33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

EXPERIMENTAL AND NUMERICAL ANALYSIS OF A PRE-STRESSED TENSEGRITY MEMBRANE

Victor A. S. M. Paiva[1], Luis H. Silva-Teixeira[1], Jaime H. Izuka[2], Paola G. Ramos[1] & Paulo R. G. Kurka[1]

[1]Universidade Estadual de Campinas, Campinas, Sao Paulo, 13083-970, Brazil
[2]Universidade Estadual de Campinas, Limeira, Sao Paulo, 13484-350, Brazil

Abstract

Tensegrity structures have caught the attention of scientists and aerospace engineers because of their potential, regarding structural efficiency and shape shifting characteristics. Furthermore, some applications require surfaces to perform structural or reflective functions, which motivate the design of tensegrity-membrane systems. Such systems can be challenging in terms of modelling and construction, therefore it is important, in the first place, to analyse the tensioned membrane component of such a tensegrity system. In this study, a triangular shaped membrane is numerically modelled and experimentally tested, under four sets of stresses. Natural frequencies are calculated and validated from image processing of membrane vibration records.

Keywords: membrane; tensegrity; modal; static; ansys

1. Introduction

Tensegrity is a class of pre-stressed structures in which tension provides integrity. The rigid components of a tensegrity structure remain always under compression, while cables and membranes work always under tension [18]. Tensegrity-membrane systems are comprised of membranes, bars and tendons. They belong to the class of flexible multibody structures and can be treated as an extension of tensegrity systems [27]. Tensegrities ideally match the definition of smart structures because they represent a special class of tendon-spatial structures. Their members may perform functions such as sensing, actuating, and feedback controlling simultaneously [16]. Additional advantages of tensegrities over traditional structures are: high structural efficiency and resistance to impact [1], controllable stiffness [2], controllable shape [31], deployability [17] and uniaxial stress of its elements [3].

Also, tensegrity-membrane configurations are generally light weighted and capable of significant shape changes, which enable these novel systems to experience relatively easy folding and unfolding between packed and deployed configurations, if properly controlled [28].

Researchers in aerospace sciences have interest in tensegrity structures. A growth adaptable artificial gravity space habitat based on a tensegrity-membrane structure has been designed by [5]. A tensegrity robot with six bars and 24 cables in an icosahedral shape was suggested by [21], to be used as a space exploration probe. The high resistance to impact of the probe is useful for landing, and the system rolls to explore the terrain, as cables are tension-controlled. Tensegrity-membrane systems can also be used in the exploration of ocean and lakes [4].

The propulsion efficiency of a spacecraft depends on a low ratio of overall mass to solar sail and antennas area. Technological solutions for in-orbit deployable, ultralightweight sail and antenna surfaces are, therefore, in high demand [10].

Traditional space systems are generally designed with rigid support frames. The modification of their configuration requires addition of numerous components, which leads to an increase in weight [27]. The mechanical properties of tensegrity-membrane systems thus, make them promising candidates for lightweight and deployable space structures that can be used in the aerospace industry, such as space antennas and solar sails. The tensegrity-membrane combination appears as an alternative solution to a pure tensegrity structure ([4], [29] and [10]).

The membrane of the tensegrity system can be covered by a reflective skin, performing structural and reflective functions ([22] and [9]). However, as membrane structures are generally very flexible, there is a need for accurate models to predict their vibration behavior because it has a direct impact on their desired geometric characteristic and efficiency [8]. A methodology that provides an analytical approximation to the behavior of membranes under a certain pre-stress limit is suggested by [20]. An umbrella membrane is modelled in ANSYS by [14] and its behavior is analysed for different sets of rain load. The numerical analysis results are validated with a prototype. Vibration studies of a plane film and an inflatable tube is performed in [6]. Their work compares numerical and experimental results for wet and dry conditions and for different internal pressures of the tube. A long inflatable boom and a triangular plane membrane are modelled in [23] and the numerical results are validated with prototypes. To reduce wrinkling of the triangular membrane, the authors suggest using catenary-shaped edges and compare the stress analysis with a straight edge model. The implementation of catenary edges on membranes is assessed experimentally by [24], analytically by [25] and numerically by [26].

Vibration studies are also useful to detect damage in a structure. A methodology is proposed by [7] to detect local damage in circular and rectangular membranes by combining 3D digital image correlation and Bayesian operational modal analysis. Numerical, analytical and experimental studies of the damped vibration response of a membrane under impact loads are also performed in ([13], [15]) and [11]). Finally, a methodology is suggested by [12] to find the stress level of a membrane from its vibration response to a local impact.

