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Biological inspired development of suction cups

Abstract

The paper deals with the biological inspired development as well as simulation and calculation of suction cups: An essential advantage of rubber-like materials is their specific compliance which enables special functions in technical systems. Elastic structures are particularly suitable for the realization of bionic approaches. The department of Mechanism Technology at TU Ilmenau is focused on such compliant mechanisms and developed a closed structure with suction effect made of silicone. The nature was source of inspiration for the bionic approach improving the monolithic suction cup in addition to engineering process of development. The created method of calculation based on FEM allows qualitative simulation of negative pressure in the suction chamber. So the comparison and evaluation of different suction cup geometries is possible.

Introduction

Besides the common usage suction cups are widely used for technical purposes because of the simple but effective functional principle. The two criteria "closed" and "open form" can be specified among several structural suction cup attributes (Fig. 1).

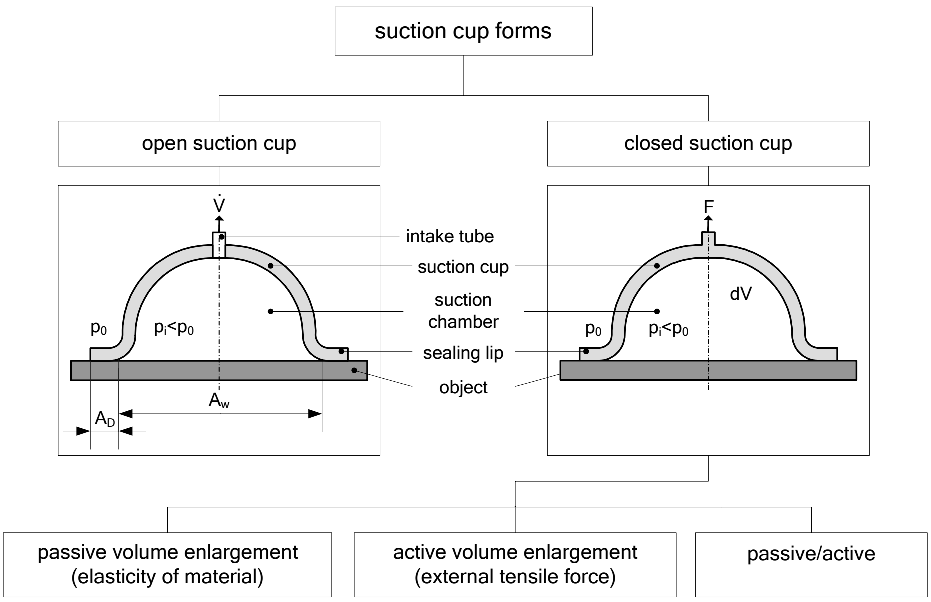

Fig. 1 *Suction cup forms depending on the negative pressure development*

Mechanical transport and handling tasks as well as innovative climbing robots are the main fields of application of technical suction cups. The advantages are obvious: Suction grippers are gentler as substance to substance grippers, more versatile as magnetic and air blast grippers and they can be used for various materials and surface roughness. Also the loading behavior is very interesting: The stronger the tensile force on the elastic structure the higher becomes the suction force.

According to the literature the dimensioning of suction cups is described in detail depending on the gripping task [1]. But regarding the holding force the simulation and calculation for the optimization of suction cups is not state-of-the-art [2].

Investigation and systematization of biological suckers

Living creatures and animals developed by nature are particularly characterized by energy and material efficiency as well as plurality of great constructions. A look at biological suckers is useful to increase the suction effect because animals have lots of well formed suckers. For the non-positive connection to a substrate three different kinds of suctorial organs can be specified in which the suckers build the major group. The list of animals with suckers looks like a foray through the whole animal world. Suckers are developed in most various forms and dimensions as suction cups, mouths, feet and discs. All of these suckers cause the holding force with negative pressure respectively vacuum.

Because of the huge diversity of forms a survey is given in the poster in consideration of functional aspects. Therefore all suckers are systemized by means of following criteria of differentiation on basis of biological studies [3]:

- Animal species,
- Function of sucker,
- Characteristic of substratum (type, compliance, roughness, medium),
- Characteristic of suction cup (number, arrangement in groups, geometric form, mechanism of ingesting) and
- Special features.

Deriving technical design principles

In spite of the plurality of types and forms there are typical suction cup principles. On the basis of investigation and systematization of the suckers, biological inspired design principles can be abstracted for technical usage. For example, a special species of sea urchin („*echinoidea*“) is source of inspiration for the application of an inherent sensor and actuator (Fig. 2). The sea urchin uses a large number of small suction feet for locomotion and can even move with them along plane walls of an aquarium. A complex system of muscles provides the specific identification, ingestion and separation from surface. At first oppositely working muscles cause the enlargement of the suction chamber. After this ingestion the sucker is being flattened again resulting in pushing off from the surface through a convex curvature. Assigned to the technical usage, the active mechanism of separation can be realized by a snap through as a result of increasing pressure.

