequency spectrum of the excitations, a frequency weighted balanced modal reduction has proven to be appropriate. To evaluate the model quality, effective mass tables can be also considered, and the transfer functions of full and reduced models can be compared.. Moreover, dynamic models of actuators and sensors can be included.

As far as actuator models are concerned, the so called thermo-elastic analogy may be used for basic investigations e.g. related to actuator position and basic performance assessment. In this analogy the formal similarity if not identity between strain-temperature relation and strain-electric field relation for piezos or even EAPs is used. Especially for the latter, this is an approximation which among others assumes linearisations of these relationships.

4.2. Special techniques for experimental characterisation

Experimental characterisation of such thin membranes and also thin actuators requires special techniques. In principle, either contact (force) free optical techniques have to be used for measuring deformations both on specimen and on structural level, or the test arrangement has to be such that small sensor contact forces or even gravity effects do not significantly influence the measurement. An example for the latter is the use of circular tube type specimen as shown in figure 8, which are achieved by rolling the thin and originally planar membrane materials.

These tube type specimen then can be tested in a dilatometer for determination of the CTE. Alternatively, 2d-testing of planar specimen e.g. via Speckle-interferometric strain measurement is in order. Stiffness and strength data are also preferably to be determined by 2d-testing with specimens sufficiently large compared to the measurement area (typically 5 cm x 10 cm). This shall compensate for spurious edge or boundary effects.

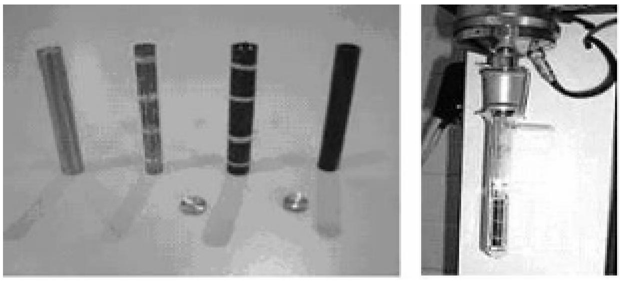

FIG. 8 Rolled membrane specimen (left) for CTE measurement in dilatometer (right)

5. CONCLUSION AND OUTLOOK

For many satellite components and subsystems, membrane or close to membrane structures are a natural approach or must especially for large deployable structures. In addition, those structures more easily lend to further active means for shape control and active damping as compared to “classical” stiff structures. Further functions such as passive or active RF reflecting elements will be also integrated [1]. In the long term it could well be that the concept of membranes stretches beyond that of structures and might even more heavily determine the overall satellite architecture. In addition to required size in orbit, it are the low sensitivity to launch loads and also an overall architecture allowing to having developed or purchased and launched different subsystems (rolled membranes or smaller hard packages)separately which then are physically and / or software-wise (data transfer etc.) coupled in orbit. One of these long term concepts are so called Furoshiki satellite architectures [7]. For example, large membranes are deployed, positioned and to some extent also shape controlled by different nano-satellites. This membrane then span some kind of “working space”. Micro robots moving along this working space then distribute other elements such as RF Reflectors needed for the overall architecture and mission.

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