OPTICAL METHODS FOR NON CONTACT MEASUREMENTS OF MEMBRANES FOR SPACE STRUCTURES

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ABSTRACT

The object of this paper is to perform a review of existing optical measurement methods that could measure membrane systems. We typically have investigated videogrammetry (static measurements), stereo-correlation (dynamic and static measurements), fringe projection (wrinkles) and 3D laser scanning vibrometry (dynamic measurements). Therefore, minimum requirements were given for the study in order to have a representative test articles covering a wide range of applications. Representative test results obtained with the different methods on the test articles are presented.

1. INTRODUCTION

Structures for space applications very often suffer stringent mass constraints. Therefore, lightweight structures are developed for this purpose, through the use of deployable and/or inflatable beams. The mass of the support for the active surface (solar cells, antenna patches, etc) shall also be reduced. Therefore, thin-film membranes are investigated for this purpose. Lightweight (Gossamer) spacecraft technology will enable very large ultra-lightweight systems for new missions, such as [1]:

- Very large aperture telescopes for imaging extra-solar planets, studying the formation of large-scale structures in the early universe, and continuously monitoring Solar System bodies from distant vantage points;
- Large deployable and inflatable antennas for space-based radio astronomy, high-bandwidth communications from deep space, and remote sensing with radar and radiometers;
- Solar sails for low-cost propulsion, station-keeping in unstable orbits, and precursor interstellar exploration missions.
- Large solar power collection and transmission systems for future exploration missions and for the commercial development of space.

Inherent properties (low mass and small thickness) preclude the use of conventional measurement methods (accelerometers and displacement transducers for example) during on-ground testing.
The exact measurement requirements obviously depend upon the specific application: sun shield, solar array, antenna or others, with sizes ranging from one to several dozens of meters. Furthermore, the surface nature of the membrane can be specular reflective, diffusing or transparent.
Many applications dealing with the mechanical behavior of materials require the measurement of displacement fields or deformation fields. In order to attain these measurements, optical methods have become unavoidable due to their non-intrusive approach, their high spatial resolution, their high sensitivity, and the large size of their measured field.
Therefore, minimum requirements will be given for the study in order to have representative test articles covering a wide range of applications. The object of the study is to perform tests with existing measurement systems able to fulfill the requirements: dot-projection videogrammetry (static measurements), stereo-correlation (dynamic and static measurements), fringe projection (wrinkles) and 3-D laser scanning vibrometry (dynamic measurements). Test results obtained with the different methods on the test articles are presented.

2. MEASUREMENT REQUIREMENTS

From the previous applications, it becomes obvious that a multitude of different properties of the possible test items for non-contact measurement is being to consider. The variety of measurement requirements is motivated by lack or imperfect modeling capabilities of membrane structures during development.

2.1. Required and desirable measurements

- Geometry in ambient condition (manufacturing or static accuracy) : < 0.1 mm.
- Dimensional stability (shape deviation due to environment condition, especially temperature).

- In both cases global shape deviations and local ones (wrinkles); need of gravity compensation also depending on stretching level etc.
- Deployment / inflation dynamics: large rigid body motions together with elastic parts; desirably (but not necessarily) in vacuum, gravity compensation essential.
- In-orbit dynamics: eigen-dynamics and low vibration levels up to 10 Hz; desirably in vacuum (air mass and damping effects). Frequency resolutions of 0.1 Hz are expected.
- Number of points: position measurement of certain points ranging from "several" to eventually many hundred over smaller areas (some hundred cm2) to larger areas (many m^2).

2.2. Measurement accuracy

- Rigid body motions can be in the order of meters (during deployment), required resolution in the order of mm.
- Surface points coordinates measurement resolution should be in the range of some mm preferably down to some 10 µm.
- Though wrinkles should be avoided by proper design and stretching techniques, they might have to be identified especially during development tests. They may have amplitude of up to some mm [2].

2.3. Typical properties of measurement items

- Planar, curved.
- Transparent, diffuse, reflective.
- Surface with wrinkles.
- Surface roughness: Lower and higher micro-geometric surface roughness.
- Surface texture: Lower and higher macro-geometric surface roughness (textile/fabric materials, meshes).
- Small sizes up to larger sizes / areas to be measured.

3. REVIEW OF PROPOSED MEASUREMENT METHODS

3.1. Introduction

In order to obtain these measurements, optical methods have become unavoidable due to their non-intrusive approach, their high spatial resolution, their high sensitivity, the large size of their field, and the increasing power of the computers that now allows the processing of huge quantities of data.

