COMPUTER MODELLING OF SUCTION CUPS USED FOR WINDOW CLEANING ROBOT AND AUTOMATIC HANDLING OF GLASS SHEETS

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Optimizing vacuum grippers of robots for glass sheets handling and developing robots for glass cleaning, it is necessary to solve a number of problems calling for a similar approach to a solution. This paper analyzes deformation behaviour of vacuum gripping elements of vacuum grippers. The extent of deformation safety of an individual suction cup is monitored depending on the vacuum level and loading character. A computer model was suggested and filtered out allowing contact area changes to be observed depending on a friction model and vacuum level.

Keywords
vacuum robot gripper, suction cup, window cleaning robot, mobile platform

1. Introduction

Robotized handling of glass sheets is a typical use of vacuum gripping heads inducing vacuum actively. Such handling requires full understanding of the process and excellent knowledge of relationships between a handling task and loading character of each gripping element – vacuum suction cup. Also locomotion mechanisms of window cleaning robots represent an important application of suction cups. Solving given problems, it is necessary to meet specific requirements. However, there are a number of common problems having similar solutions. Figure 1 resumes schematically specific demands as well as particular problems common and similar to both spheres.

When applying suction cups to the robot vacuum gripper for handling of glass sheets, it is necessary to meet a number of specific requirements. Variable combined axial (F_{AX}) and radial (F_{RAD}) loadings of suction cups are characteristic. Due to changes in orientation of the glass sheet gripping plane to horizontal line changes in ratio of loading components (F_{AX}/F_{RAD}) during loading are significant. The course is modified substantially by inertia and impact forces. Therefore a structural design of the active vacuum gripping head requires to apply spring compensators and to optimize setup of the handling cycle. It is favourable that for application studied friction coefficient of the contacting pair remains virtually changeless during the handling cycle. Taking account of a small lateral rigidity of glass, it is possible to minimize the amplitude of the gripped sheet oscillating motion at the moment of the sheet gripping and especially putting down using a suitable setting up of the handling cycle run-up and run-out phases combined with an optimized arrangement of suction pads. A number of authors' works deal with this aspect of problems solved, e.g. [Horak 2005a, Horak 2005b, Horák 2005c]. A local overloading of suction cups can be partially eliminated by compensators for the suction cup position and orientation on the gripper [Novotny 2008a, Novotny 2008b].

When suction cups are applied to solve climbing of the window cleaning robot, special characteristics are incorporated into the requirement to minimize the mobile platform weight and to achieve an extreme safety during a combined loading of suction cups that are loaded mainly radially (in the gripping plane). During radial loading, the friction coefficient, being markedly variable at intended application region, is a dominant factor limiting a safety stable contact of the suction cup and wall. Axial loading of suction cups is secondary one due to an overturning moment of gravitation forces. When the mobile platform moves on a vertical wall, this loading loads additionally its upper suction cups discharging lower ones. One can say that in this case the ratio in view (F_{AX}/F_{RAD}) has maintained cyclically being tied to a step-by-step operation within certain limits but a dominant factor is a variability of the friction coefficient f_k of contacting surfaces both at random (weather) and goal-directedly by technology used.

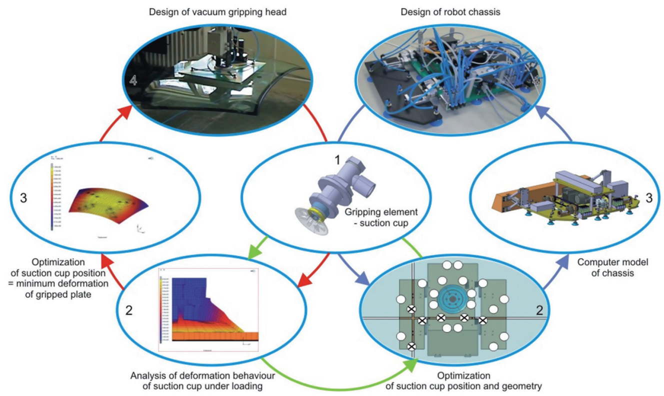

Figure 1. *Specific properties of the suction cup applications in view*

Authors place stress on an analysis of deformation behaviour of the suction cups as well as on a confrontation of typical force and deformation approaches to defining safety of gripping and also on defining and running the computer model for a single suction cup loading. There was a next goal, namely to describe the mechanism of the suction cup deformation behaviour during loading as well as to specify its use for above-mentioned applications.