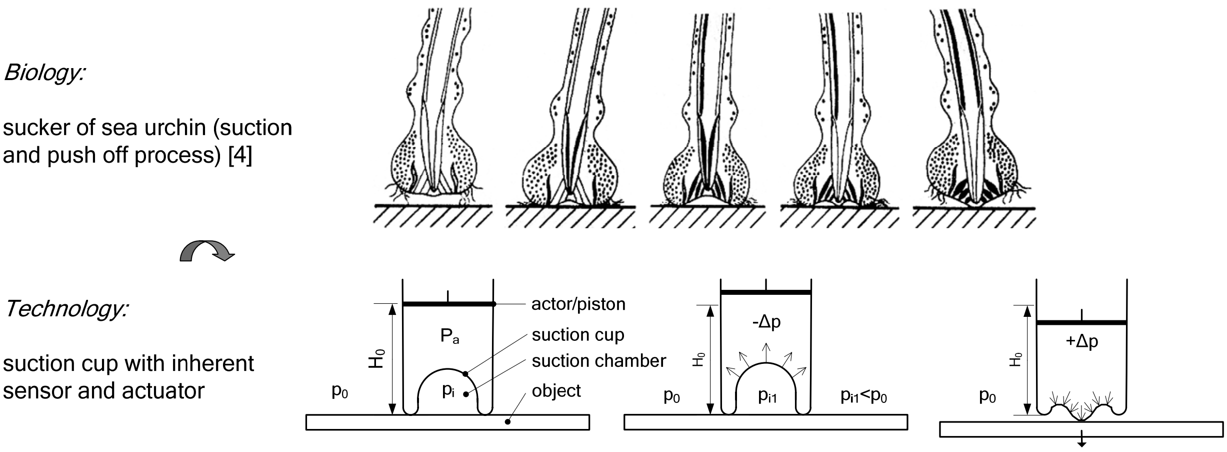

Fig. 2 *Biological inspired design principle of an ingestion and separation mechanism*

Further principles which can be used for the technical development of suction cups are:

- Mechanical stiffening of the suction cup with additional material (radial or equatorial stiffeners at the suction chamber),
- Usage of elastic materials with high stiffness for a self-holding function (enlargement of volume as a result of the residual stress of suction cup),
- Functional retention by using several suction cups (construction of an array),
- Additional holding function by combining different functional principles,
- Special design of the sealing lip to improve the suction effect (e.g. increasing of the adherence as a result of micro or nano-structuring).

Method of calculation based on FEM

A method of calculation for the qualitative simulation of the negative pressure at vacuum stage based on a rotation-symmetric finite element method (FEM) model of a two-dimensional suction cup was developed for the structural optimization with ANSYS®. The non-linear behavior of the silicone material is described with hyper elastic material law of behavior. Based on a determined pressure level the iterative consideration (loadstep t) of suction cup stiffness enables the calculation of permanent deformation (volume V) and thereby the simulation of resulting pressure in the suction chamber for any structure (Fig. 3) [3].

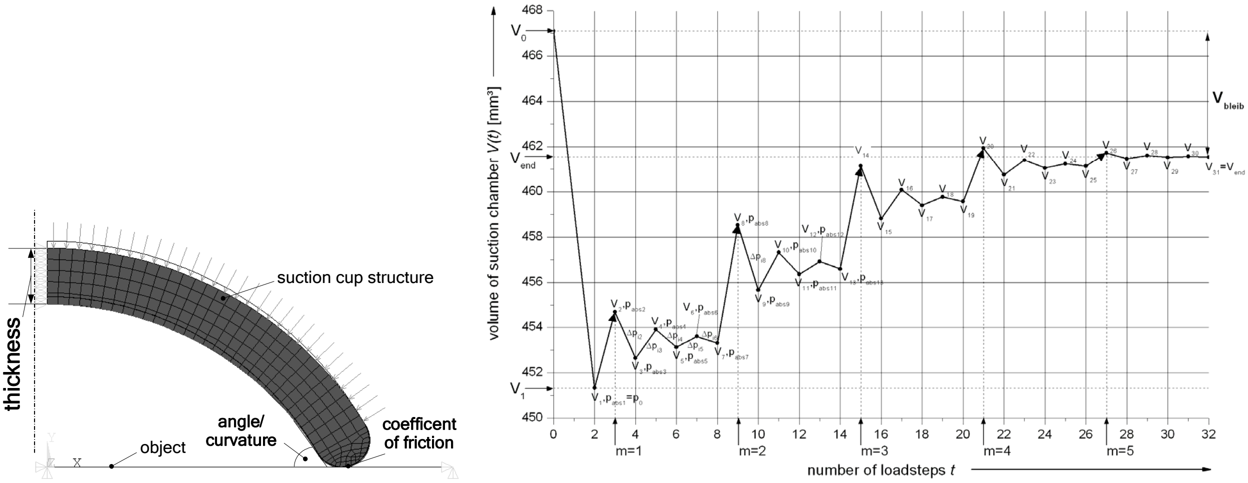

Fig. 3 *2D FEM model of suction cup with examined parameters (l.) and diagram of the calculation method to simulate the negative pressure as a result of permanent deformation (r.)*

