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Pursing of planar elastic pockets

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ABSTRACT

The pursing of a simply- or doubly-connected planar elastic pocket by an applied pressure is analysed from the bending to the stretching regimes. The response is evaluated in terms of maximum deflection and profiles across a range of simply- and doubly-connected circular and square shapes. The study is conducted using experimental and numerical methods and supported by previous analytical results. The experimental method is based on an original 2D optical method that gives access to the pursing direction perpendicular to each image across the field of view. The equations for maximum pursing deflections are developed and compared for a range of thicknesses of silicone samples and shapes from the bending to the stretching regimes. In the case of doubly-connected shapes, dependence of maximum pursing deflection on clamped central circular and square areas or holes is quantified for both regimes. Good agreement is established between the three methods and the study also shows that the optical method may as well be successfully applied to problems of pursing of rubber pockets.

1. Introduction

An elastic pocket can be created by introducing a fluid between two elastic sheets fixed together along a common edge (Adkins and Rivlin, 1952). When the fluid exerts a pressure on the sheets, a purse is formed. Studies on inflating flat circular disks were initially carried out to understand elastic properties of gum rubber (Klingbeil and Shield, 1964; Hart-Smith and Crisp, 1967) with the eponymous model of strain-energy density from Mooney (1940) widely used to characterise incompressible and isotropic material such as rubber. His theory of large elastic deformation (Mooney, 1940) matches experimental tension data of soft rubber from compression to large stretching (50–400% of original length). Pursed flat circular disks with clamped edge were therefore used to determine the strain energy density function of soft tissue (Wineman et al., 1979).

When considering a clamped pursed pocket, two regimes can be distinguished; when the deflection is smaller than the thickness of the initial flat pocket, the sheets bend and the equations of deflections are linear, while when the deflection is larger, the sheets are stretched. In the case of bending, the analytical solution of circular clamped pockets presents limited interest, and several groups have focussed on the analytical solutions for bending of rectangular or square plates with clamped edges (Timoshenko, 1910; Pistriakoff, 1910; Levy, 1942; Meleshko, 1997; Imrak and Gerdemeli, 2007a, 2007b). Meleshko (1997) wrote a detailed account on the differences between each solution. More generally, a wide variety of studies have analysed elastic sheets that were pinned along

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an edge with the majority of studies focussed on circular or rectangular sheets that undergo large deformations (Dickey, 1967; Feng, 1976; Pujara and Lardner, 1978; Wineman, 1978; Roberts and Green, 1980; Weinitschke, 1988; Chaudhuri and DasGupta, 2014). More specifically, Yang and Feng (1970) studied the large deformations of hyper-elastic (Mooney-Rivlin) circular membranes, with stretching rising up to 600% (meridian stretching). Christensen and Feng (1986) extended this description to include deflection of neo-Hookean materials; comparisons with the numerical results of Yang and Feng (1970) showed that the approximate model is accurate up to 400% strain. One of the limitations of their model is that the stretch ratio can be considered as averaged, as their model assumed a uniform inflation over the surface of the disk. More recently, Hewitt et al. (2015) developed an elastohydrodynamic lubrification theory that characterise deflection of elastic sheets under different conditions. Lister et al. (2013) applied an optical method to measure deflection with high resolution along a line when peeling sheets are bent or stretched. The same method was applied by Pihler-Puzović et al. (2015) to measure the shape of a circular elastic pocket in the stretching regime as a method of calibration.