Very good reviews on co-ordinate, surface and shape metrology methods can be found in [3][4]. Nevertheless only a few of them can really be considered as subject of interest for membrane measurements. Some methods are simply too restrictive and are consequently disregarded at least for the near future applications. These methods have high resolution, but they are very sensitive to the environment and have limited dynamic ranges.

1. Wavefront measurement methods: visible and infrared interferometry has a potential high wavefront measurement resolution (micron and sub-micron) [5]. But these methods have strong limitations on the surface slopes. Recent papers [6] have shown these limits in measurements on carbon-fiber reinforced polymer (CFRP) reflectors.

Other characteristics are:

- high surface reflectivity (no transparent or diffuse surfaces)
- low surface roughness (Ra < 1 micron)
- stigmatic test: require high quality auxiliary optics or null lens and fine alignment
- high mechanical stability
- absolute shape at the expense of high accuracy auxiliary optics

2. Holographic interferometry: This is a surface measurement method with imaging. It is as sensitive as interferometry. It does not require auxiliary optics. And recent developments show that both reflective and diffuse surfaces can be measured [7]. As for interferometry, this method requires a high mechanical stability.

The attention is deliberately focused on methods which could be used in a more industrial environment based on 4 criteria:

- The measurement equipment is marginally sensitive to the environment (specifically vibrations: no interferometry, holography): this has the advantage of using methods in the development programs of membranes.
- Easily scalable methods. It would be nice to explore methods that do not excessively increase in hardware complexity. Small or large membrane surfaces or objects can be measured with a change of measurement geometry and not at the expense of acquiring hardware (e.g. auxiliary optics in wavefront sensors).
- A 10-100 µm resolution could be sufficient. It is believed that in the short terms the membrane applications will require this accuracy, because optical reflectors are not yet envisaged.
- Non-contact and non-intrusive methods.

Based on the experience gained during past studies performed at CSL under ESA projects, we can limit the scope of review to non contact optical methods that enter into 2 of these 4 criteria. In summary, the following series of methods are addressed.

- Videogrammetry
- Stereo-correlation
- Fringe projection
- 3-D Laser scanning velocimetry

3.2. Videogrammetry

The increasing power of the computers that now allows the processing of huge quantities of data, has generated a rapid progress in the application of triangulation systems for measuring 3-D shapes or 3-D displacement fields using multiple images approaches.

Videogrammetry is based on triangulation and uses digital photographs as the recording medium for metrology. By taking images from at least two different locations, the so-called "lines of sight" can be developed from each camera to points on the object. These lines of sight are mathematically intersected to produce the 3-dimensional co-ordinates of the points of interest. Knowing the camera parameters, a linear position on the detector is translated into an angular position of the point. A series of points are materialized on the structure by self-illumination, by projection of an array of points on the structure, or by detecting the contrast with respect to the surrounding background (a source illuminates white dots on a black plate, retro-reflective targets).

At least two sensor stations measure the two 2-D angular positions in the sensor reference frame. The sensors also measure a calibrated scale bar to fix the absolute length scale. Numerical methods are used to compute the intercept (co-ordinates of the target) of different lines of sight (angular measurements of sensor-point direction) which is called bundle-adjustment. One can measure multiple points at a time with virtually no limit on the number of simultaneously triangulated points. Typically, 100 to 1000 points can be recorded with this method.

The weak points of videogrammetry for membrane measurements are:

(a) Re-positioning of sensors is necessary
(b) A discrete number of points
(c) Co-operative targets are sticked on the surface

In order to by-pass problem (a) multiple sensor configurations are possible, but could be very expensive. In order to circumvent problems (b) and (c) a dense pattern projector can be used, meaning in this way a larger number of points and avoiding damaging the surface to be measured.

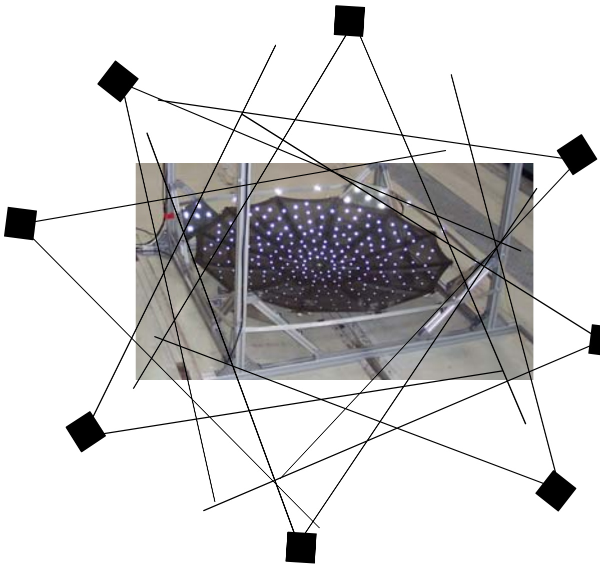

Fig. 1. Dot projection videogrammetry test configuration for FLAME, showing typical camera stations (black squares). The typical stand-off distance of the cameras is 2.5 m.

