Pneumatic Structures
A revival of formal experiments
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Introduction

Our society has drastically changed since the 1960’s. Not only did sociological concepts and issues in the field of politics and social life change drastically, also a handful of technical innovations have improved the overall quality of life. Televisions were introduced in our living rooms; communication via telephone was made available to anyone; and popular rock music got introduced to the masses.

In the field of architecture innovative materials and new knowledge allowed for more intensive formal and structural experimenting. Building upon the foundations from the 1950’s towards formal experiments and freeform thinking that Richard Buckminster Fuller help lay, a new generation of engineers and architects introduces the population to an architecture for the new era. An overwhelming embrace of bubbles in their numerous connotations (lightness, transparency, embrace, equality, difference) characterizes this period of the 60’s. An environment in which free thinking was allowed and stimulated, resulted in the use of airy constructions for shaping enclosures. Nevertheless, due to budget restrictions and technical obstacles, the whole subculture of pneumatic constructions silently died out.

Of those exploring inflatable architecture in the sixties and seventies, Ant Farm was the most prolific, gearing a number of projects around air and plastic, and even creating an Inflatocookbook. Fellow Americans like Jersey Devil also explored what they called Inflatables in the early seventies, created as “happenings” that stood out in their urban contexts, such as alien crafts landed amongst the stone, glass and grass. In Austria renowned artists like Coop Himmelb(l)au and HAUS-RUCKER-CO explored the possibilities of pneumatic dwelling units. Yet without clients or sites they failed to get beyond the prototype stage. Even critic Reyner Banham got in on the act, combining the ideas of Buckminster Fuller and Marshall McLuhan in a transparent igloo he designed with Francois Dallegret.
Nevertheless, our present-day architectural scene is characterized by a certain renaissance of pneumatic constructions. Although mostly encountered in temporary building projects, they also take an important role in art installations and experimental construction techniques. There is no doubt that technological and other improvements have contributed to the durability and cost-effectiveness of these constructions.

This research document will first discuss the general principles of pneumatic constructions, their advantages and the possible disadvantages or caveats. Secondly the necessary technical background will be outlined. In this chapter the usefulness of techniques and materials in relation to membrane and pneumatic constructions will be described. Finally the subject will be practically illustrated on the basis of a couple of real life examples, both from the past and present.
Air-inflated and air-supported structures represent a special area of membrane construction. In pneumatic constructions, pressure differences between the enclosed space and the exterior are responsible for giving the building its shape and also for stabilizing the hull. Fabric is pretensioned by an internal overpressure of the air. While this might seem at first to be uncomfortable to the occupants of the structure, the pressure differential is no greater than that of ordinary barometric fluctuations.

Pneumatic structures are a combination of two components with very different properties: an airtight membrane and compressed air. Air is a gas, essentially composed of nitrogen, oxygen and carbon dioxide, and its properties are merely defined by its composition, the temperature, the pressure and the volume. The membrane is in a solid state and its properties are defined by the material properties and geometry of the constituents, as well as by the way materials are used for its construction, such as the chemical composition and the elastic modulus of the yarn, the mass density of the coating, the type of weaving and so on. The compressed air pretensions the membrane and forms the volume of the structure defined by the membrane-cutting pattern. Such a pre-stressed membrane can support both tension and compression and thus can withstand bending moments. Obviously, the pre-stress in the membrane is a function of the air pressure.

The membrane’s minimal weight and small size when deflated allow for easy manipulation and transport, hence offer a lot of perspectives towards repeated use at different locations. However, proper attention should be paid to deflating the construction. Depending on the materials used for constructing the skin, there is a danger that folds damage the skin when improperly stowed. Should any cracks and leaks appear, a prompt repair is necessary although a damaged inflated structure will most likely maintain its form because of the minimal difference between inner and outer air pressure.