2. Analysis of the suction cups deformation behaviour during loading

Loading of particular suction cups of the vacuum gripping head during the handling cycle is highly variable. When specifying causes of the stable gripping collapse, it is necessary to carry out deeper analysis which is further seen from two points of view. First a conventional force approach to defining of gripping safety is analyzed and subsequently a deformation approach is formulated based on results of the computer model. Such approach shows the loading cycle process in relation to the suction cup deformation behaviour.

2.1 Conventional force conception of a single suction cup safety gripping (keeping)

When designing a gripping head with vacuum gripping elements, it is important to determine gripping forces necessary for the ob-

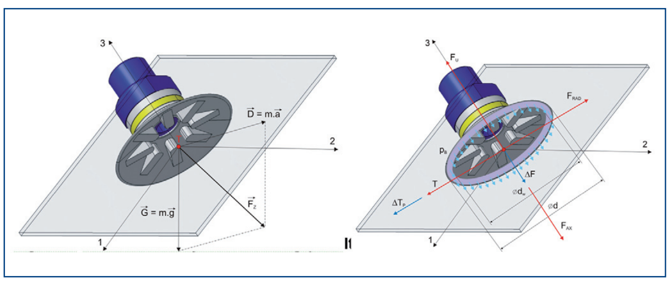

Figure 2. *The suction cup force loading (resultant load force, analysis of equilibrium of Figure 2. The suction cup force loading (resultant load force, analysis of equilibrium of balances)*

ject safety holding during handling. To describe force loading the suction cup, a local system of coordinates was chosen in accordance with Figure 2.

The system initial point O=T lies together with axes 1 and 2 in the plane of gripping and the axis 3 is identified with the suction cup axis. For the resultant load force resolved to components it is valid:

$$m \cdot \vec{g} + m \cdot \vec{a} = \vec{F}_{Z1} + \vec{F}_{Z2} + \vec{F}_{Z3} . \quad (1)$$

Then the force F_{Z3} along the axis 3 represents the suction cup axial loading and forces in the plane of gripping create its radial component

$$F_{AX} = F_{Z3} \quad \text{and} \quad F_{RAD} = \sqrt{F_{Z1}^{\ 2} + F_{Z2}^{\ 2}} . \quad (2)$$

As for a centric gripping, the real gripping force will be:

$$F_U = k_1 \cdot F_{AX} + k_2 \cdot \frac{F_{RAD}}{f_k} , \quad (3)$$

where k_1 is safety against break-off, $k_2 > k_1$ is safety against sliding. The relation (3) can be rewritten to the form

$$F_U = k \cdot F_Z \left(\cos\alpha + \frac{\sin\alpha}{f_k'} \right), \quad (4)$$

where $f_k' = \frac{k_2}{k_1} \cdot f_k = (0{,}75 \div 0{,}6) \cdot f_k$ is the friction coefficient reduced value (more details in [Novotný 2004]), involving also a degree of uncertainty at the exact determination of this coefficient for the pair of contact materials intended.

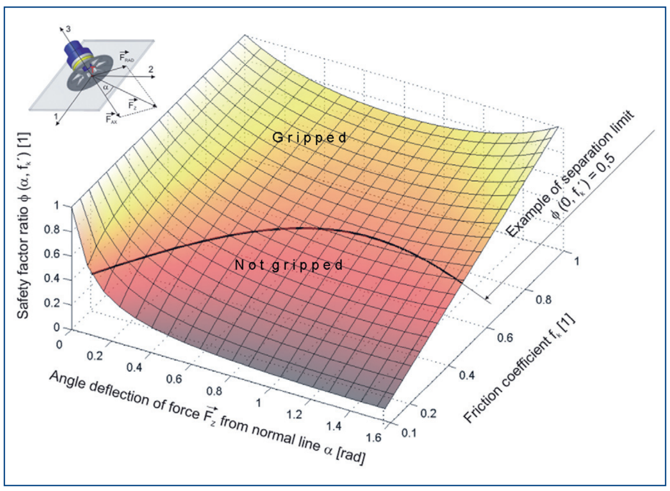

Figure 3. *Analysis of force depending on friction size*

Depending on the direction of the load force carrier and friction, the resultant degree of safety will be

$$k(\alpha, f_k') = \frac{F_U / F_Z}{(\cos\alpha + \sin\alpha / f_k')} , \quad (5)$$

and by reason that will be , ratio will be

$$\Phi(\alpha, f_k') = \frac{k(\alpha, f_k')}{k(0, f_k')} = \frac{1}{(\cos\alpha + \sin\alpha / f_k')} . \quad (6)$$