In the framework of membrane measurements, dot projection videogrammetry has proven to be a good solution, since the dot projection has no intrusive characteristics [9].

The “Lehrstuhl für Leichtbau“ has measured the FLAME membrane with a videogrammetry system using retro-reflective targets [8].

3.3. Stereo-correlation

Stereo-correlation is a variant of triangulation developed very recently. This method allows: (1) the measurement of the 3-D object shape using a single pair of stereoscopic images of this object and (2) the measure of the 3-D displacement field using at least two pairs of stereoscopic images of an object corresponding to two states of its deformation (or the processing of a sequence of pairs of images acquired during the deformation). The main features are: the strong calibration of a camera or a stereo-vision sensor, the 3-D reconstruction by stereo-vision, the measurement of the 3-D displacement field using a combined stereo-correlation and tracking approach in a sequence of images.

Stereo-correlation is a technique for building a three dimensional description of a scene observed from two slightly different viewpoints. From a pair of images, it is possible to compute the 3-D co-ordinates of a physical 3-D point by triangulation under 2 conditions:

The two image points have to be matched, i.e. identified as corresponding to the same physical point. This is called the stereo-matching (correlation) problem.

The geometry of the stereo rig (i.e. the relative position and orientation of the two cameras) has to be known. This problem is solved by means of an off-line camera calibration procedure.

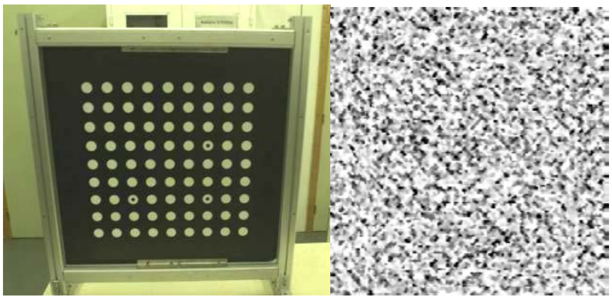

Fig. 2. Calibration plate (Left) and projected speckle pattern (Right).

Fig. 3. Stereo-correlation camera, speckle projector.

The calibration parameters will be used at different stages:

- the rectification of the stereo image pairs,
- the correction of lens distortion,
- the calculation of the 3D position of a scene point from its stereo projections by triangulation.

The main difficulty in stereovision is to establish correspondences between pairs of images. The trick used in this method, is to project a speckle pattern or to use the surface texture as basis for the image correlation. The stereo-correlation technique gives a dense 3D reconstruction (almost all the pixels of the stereo images can be matched).

3.4. Fringe projection

Fringe projection consists in the projection of several fringe patterns with different spatial frequencies and to record the image on a camera at several different places [10].

The fringe projector is either a slide projector or an interference pattern projector.

In both cases there are means to vary the fringe density (scanning slides) or variable interference fringe spacing, which help in covering the dynamic range and adapt the depth resolution. In any case the lateral resolution is given by the camera pixel resolution. The depth resolution is scaled by the angle between camera and projector.

The decoding of the fringes is carried out in the camera space. The method achieves an accuracy of 1000 ppm and a resolution of 100 ppm. The advantage of the method is that the fringes can be easily projected and that they can be easily localized on the camera image either if they are out of focus. Because of the weak demands in accuracy, fringe projection is a good candidate to measure membranes.

In comparison to videogrammetry it offers a much denser cloud of measured points. Typical resolutions are 0.5 mm for 0.5 m by 0.5 m object. Larger field can be measured using some stitching technique of the sub cloud points.

Fig. 4. Fringe projection system: the camera (Left) and the laser projector (Right).

3.5. 3-D Laser scanning vibrometry

Unlike traditional contact vibration transducers, laser-based vibration transducers, or laser vibrometers, require no physical contact with the test object.

Remote, mass-loading-free vibration measurements on targets that are difficult or impossible to access are typical examples of applications where a laser-based vibration transducer would be the natural choice. Furthermore, the ability to incorporate advanced, miniaturized, optical mirror systems together with the laser source provides automated scanning measurements, where a high number of measurement points can be measured consecutively.

Non-contact vibration measurements with very high spatial resolution are possible with such a scanning system and can lead to significant improvements in the accuracy and precision of experimental modal models.

The measurement principle of a laser vibrometer is based upon the Doppler effect. When monochromatic laser light is scattered back from a vibrating target it undergoes a frequency shift proportional to the velocity of the target. This is known as the Doppler effect. As the target moves towards the light source, the back-scattered light undergoes an increase in frequency. As the target moves away, the back-scattered light undergoes a lowering of frequency.