One of the main disadvantages of pure pneumatic constructions however is that a constant high air pressure is required to keep the elements in shape. This leads to higher energy costs, a parameter which cannot be relentlessly denied in a century of energy awareness. Innovations in this field have led to a new structural concept, Tensairity®. It counters the major energy-related disadvantage, by combining the classic pneumatic structure with an internal cable-strut structure. The main function of the pneumatic structure is to stabilize the cable-strut structure. Tensairity structures have a multitude of very interesting properties. Not only is the beam very light, but it can also keep its shape under very low pressure. Compact transport and compact storage is possible, as well as fast and easy deployment on site. Furthermore, new lighting possibilities and special forms can be realized with Tensairity. One of the most outstanding properties of Tensairity is that the structure is adaptable to changing load conditions.

However, because of the specifics of Tensairity structures – an explanation of which would fall beyond the scope of this research – it is likely that focus will remain on classic pneumatic structures.
Typical pneumatic structure, deflated and inflated - Simulated via nParticle method in Maya
Technical Background

Form

Pneumatic structures follow strict physical rules, which influence their form-finding and their design process. The form of a pneumatic structure can always be derived from a specific formula: \( p = \frac{n_k \cdot r_k}{r} + \frac{n_s \cdot r_s}{s} \).

In this formula, \( p \) is the internal pressure appearing on the inside of the construction. Both \( n_k \) and \( n_s \) define the membrane stress, whereas \( r_k \) and \( r_s \) define the radius of the curves. Based on the results of this formula, a classification of three different types of constructions can be drafted.

A first group of constructions are the air-supported halls, which are fixed circumferentially to a foundation and have a great synclastic curvature. The external loads like forces of nature and weight of the skin itself, are supported by the air residing inside the hall. Internal loads pointing outwards are carried by the membrane and have a tension-increasing effect.

Secondly, cushion structures are pneumatic structures in two layers. They are attached to an internal structure coupling high lateral forces of the border in the cushion. Another option is to implement them as a cover on a primary structure and allowing them to guide horizontal forces into the main structure. Compression load is carried by an increase in pressure on the other side of the cushion.

Nevertheless, in modern constructions, we tend to notice the use of air beams mostly. Air beams are cushions in the form of a tube or sphere. These can be used for either compression struts or beams, as compression of bending leads to a reduction of the implemented volume. Therefore, inner pressure is increased, as well as pressure and bending resistance.

Tension diagrams for air-supported halls, air cushions and air beams.
Materials

Made from laminated membranes such as fiberglass, nylon, or polyester, coated with polyvinyl chloride (PVC), silicon rubber or Teflon for weather protection, the electronically welded components are tailored to define the building shape. The durability and heat- and light-filtering properties of the membrane are determined by the careful choice of surface finishes and inner lining. Because of its lightness, the air-supported structure is among the most efficient structural forms, combining high-tensile strength materials with the shell form.

The fabric is not made and shipped in one piece. It is made in sheets, usually about 3.6m wide and with varying length. The easiest and most common method of joining the fabric together is the standard lap joint. The two pieces of fabric are overlapped by approximately 8 cm and Teflon FEP (fluorinated ethylene-propylene) film is inserted between them. The joint is then heat welded together. When completed, the joint is stronger than the fabric, and completely water- and airtight.

In structures where cables are necessary to maintain the form, mostly steel cabling is used. Although Kevlar and glass fiber cables are stiffer and stronger, they are not widely used because of a high cost and degradation issues when exposed to ultraviolet light.

Construction

With the present-day digital possibilities in mind, the design and construction of membrane structures has become more straightforward. Through digital design software, a project can be drawn in 3D, then this three-dimensional model can be translated – through scripting – to a two-dimensional comparative. The final step before receiving a final result, is to transfer these images to professional printing and/or cutting machines.
Real-Life Examples

Parasite - Michael Rakowitz (USA)

A sustainable design philosophy should definitely be combined with an aesthetic sensibility and a constructively critical approach to the production of art. Rakowitz succeeds very well in combining these different aspects. Parasite is his interpretation of how to use citywide ventilation outlets to provide comfortable housing for the homeless people. While clearly not trying to be aesthetically pleasing it surely gives the spectator something to think about beyond mere beauty.

