Yixiang Xu : A computational study of lobed balloons

Abstract

High altitude balloons have been used for decades to conduct scientific studies. In the early 1960s, there came a new era in balloon design when the 'pumpkin shape' was adopted for super-pressure balloons. Pumpkin balloons are currently being investigated by NASA's Ultra Long Duration Balloon (ULDB) Program, which aims to develop a low cost, long flight duration balloon system to support global scientific observations.

The pumpkin shape, although attractive in terms of pressure-carrying efficiency, has been found to be unstable, with the result that several test balloons have been unable to pressurize into the desired axi-symmetric equilibrium configurations. Instead, they have settled into distorted configurations.

The research presented in this thesis aims to provide computational techniques and solutions for the study of the shape and stability behaviour of balloon structures.

Before tackling the stability of pumpkin balloons, a preliminary investigation of a lobed cylinder, which consists of a stack of four truncated isotensoids is given. A finite element analysis using the ABAQUS commercial package has been carried out to predict the initial equilibrium stress distribution and the stability behaviour of this structure. A large-perturbation analysis in the post-buckling regime shows that the structure has a stable distorted configuration, which is triggered by a particular type of geometric imperfections.

The shape of a pumpkin shape balloon is studied and the reasoning behind using the pumpkin shape for ULDBs is explained. The meridional shape of an isotensoid whose profile is close to the initial shape of the load bearing tendons of the pumpkin balloon, is computed. The shape of the lobe cutting pattern is then computed.

A finite element model of a 10 m diameter pumpkin balloon with 145 lobes of approximately constant radius is set up. This model takes into account the tension-only behaviour of the balloon skin and contact between different parts of the surface is included in the model. The inflation of a single lobe, whose material is modelled as linear-elastic, is simulated and a study of visco-elastic behaviour is then carried out, to investigate the time-dependent response of a pressurized gore. The balloon is found to carry stresses biaxially. Time-dependent effects will lead to significant stress redistribution and large increases in the hoop strains.

Eigenvalue buckling analyses are carried out to predict the critical buckling pressures and buckling modes. The balloon is found to have a 4 up 4 down critical mode with a critical pressure of 2200 Pa. The sensitivity of these results to the material properties is studied.

A new finite element model is then set up with an initial geometric imperfection based on either the critical buckling mode or a linear combination of the first 10 eigenmodes. With this model, geometrically non-linear post-buckling analyses are carried out to simulate the response of the balloon beyond the critical pressure. Both global and local deformation modes are captured, followed by a thorough investigation of the stress distribution, the volume and the energy variation of these deformed shapes. It is found that these stable distorted configurations enclose a larger volume compared to an unbuckled balloon.

Key words: balloon, membrane, stability, visco-elasticity, wrinkling