If the target is vibrating, the frequency of the back-scattered beam will be frequency modulated at the so-called Doppler frequency. The Doppler frequency is directly proportional to the velocity of the target. Therefore, tracking this Doppler frequency provides a direct measurement of the target's velocity relative to the motion of the light source.
Scanning laser vibrometry is used to determine modal frequencies of structures. For each point of a pre-defined measurement grid, the laser vibrometer software can then generate the frequency response function. By scanning, the modal frequencies and shapes can be measured.

Fig. 5. Two views of the three 3-D laser scanning vibrometry heads. A stereo-correlation system is interlaced, in order to allow performing simultaneous acquisitions. The distance to the membrane is about 3 m.

At low frequency, this process may be time consuming, as it is necessary to record at least one period on each point (20 minutes to scan 120 points with a frequency resolution of 0.1 Hz).

The typical accuracy on the shape is 50 ppm of the measured length (range).

4. SAMPLE TEST ITEMS

A series of evaluation tests is defined that cover typical measurement cases from the wide variety of applications.

- A rigid reference structure: a planar CFRP sandwich plate (size in the order of 1m) is used as a reference plate for checking and verifying measurement accuracy.

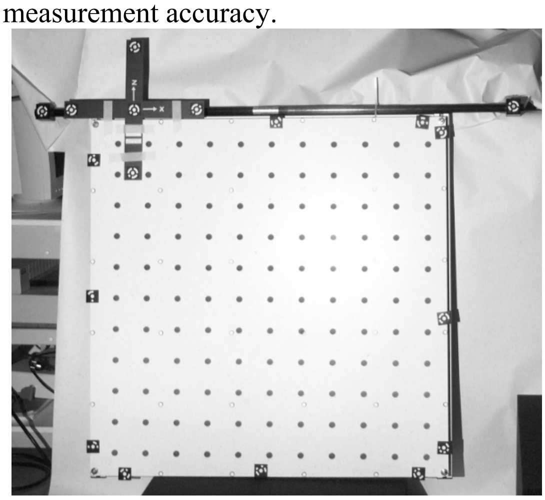

Fig. 6. Rigid CFRP structure

- Planar membranes (1 m x 1 m) made out of KAPTON, Nylon foils and a “textile” material (e.g. 0/90 or silicone reinforced tri-axially woven carbon fiber fabric: CFRS [11]), which are candidate (preferred) materials in membrane technology. These membranes will be deformed to introduce wrinkles (Fig. 7).

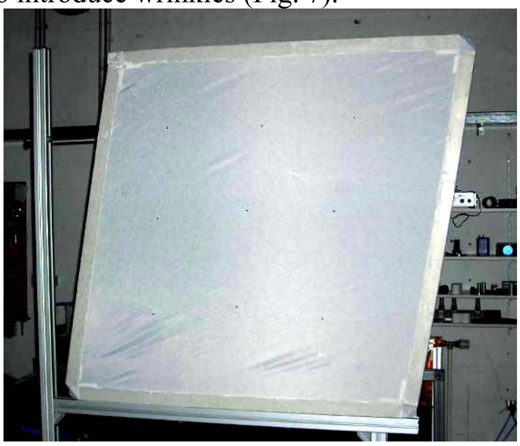

Fig. 7. CECONITE wrinkle membrane. The wrinkles are generated with a shear in the frame.

- A representative curved membrane: The FLAME membrane reflector (diameter around 1.6 m) with reflecting surface made out of woven CFRS. It has a parabolic shape (Fig. 8).

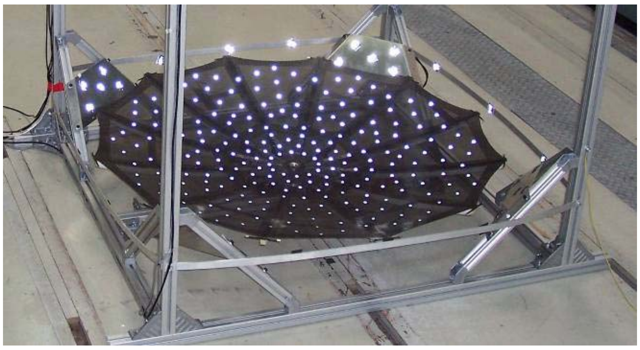

Fig. 8. FLAME reflector with measurement support structure.

- A test item with dynamic variable surface curvature (Fig. 9). This will be generated by pushing a tensioned membrane periodically.

Fig. 9. Views of the moving pusher in the Z-direction mounted on linear translation stages, which will deform the membrane.