The present work, therefore, contributes to the validation of a pre-stressed membrane model. A finite element model of a membrane is built in the ANSYS platform to analyse the behavior of a pre-stressed tensegrity-membrane structure. Different pre-stressing conditions are simulated and analysed, and a triangular stressed membrane prototype is assembled and experimented to validate the numerical model of the structure.

2. Methodology

A membrane pulled at its vertexes (Figure 1) through cables c_1, c_2 and c_v, develops pre-stresses, and its natural frequencies and modes of vibration are acquired. The triangular shape is convenient because the traction in one cable allows the calculation of the traction in the other two, so the experiment requires traction measurement of only one cable. Four sets of pre-stresses generated by four different forces in c_v are simulated in the commercial software *Ansys Mechanical APDL* and experimentally tested.

2.1 Numerical static analysis

The pre-stresses in the membrane are used to calculate the stiffness for the vibration analysis. Movement constraints in axes X and Y are applied to the vertexes 1 and 2 of the membrane. All nodes in this analysis are constrained to move in the Z direction. The elements LINK180 and SHELL281 are used in the FEM platform to model the cables and the membrane, respectively.

2.2 Numerical vibration analysis

All cables ends are fixed, and the pre-stresses from the static analysis are used to calculate the stiffness. However, these stresses do not contain the forces in c_1 and c_2 because they do not participate in the static analysis. Therefore, the stress in the cables are inserted manually. Movement along the Z-axis is free in the vibration analysis. The INISTATE command is used to store, load, and insert the pre-stresses. With such boundary conditions applied, a numerical modal analysis is performed to estimate the pre-stressed structure's natural frequencies and mode shapes. Figures 2a and 2b show the static and modal analyses (respectively) of the second set of pre-stresses, as an example. Modes of vibration associated with wrinkling of the membrane (Figure 3) and rigid body modes were discarded.

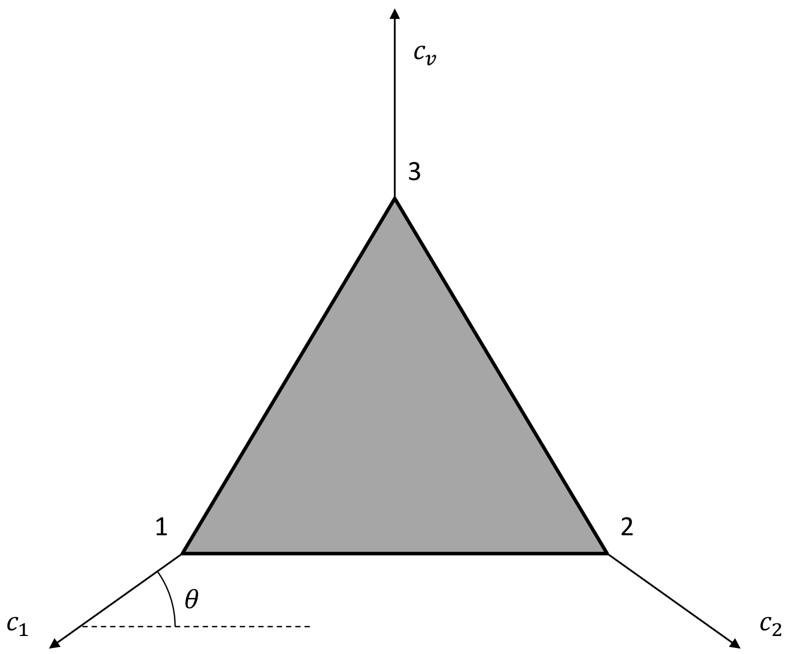
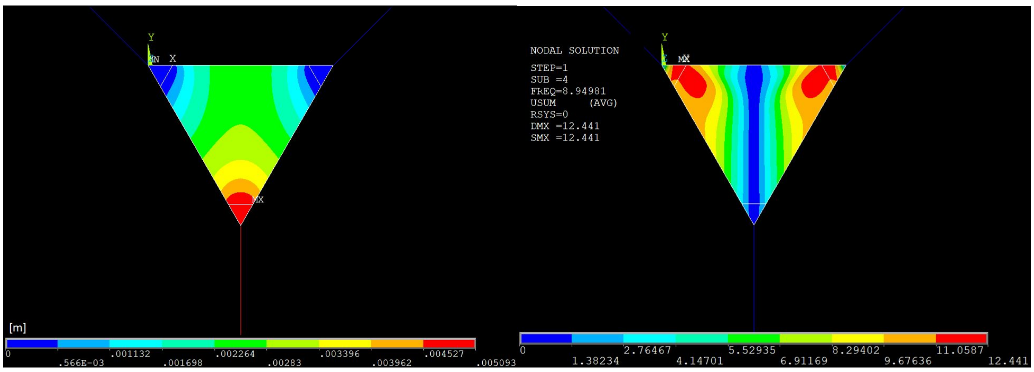


Figure 1 – Membrane configuration.