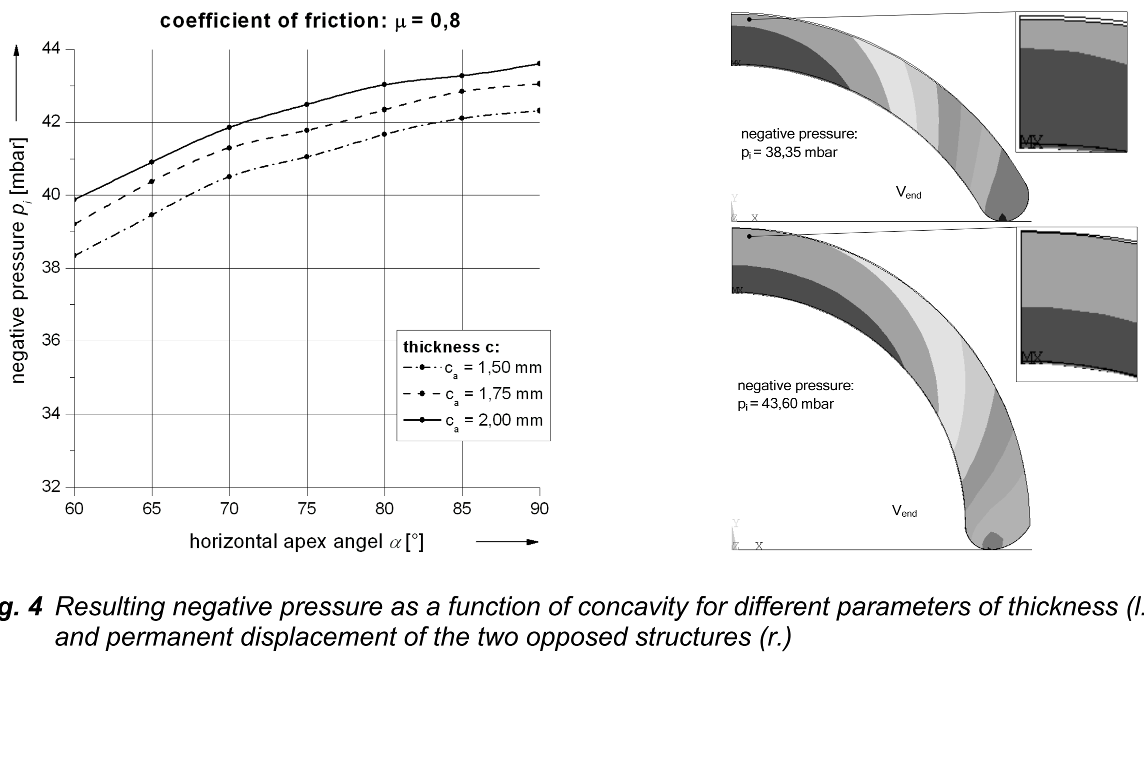

Fig. 4 *Resulting negative pressure as a function of concavity for different parameters of thickness (l.) and permanent displacement of the two opposed structures (r.)*

In this way comparative investigations for different suction cup geometries allow statements about the structure with the highest holding force depending on the used loading (actor system) for the process of passive volume enlargement:

- *Steady state loading forces:* Thin-walled suction cups with small curvatures are especially suitable.
- *Steady state volume changing*: Suction cups with high thicknesses and large curvatures effect an increasing stiffness and so high negative pressures, as shown in Fig. 4.

Application and conclusion

In addition to the design recommendations the FEM-based simulation allows an analysis and evaluation of biological inspired principles in an early stage of the development process. The usage of closed compliant suction cups has innovative advantages for the technical application:

- *Robotics*: Because of the energy autonomy and because of the small influence of friction to holding force suction cups with large curvatures are very promising for climbing robots and several surface attributes
- *Biomedical engineering*: Suction cup structures from biocompatible silicone are well tolerated and have a low complexity.
- *Micro and nanotechnology*: The active separation mechanism is very interesting for the compensation of adhesive forces which allows a local and time defined pushing off from object.

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