The measurement techniques and the sample membranes, are summarized in the table TAB 2. Note that this table does not consider the surface texture or artifacts that need to be used to make the measurement. It is also very qualitative.
It mainly shows the link between test cases (with specific membrane characteristics) and measurement methods.
In order to make comparison between possible methods we see that stereo-correlation is common to a lot of cases. It would be suited for a common basis for comparison.

5. TEST RESULTS

5.1. Resolution and accuracy test on rigid 2- D structure

The repeatability of the stereo-correlation system was characterized with 20 static measurements (TAB 1).Then a rigid body motion is applied in the Z-direction. The motion is monitored with a linear interferometer, with absolute accuracies of better than 10 µm. In order to verify that it corresponds to a real rigid body motion, the displacement of two points, measured with stereo-correlation, is subtracted. The difference is in the range of the static measurement repeatability (about 0.05 mm).

Z=	X repeatability (mm)	Y-repeatability (mm)	Z-repeatability (mm)
0 mm	0.03	0.03	0.05
0.1 mm	0.03	0.03	0.05
1 mm	0.03	0.03	0.05

TAB 1. Repeatability of the stereo-correlation system.

	Rigid structure	Plane Membrane with wrinkles	FLAME Curved membrane	Dynamic membrane
-Videogrammetry	x		x	
-Stereo-correlation	x	x	x	x
-Laser scanning	x	x	x	
-Fringe projection	x	x	x	
-Scanning laser vibrometry				x

TAB 2. Measurement methods versus sample membrane matrix (x) applicable methods. In white box test that has been implemented in this work.

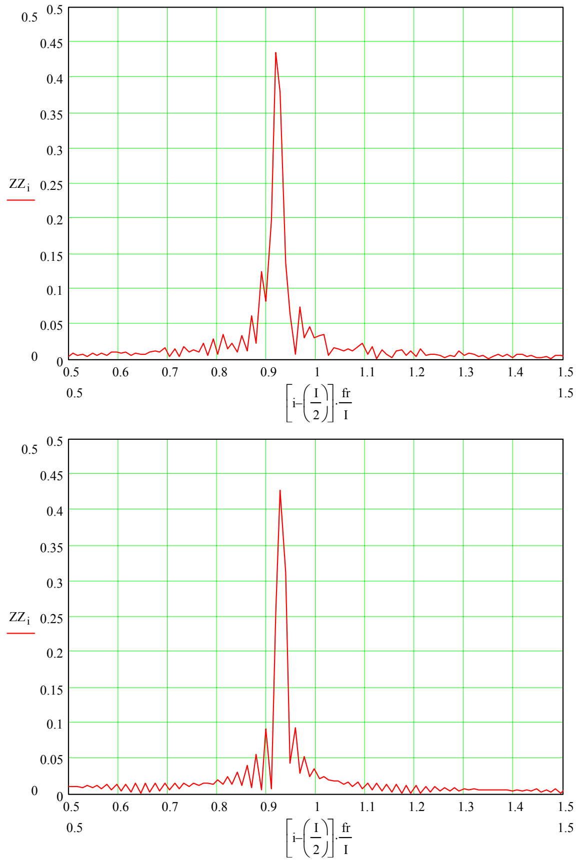

Fig. 10. Frequency spectrum (Y-axis in mm) of the periodic rigid body displacement motion, measured with stereo-correlation (Left) and HP interferometer (Right).

The next step consists in assessing the accuracy in a dynamic measurement. The displacement of a point of a moving plate is compared to the displacement measured with a linear interferometer. For a triangular excitation, we look at the first harmonic (Fig. 10). It results in a match of better than 0.02 Hz in frequency and 0.01 mm in amplitude:

Stereo-correlation:

0.92 Hz ± 0.02 Hz; 0.43 mm ± 0.05 mm

HP-interferometer:

0.93 Hz ± 0.02 Hz; 0.43 mm ± 0.01 mm

5.2. Shape measurement on FLAME membrane

5.2.1. Videogrammetry results

Very accurate shape measurements were performed with videogrammetry. The RMS accuracy on the points is better than 0.007 mm. Post processing results give the RMS deviation with respect to the best fit parabola 0.506mm, and the focal length: 1215.5 mm.