(a) Static analysis. (b) Modal analysis.

Figure 2 – Numerical results for the second set of pre-stresses.

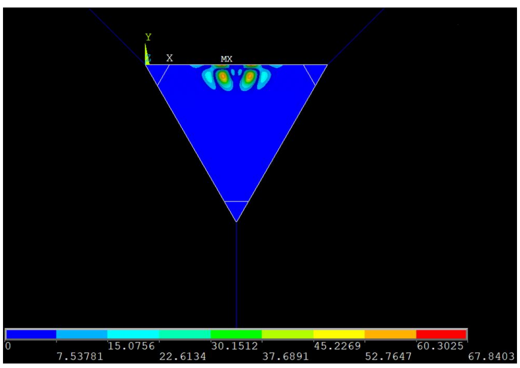


Figure 3 – Example of a mode of vibration associated with wrinkling.

Materials properties and geometrical parameters for simulation are indicated in Table 1. The influence of air displacement in the vibration of the membrane can be represented numerically by increasing the material density to $3500 kg/m^3$ (actual density of the material is $1350 kg/m^3$) [30].

Table 1 – Simulation parameters.

Young modulus	2.5 MPa
Density	3500 kg/m^3
Membrane thickness	0.43 mm
Membrane side	0.17 m
c_1	0.01 m
c_2	0.08 m
c_v	0.08 m
θ	$\pi/4$ rad

3. Experimental procedure

Similarly to the numerical model, the ends of the cables are fixed. However, one of them is fixed to a hook scale (10 g resolution) that indicates the traction in that cable (Figure 4). This measured value is the input for the numerical analyses. The membrane is made of rubber, and the nylon cables have a diameter of $0.4mm$.

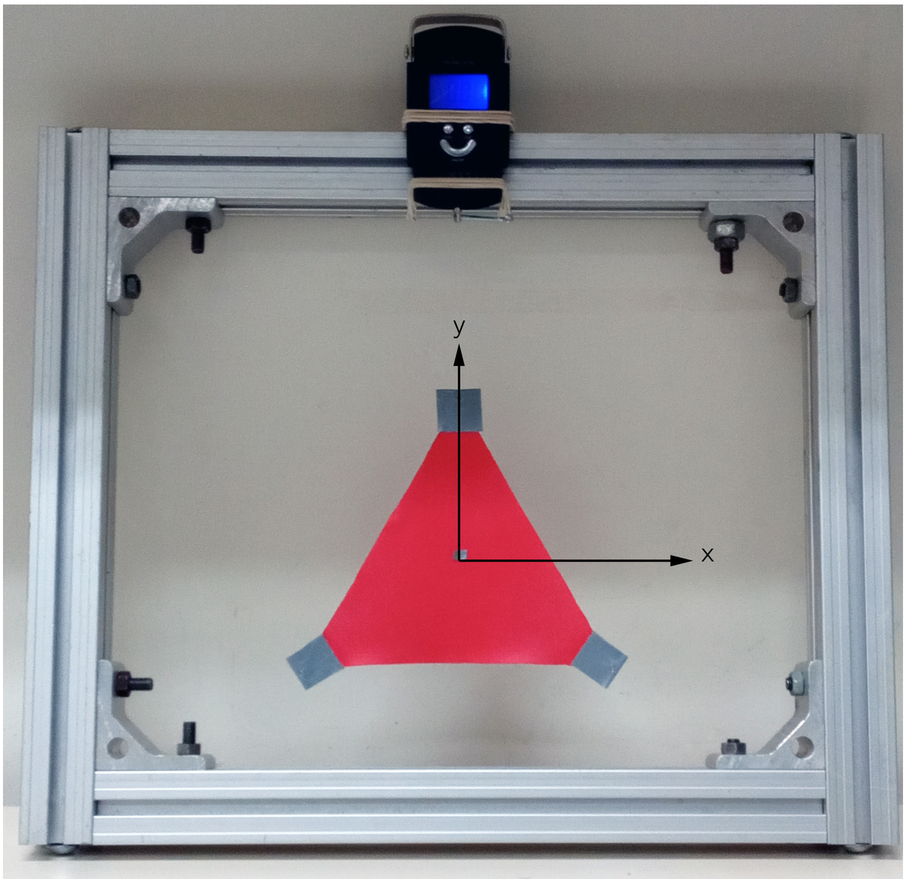
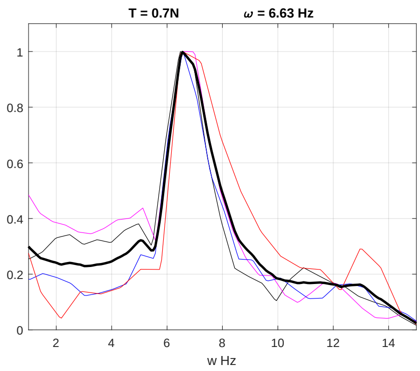
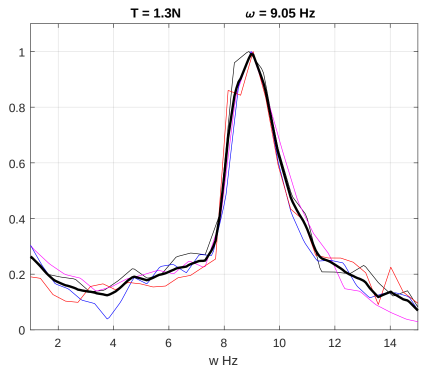