For the last approximately 20 years, a large numbers of studies have focussed on inflating axisymmetric balloons for technology applications, for example in the context of artery interactions during stent placements (Liang et al., 2005; Prendergast, 2003; Martin and Boyle, 2013), in electro-elastomers used in novel prosthetic blood pumps (Goulbourne et al., 2007, 2004), in novel endoscopy devices (Glozman et al., 2010), as urinary sphincters for patients suffering from severe stress incontinence (Hached et al., 2014), as pressure sensitive buttons, to strain cells in a controlled manner (Smith et al., 1998) and even as a tool to break into rental cars on holidays! (by levering doors open, so that grapples can be inserted). Moreover, inflatable membranes are also used in a number of space applications such as solar sails and arrays, scientific ballooning, thermal shields, pressurised habitats in space, actuators and telescope mirrors (Marker and Jenkins, 1997; Patil and DasGupta, 2013) as well as in the development of airbags, suspensions for cushioning and shock absorbers (Kumar and DasGupta, 2013). Inflatable membranes as elastomer based tunable devices (Song et al., 2012) have been used in the development of dielectrophoretical tunable optofluidic devices, leading to a number of applications such as beam steers, optical switches and single pixel displays (Xu et al., 2013). Laparoscopic gastric banding is an example of a doubly-connected inflatable structure. They are annular silicon membranes loaded with a saline solution that, under different pressure loads, limit the passageway of food through the stomach to reduce the nutritional intake of morbidly obese patients (Morino et al., 2003). Finally, the understanding of deformed elastic membranes is applicable to biological systems, such as fetal dura mater (Kriewall et al., 1983; Bylski et al., 1986), cell membranes to plant cell walls (Chaplain and Sleeman, 1990; Davies et al., 1998; Selby and Shannon, 2009), cell replication and motility to pathogenesis of disease (Karimi et al., 2014; Jenkins and Leonard, 2015).

Much of the research on the physics of clamped inflatable pockets has been conducted either looking at analytical solutions for small deformations such as in the work of Meleshko (1997) among others, or for large deformations of shapes such as Yang and Feng (1970) as explained previously. This paper is novel as it looks at the differences between those two regimes, while including not only simply but doubly-connected shapes (presence of a hole in the shape) using a three-fold approach: numerical and experimental approaches backed up by previous analytical results. It is believed by the authors that the experimental optical method is used for the first time to assess the pursing of silicone pockets. This original method gives a 3D deformation field from a single plane of measurements.

2. Mathematical model

The elastic pocket is modelled as a membrane of initial thickness T that sustains a deflection h due to an applied pressure p, as shown in Fig. 1. To understand the implication of pressurising an elastic pocket, we apply a scaling analysis to identify the adjustment in the bending and stretching regime. The bending regime is examined explicitly. The response is studied using Finite

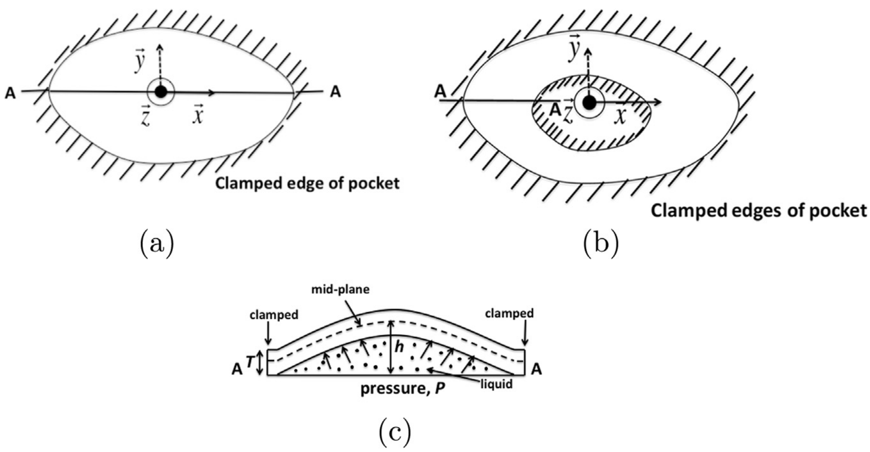

Fig. 1. Schematic of plan-view of the problem showing the notation used and the boundary of (a) simply-connected and (b) doubly-connected pockets with the (c) side view.

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