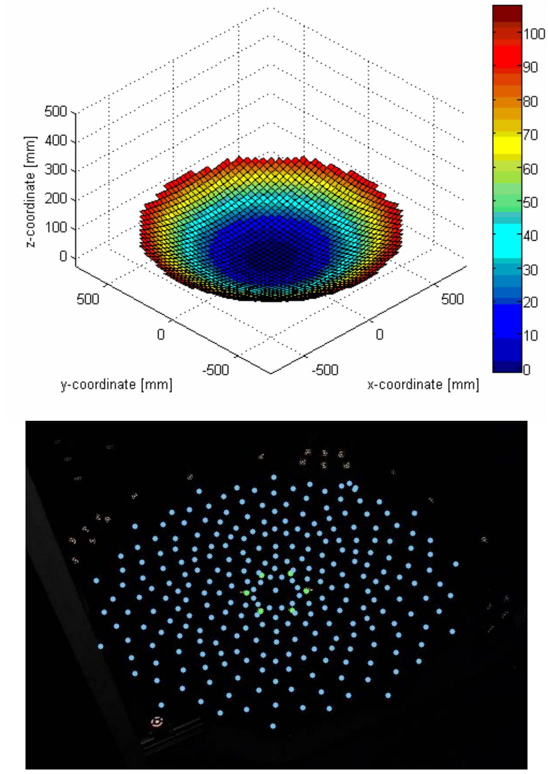

Fig. 11. Results of the videogrammetry measurement (top): the shape and the measured points (bottom).

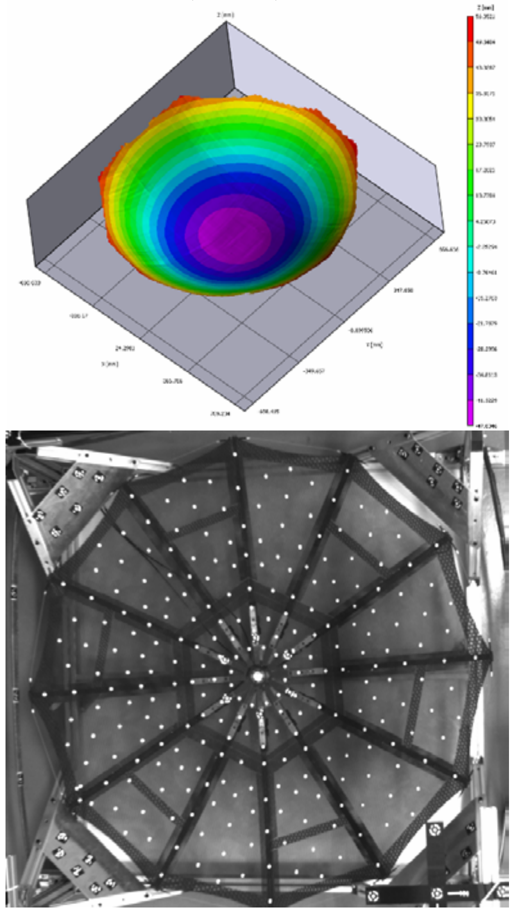

Fig. 12. Results of the stereo-correlation measurement the shape (top) and image seen by a stereo-correlation camera (bottom).

5.2.2. Stereo-correlation results

The apertures of the CFRS structures make the use of stereo-correlation based on speckle projection impossible. In the current conditions correlation the patterns created by the retro-reflective targets are used (Fig. 12).
Correlation areas covering typically 3 retro-reflective targets were chosen (100 camera pixels). The shape was computed with the result of the correlation of the patterns created by the retro-reflective targets. The best fit parabola gives a focal length of F:1214.2 mm.
The two data-sets have been compared. It required to triangulate the two data-sets and to re-interpolate them at the same sampling rate. The RMS difference is 0.5 mm.

5.3. Wrinkled membrane test

The measurement of wrinkles requires methods with a high lateral sampling rate. Two methods were adopted: fringe projection and stereo-correlation. The methods ware applied on different materials: CECONITE (diffuse), Nylon (transparent) (Fig. 13), Aluminized KAPTON (Reflective) (Fig. 14) and CFRS (textured with aperture). KAPTON, Nylon and CFRS have been made diffuse with a fog of white paint.
Fringe projection can measure all types of pre-processed surfaces. Stereo-correlation fails in measuring the CFRS surfaces.

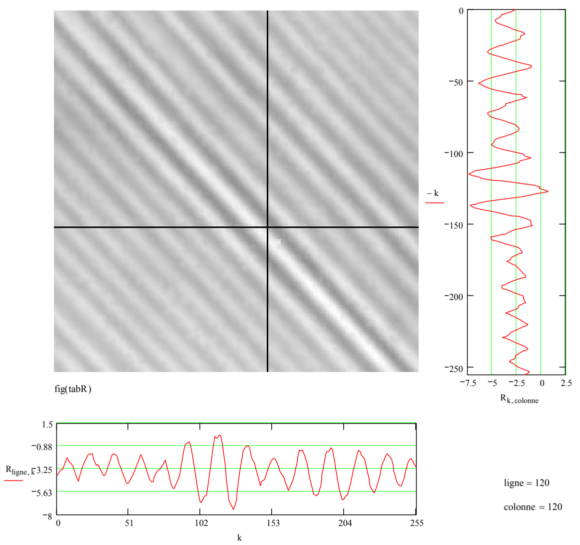

Fig. 13. Wrinkle profile measurement result with fringe projection on painted Nylon.