The plastic structures are easily transportable when deflated. When hooked to a building exhaust vent, the air inflates the double-membrane structure into its habitable shape, while also heating the inside.

Parasite - Michael Rakowitz (exposition at MoMA)
Yorkshire Pavilion - VA (Norway)

The project is an attraction in itself with a striking exterior in the form of inflatable tubes arranged in the atomic structure of diamonds. The 20 x 26 x 10 meter diamond grid volume is mined out to form a cavernous interior space reminiscent of the coalmines of Yorkshire. Light and airshafts pierce the structure providing natural light and ventilation. At night the translucent shafts and outer skin radiate light in all colors and directions like a diamond twinkling in the sunlight.

A focus on flexibility gives the pavilion multiple configurations that allow it to be used for everything from small gatherings to large conferences or public presentations. The voluminous internal space will surprise and delight when installed in close quartered public squares. The pavilion can also be turned ‘inside out’ to open up a large covered area to open outdoor spaces to create the ultimate mobile venue for concerts or big-screen events.

Yorkshire Pavilion - Various Architects (model view)
Section over the Pavilion’s interior space

Scheme of possible interior organisation
Spacebuster - Raumlabor (Germany)

Spacebuster is a mobile inflatable structure - a portable, expandable pavilion - that is designed to transform public spaces of all kinds into points for community gathering. A new iteration of a past Raumlabor project, the Küchenmonument (presented in Europe in 2006-8), the Spacebuster will travel throughout the United States, starting in Manhattan and Brooklyn. The main goal of the Spacebuster was to offer a venue for community events.

The pavilion is comprised of an inflatable bubble-like dome that emerges from a step van that also houses the compressor that keeps the Spacebuster inflated. The dome expands and organically adjusts to its surroundings, be it in a field, a wooded park, or below a highway overpass. The material is a translucent plastic that allows the events taking place inside of the shelter to be entirely visible from the outside.
Air Forest is a 56.3 by 25 meter pneumatic structure, composed of 9 hexagonal canopy units, at 4 meter height. These units are interconnected as one large piece of fabric, which are then inflated from the 14 blowers that are located at the base inside its 35 columns. These columns are 5m apart, and are weighed down by dirt and lighting elements, which are also inside the columns, which light up at night and provide a public space after dark as well.

Each 6 of these pneumatic columns form a unit as they are connected in a hexagonal manner creating a circular opening from their inside perimeter. Out of the 9 total hexagonal units formed, 3 of them are left open-air while the remaining 6 have vortex-shaped meshes that hang from them, providing shades for the public from any harsh sunlight. The nylon fabric is coated with a gradient of silver dots, whose reflective surface mimics the colors of its surrounding environment, as well as providing a playful dotted shadow on the people under the structure.

The structure also acts as a giant device to measure the site’s conditions. Not only does it sway gently with the wind, it also acts as a barometer, since the installation becomes structurally weaker (and thus affected by the wind more) as the air pressure drops due to cooler weather or even after sunset.
Structural principles of the installation
Inflatable Teahouse - Kengo Kuma (Japan)

Last summer Japanese architect Kengo Kuma presented an inflatable tea house at the Museum für Angewandte Kunst in Frankfurt. The temporary space was set up in the museum’s garden and once fully inflated, covered approximately twenty square meters. The structure’s interior is illuminated using integrated LED technology and fits nine tatami mats, a stove for the water kettle, as well as a preparation room. Moreover, the interior can be heated by way of the membrane.

The teahouse does not rise up from the ground as a fixed wooden construction, but unfolds as an airborne form. When a ventilation system is activated, the teahouse swells into shape like a white high-tech textile blossom.
Structural system

Interior view