Figure 4 – Prototype.

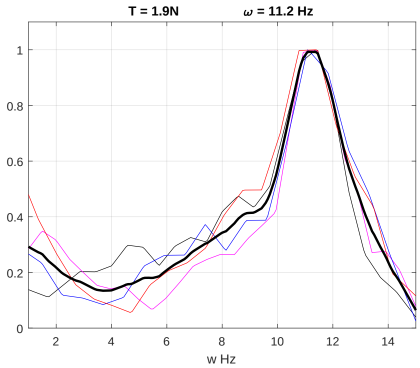
An impulse is applied perpendicular to the membrane, and a $30fps$ camera, parallel to the XY plane of the membrane surface, records its vibration as shown in Figure 4, . From this position, the membrane is seen from its side and the vibration happening in the Z direction is tracked by the vertexes and by a marked point in the middle of the prototype. An image processing software acquires the position of these markers over time, the data is treated, and a Fourier transform is applied to obtain the response in the frequency domain. Each pre-stress set is analysed multiple times, its specters are normalised to unity, and a mean curve is plotted with a thicker line (Figures 5a, 5b, 5c and 5d).



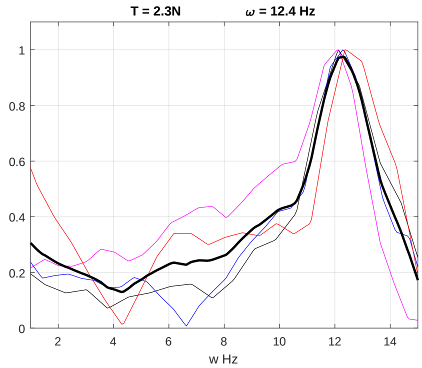
(a) $c_v = 0.7N$.



(b) $c_v = 1.3N$.



(c) $c_v = 1.9N$.



(d) $c_v = 2.3N$.

Figure 5 – Modal analysis for different sets of membrane stress.

4. Results

Results from the experiments are collected and organized along with the numerical outputs (table 2). The first mode of vibration is the highest energy one and is most relevant to the membrane dynamics. The experimental analysis compares the measured frequencies of the first mode with those obtained numerically. Spurious modes [19] were discarded.

Table 2 – Natural frequencies.

c_v	Experimental	Numerical	Error
0.7N	6.63Hz	6.95Hz	3.17%
1.3N	9.05Hz	8.95Hz	2.55%
1.9N	11.2Hz	10.89Hz	4.33%
2.3N	12.4Hz	13.24Hz	5.02%

5. Conclusions

The numerical model of the membrane of a tensegrity structure is implemented. Simulations and experimental tests on a prototype are performed under different pre-stressing conditions. Higher stresses generate higher natural frequencies, as expected. The obtained results are compared and errors between numerical and experimental procedures are not greater than 5.02%, which indicates good agreement between model and prototype. Furthermore, the uncertainties of the simulation and experimental procedures do not invalidate the proposed methodologies. It indicates that the numerical model of the membrane can be successfully used and integrated with previously validated numerical models of tensegrity structures. Future steps involve building and modelling a membrane with catenary edges and combining it with a tensegrity to assemble a tensegrity-membrane system.

6. Contact Author Email Address

mailto: v140962@dac.unicamp.br and kurka@unicamp.br.

7. Copyright Statement

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