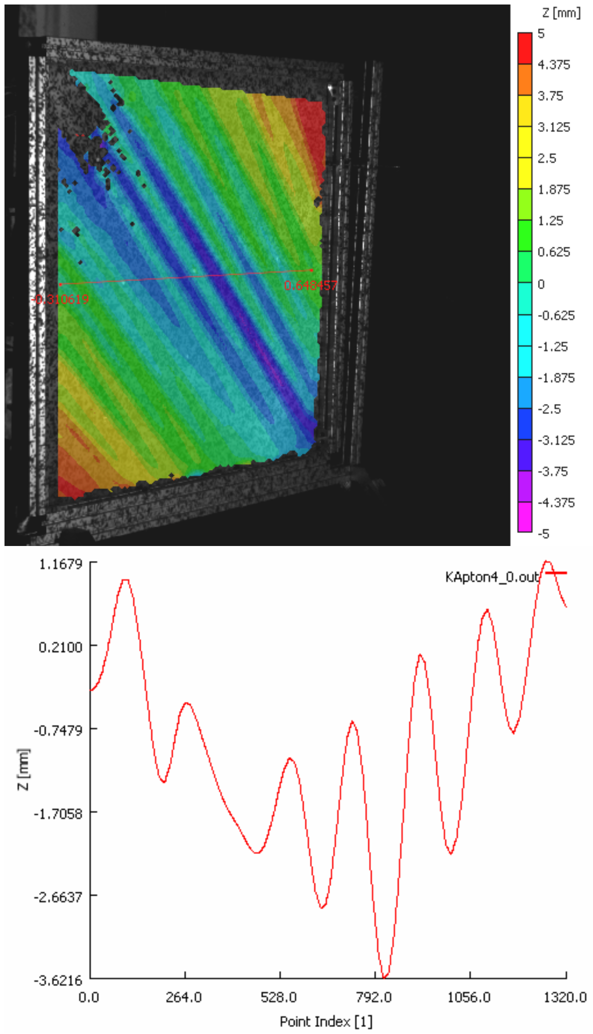

Fig. 14. Wrinkle profile measurement result with stereo-correlation on painted KAPTON.

5.4. Dynamic test

During the dynamic test, stereo-correlation and 3D laser scanning vibrometry were compared. A linear interferometer monitored the rigid body motion of the pusher (Fig. 5).
Both methods gave a frequency difference of better than 0.2 Hz. The amplitude error rose to 70 micron which is in agreement with the system resolution and repeatability (TAB 3).

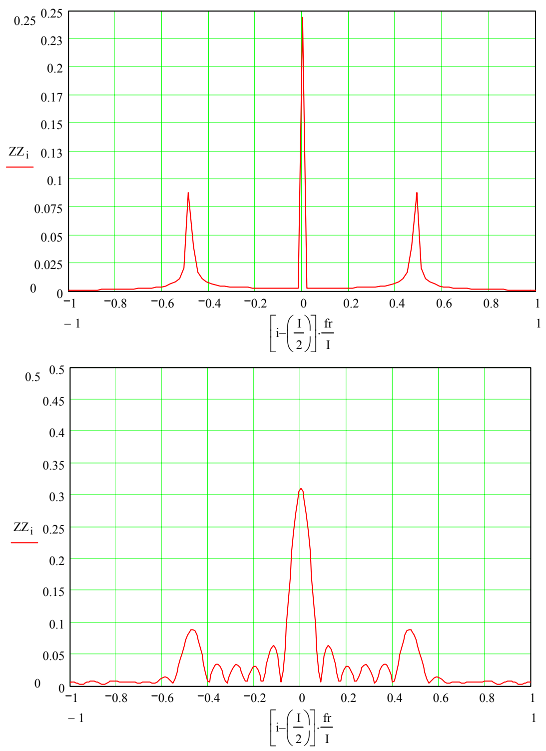

Fig. 15. Frequency spectrum (Y-axis in mm) of the periodic membrane deformation measured with stereo-correlation (Left) and the rigid body displacement motion of the pusher with a HP interferometer (Right).

