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Analytical and Numerical Studies of Superpressure balloons

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Abstract

NASA is currently developing a general purpose balloon platform capable of carrying payloads of several tonnes for up to 100 days in the upper atmosphere. Large spherical balloons were initially investigated but were abandoned due to the difficulty of providing an efficient mounting of the payload. However, the current design, based on a pumpkin shape, turned out to be prone to buckling.

This thesis investigates the buckling of pumpkin balloons and studies optimal cutting patterns as well as novel topologies for superpressure balloons. In a first step we derive analytical solutions for inflatable structures, like lobed columns and cylinders, to obtain insight into the buckling phenomena. It is shown that the buckling behavior of these simple structures is similar to that observed in pumpkin balloons. Furthermore, the governing equations of pumpkin balloons with an infinite number of lobes are presented.

Next, we develop an accurate and efficient numerical tool to simulate the critical pressures of fully inflated, rotationally symmetric pumpkin balloons by using membrane/bar finite elements and load stiffness matrices. This tool makes use of novel symmetry transformation matrices in closed form that are used to block diagonalize the stiffness matrices. It is shown that these transformation matrices can be obtained, for structures with a major rotation axis, from a Fourier series and, for structures with tetrahedral, octahedral and icosahedral symmetry, from vector spherical harmonics.

A major result of the stability study is that the critical pressure of pumpkin balloons decreases according to an inverse power law for an increasing number of lobes. Furthermore, it is found that the buckling pressure depends heavily on the design of the cutting pattern. Motivated by this high sensitivity, an optimization of the geometry of the cutting patterns is carried out. This study shows that the stability of pumpkin balloons is maximized if their surface area is minimized for a given stress constraint. Thus it becomes possible to increase the buckling pressures by up to 300%. Balloons based on this new design paradigm are currently considered by NASA and recent test results with small-scale experimental balloons are very promising.

A novel creep algorithm is developed to model the viscoelasticity of currently used balloon films. The efficiency of this algorithm is demonstrated by three benchmark tests that highlight the influence of a viscoelastic material on the load carrying behavior of simple membrane structures. The time-dependent stresses in the film and tendons of a flight-size pumpkin balloon are studied. It is found that stress concentrations, as well as stresses caused by the incompatibility of a flat and doubly curved surface, decay by about 90% in the first second.

Finally, novel designs for superpressure balloons are derived by using topology optimization. These balloons carry the differential pressure "truly" biaxial by the film and have an overall shape that is very close to a sphere. Furthermore, they possess a topology similar to radiolaria that float in the seas.

Keywords: superpressure, balloons, buckling, symmetry, shape, topology, optimization, viscoelasticity, radiolaria