The dependence $\Phi(\alpha, f_k')$ graphic presentation is obvious from Figure 3 and shows decisive changes in degree of force safety during the object holding while the object position has been changed towards the vertical line when high values of safety coefficients are necessary especially if the friction coefficient values are low (wet or oil-soiled surfaces). E.g. for $f_k = 0{,}1 \div 0{,}2$ the value of minimum safety at limit of break-off is $k_{min}(0, f_k') \cong 10 \div 5$ and to provide safety gripping at any position this value will be $k_{sk}(0, f_k') \cong 20 \div 14$.

2.2 Computer simulation of the suction cup deformation behaviour

Analysis of the suction cup deformation behaviour comes under the sphere where deformation contact tasks are solved having specifically defined boundary conditions and a material model of contacting bodies. Common shapes of suction cups resistant to combined stress are more complicated because they are provided with supporting beams. A basic analytical modeling of this problem [Liu 2006] does not allow describing satisfactory such complicated contact task which presents deformation contact of the flexible suction cup. Therefore the problem was solved by means of the computer simulation using FEM.

To describe non-linear behaviour of the suction cup elastomeric material, the Mooney-Rivlin rheologic model characterized by material constants c_{01} and c_{02} which were defined on the basis of a dependence between main stress and real deformation (more details in [Horak 2005a], [MSC 2004]).

With respect to a changing active surface of the suction cup being defined by its effective diameter d_w it was necessary to set up a boundary condition using a special sub-routine. This boundary condition reduces the effect of vacuum, i.e. it defines the surface where vacuum is effective or not on the element surface given (it has its share in a cumulative creation of gripping force).

The surface was actualized depending on loading. The current contact surface corresponding with the loading level was detected considering contacting body states (the contact quality) at each step of calculations. This effect realized using a program sub-routine promotes the accomplishment of the representative computer model of the suction cup real behaviour during external loading.

For four levels of vacuum cases of simple axial, radial and also combined loadings of the suction cup with the geometrical diameter of 60 mm were solved. Friction ratios were described by variable values of the friction coefficient at the interval between 0.1 up to 0.7 respecting the friction force dependences on a relative friction velocity using the Streebeck relation.

Calculation parameters were debugged from the standpoint of calculation, effective utilization of PC RAM and attainment of a satisfied calculation time. Results of simulation were compared to data measured during laboratory experiments. A good agreement was observed (Figure 4).

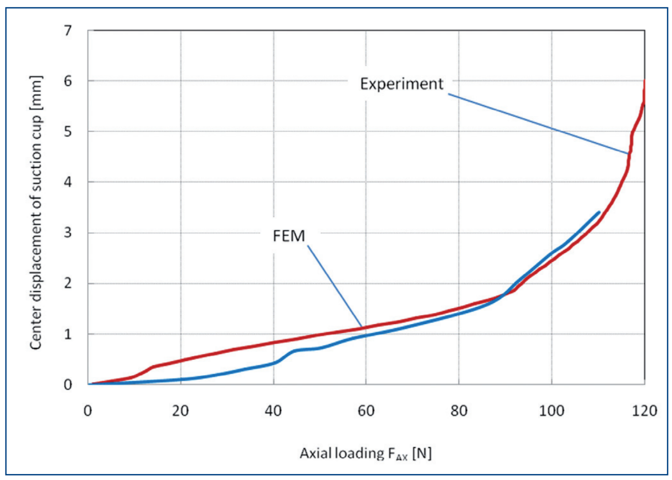

Figure 4. *Verification, vacuum level 60 kPa*

3. Deformation formulating the safety coefficient

Based on the computer model results, the suction cup deformation behaviour can be formulated for main loading types as follows:

A. For a simple axial loading (according to Figure 5 - row 1) to identify uniquely and limit 4 phase of the suction cup deformation behaviour during the loading process:

1st phase – the suction cup touch down without loading, i.e. the moment of the first contact;
2nd phase – the suction cup loading increases and active surface under the suction cup (beams reduce their contact surface with the object);
3rd phase – beams are never in contact again and the suction cup axial deformation increases and the degassed active surface diameter limited by a sealing lip decreases;
4th phase – the lip stable contact with the object is cut off, the suction cup degassed cavity tightness is disrupted and the contact subsequently collapsed due to air intake.

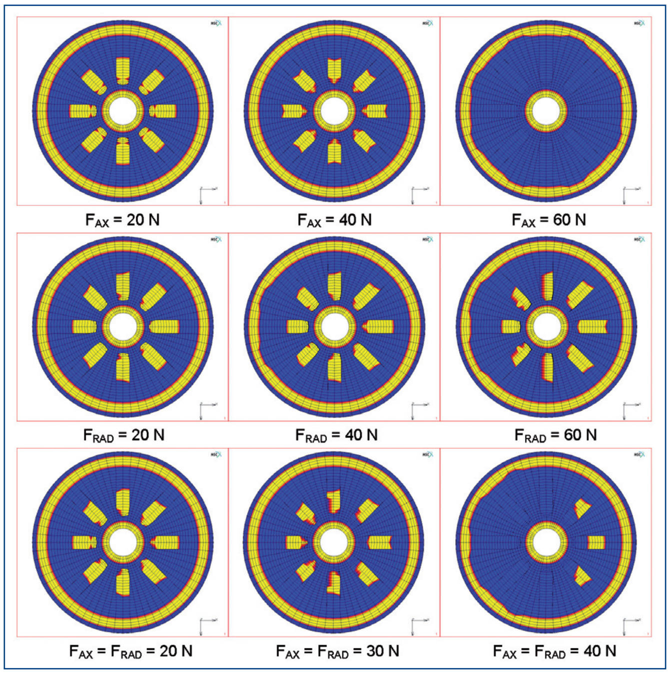

Figure 5. *Deformation of suction cup (1st row – during axial loading, 2nd row – during radial loading, 3rd row – during combined loading)*

B. To describe the radial loading (according to Figure 5 – row 2) it is more difficult seeing that dominant deformations take place in the plane of gripping, beams are in contact, and contact surfaces of particular beams are markedly different peripherally whereas the greatest difference occurs at direction of loading. The active surface does not change notably and remains preserved up to the state of metastable equilibrium which is accompanied by the sealing lip motion on the object surface and as for the limit value, it is followed the contact momentary collapse.

C. During combined loading (according to Figure 5 – row 3) a deformation response of the suction cup the material being observed on the contact surface is analogous to the character of loading by radial force with the exception that the contact area is reduced distinctly to the extent greater than it corresponds with the resultant size of load forces F_L.

It can be stated that formulating safety in term of deformation, it is necessary to tie safety holding to the stable contact emerging during loading at the moment defined for the contact predetermined point. If the contact at this point is kept, gripping is considered as stable. Based on the computer model, it is possible to choose a usual point of stability for given suction cup and loading method and to determine corresponding force loading for this point. It is evident that for the same point a value of permissible force will be different for particular loading types.

The deformation definition of stable vacuum gripping using the suction cup gives better starting point for each suction cup dimensioning because determination of a limit holding capacity is not applied to the limit of break-off but to the permissible degree of the profile deformation, which values are lower. This degree of safety chosen respects the suction cup real loading better.

4. Computer simulation outputs

Summary representative results rendering deformation courses during the suction cup increasing loading were selected from extensive outputs of the computer simulation. In all cases, the usable point was chosen (in figures it is marked by A) which presents shift forms (it defines deformation) for particular loading types, vacuum values range from 20 to 80 kPa.

In Figure 6 results are given consistent with a simple axial loading of the suction cup by axial force F_{AX} at the normal to plane of gripping. For vacuum value chosen, points of break-off allows determining the suction cup holding capacity derived from the deformation theory of gripping safety and comparing with values declared by a manufacturer.