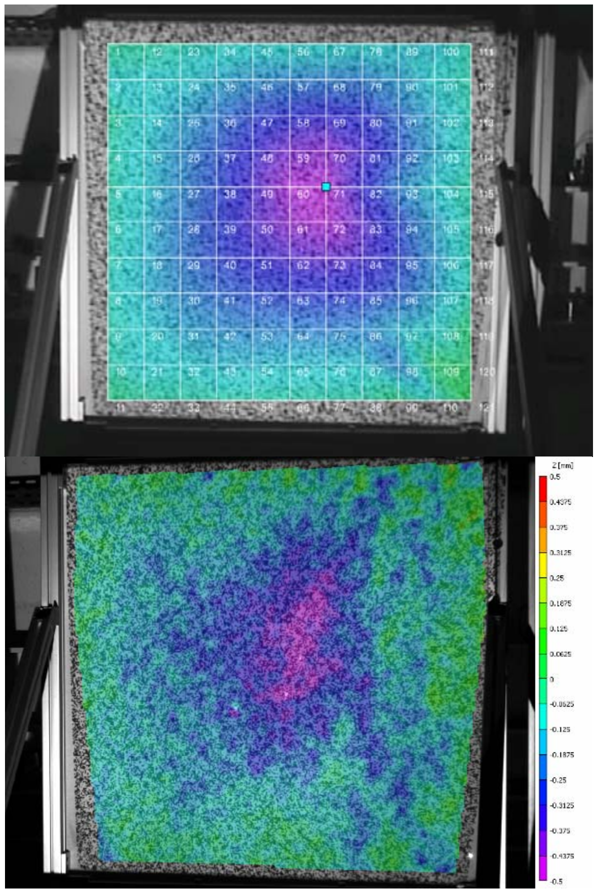

Fig. 16. First mode of the deformation measured with 3D laser scanning vibrometry (Top) and full deformation measured with stereo-correlation (Bottom).

	Linear interferometer (Rigid Body : Pusher)		Stereo-correlation (membrane)		3D LSV (membrane)	
Material	amplitude	frequency	amplitude	frequency	amplitude	frequency
	mm	Hz	mm	Hz	mm	Hz
CECONITE	0.210	2.95	0.187	2.77	0.148	2.83
CECONITE	0.119	2.95	0.089	3.11	0.114	2.93
CECONITE	0.183	0.92	0.192	0.91	0.172	0.88
CECONITE	0.087	0.48	0.088	0.48	0.092	0.49
Painted NYLON	0.210	2.95	0.187	2.77	0.503	2.83
Painted NYLON	0.124	2.94	0.194	2.98	0.108	2.93

TAB 3. Comparison between rigid body motions of the pusher recorded with HP interferometer and membrane deformation recorded with 3D laser scanning vibrometry and stereo-correlation. The columns compare amplitude and frequency of the first harmonic (mode). Note that 3D laser scanning vibrometry (3D LSV) can also measure non processed Nylon membranes.

	FLAME-CFRS	Ceconite	Nylon	CFRS	Kapton	Ceconite	Nylon
Material	Textured	Diffuse	Transparent	Textured	Reflective	Diffuse	Transparent
Characteristic	Absolute Shape	Absolute Shape wrinkles	Absolute Shape wrinkles	Absolute Shape wrinkles	Absolute Shape wrinkles	Relative Shape	Relative Shape
	Static	Static	Static	Static	Static	Dynamic	Dynamic
Videogrammetry	**yes (on the targets)**	**no**	**no**	**no**	**no**	**yes [9]**	**yes [9]**
Stereo-correlation	**yes (on the targets)**	**yes**	**yes (painted)**	**no**	**yes (painted)**	**yes**	**yes (painted)**
Fringe projection	**yes (very slow and painted)**	**yes**	**yes (painted)**	**yes (painted)**	**yes (painted)**	**no**	**no**
Scanning laser vibrometry	**no**	**no**	**no**	**no**	**no**	**yes**	**yes**

TAB 4. Summary table of applicability of methods and test cases. The boxes in grey were not tested.

6. CONCLUSIONS

This work had the ambition to cover different membrane test cases with different optical methods. It has to be noticed that every test case was always covered by two methods. There is no universal method. Our tests have revealed complementarities in all the test cases.
Whenever two methods were applicable it could be shown in some cases that the accuracies where comparable within 0.1 mm.
The tests were applied to membranes of about 1m^2. If the size of the membranes increases in area, it will quickly lead to problems with the light intensity. It decreases with the square of the distance to the object. This leads to an increased acquisition time, which is not recommended at all, since membrane structures are very sensitive to the environmental stability.
The current stitching methods (sub area measurements) become quickly unusable.
Methods directly affected are: stereo-correlation, fringe projection, dot projection videogrammetry.
It is the major concern in our future work, to investigate for adapted illumination systems.

7. ACKNOWLEDGEMENTS

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