In Figure 7 and 8 outputs are resumed recording radial loading in plane of gripping. Figure 7 declares results fully corresponding with values of variable parameters of axial loading. Figure 8 presents results – for the value of vacuum chosen (60 kPa) – relevant to different values of the friction coefficient from which is obvious that the friction coefficient decrease under $f \leq 0.3$ leads to decisive reduction of gripping stability, i.e. the usable point is shifted for values ca 15 N.

Different mechanisms of the deformation model of axial and radial loadings are also reflected in the course of loading characteristics. A collapse of the suction cup loaded radially is initiated by a very small increase of loading force (4 – 5 % of the entire range is sufficient to such collapse) while loading resulting in a collapse is at 12 – 15 % level of load force in the case of axial loading.

As for combined loading (according to Figure 9) using the force F_L = 56.5 N, radial loading is limiting again, however with reduced value the degree of which is more distinctive by ca 30 % compared with the case which would correspond with the principle of superposition when would be valid.

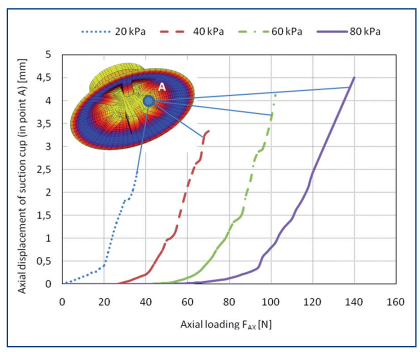

Figure 6. *Axial loading of suction cup (in dependence on vacuum level), f = 0.5*

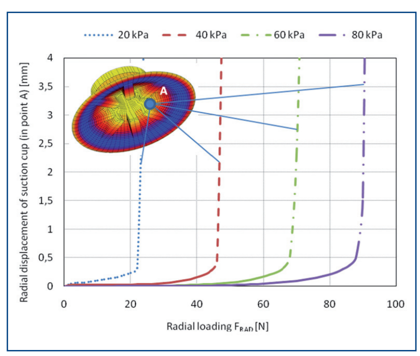

Figure 7. *Radial loading of suction cup (in dependence on vacuum level), f = 0.5*

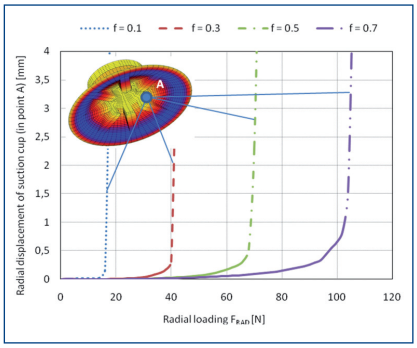

Figure 8. *Radial loading of suction cup (in dependence on friction), vacuum level 60 kPa*

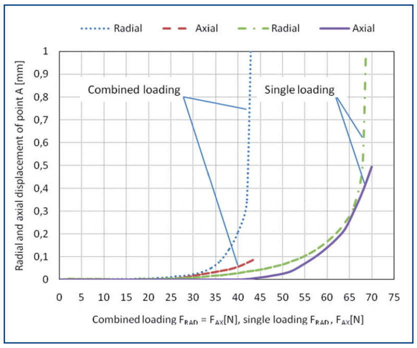

Figure 9. *Combined loading, vacuum level 60 kPa, friction f = 0.5*

5. Conclusion

The paper analyzes the conventional force process for dimensioning of the gripping element with combined loading by axial and radial forces. Owing to necessity to define deformation and mechanical loading capacity, the computer simulation of the suction cup deformation behaviour was carried out. The verified computer model was applied to describe the course of the suction cup deformation cycle during loading when simple axial, radial and combined stresses were used. FEM outputs were presented by deformations of the suction cup profile at contact point chosen and allow contractual values of deformation safety to be defined.

Using modelling, it was found that especially radial loading of suction cups is hazardous. Mainly their combined stress (radial and axial loadings simultaneously) changes the contact surface geometry (the contact profile shape) due to friction and material properties of elastomer and degree of vacuum.

Based on the analysis performed, it is necessary to determinate the safety level using deformation behaviour theory as it applies to suction cup loading in practice. In the case dominant radial loading of suction cups, it is necessary the standard safety level value to increase by approximately 60%.

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