ANALYSIS OF SLIDING SUCTION CUPS FOR NEGATIVE PRESSURE ADHESION OF A ROBOT CLIMBING ON CONCRETE WALLS

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The success and efficiency of wall-climbing robots is not only a question of closed-loop control and electronics. Also materials have a large influence on the operability to make the systems light-weighted or more robust. This paper presents findings based on experiments to find an optimal material for inflatable adaptive sealings. Demands of such sliding sealings are robustness and good sliding characteristics but also fexibility for high sealing performances. The paper gives an overview on several materials and on their characteristics.

Keywords: Climbing Robot, Negative Pressure Adhesion, Adaptive Sealings

1. Introduction

Wall-climbing robots are a wide-spreaded research area all over the world using different locomotion and adhesion principles like magnets,[1] suction cups[2] and claws[3] or new approaches like electroadhesion[4] or van-der-Waal adhesion.[5] Nevertheless, no robot is available so far which can be used to inspect large concrete buildings. The wall-climbing robot CROMSCI[6] (figure 1, left) tries to close this gap by using active negative pressure adhesion in combination with an omnidirectional drive system. This setup has been chosen to make the system applicable for prevention maintenance which requires high velocities of up to 9.81 m/min for a sufficient fast navigation between inspection points and to carry a payload of 10 kg in terms of inspection sensors.

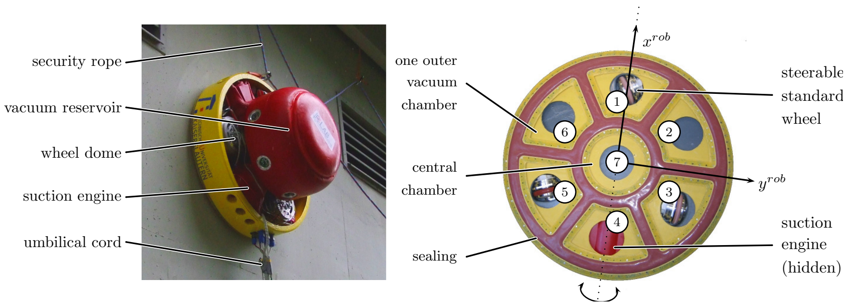

Fig. 1. CROMSCI (left) with its inflatable rubber sealing (bottom view, right)

This paper presents results to find the best materials for the inflatable sealings (figure 1, right) which are needed to seal the negative pressure adhesion system to the ambient air. In this special application the sealing has to deal with a very rough surface, temperature differences of up to 100° C and needs to be relative leak-tight. Literature mainly deals with static rubber sealings[7] or sliding suction cups[8] on glass surfaces, but the combination of rubber, rough concrete and negative pressure adhesion is nearly unexplored. So far, a silicone rubber of shore hardness (SH) 27 is used with a sliding material[9] which has been glued on the inflatable rubber. This combination works as a proof-of-concept, but is not robust enough for longer periods of inspection. Therefore, a couple of other rubber materials is taken into account and tested against demands which might be conflictive like robustness and flexibility. The main challenge is now to find the optimum which fulfills all requirements in a sufficient manner:

Low friction value: Sideward forces of the sealings must be reduced since they have to be overcome by the drive system.

Low wear: The abrasion should be low enough to be able to perform the desired task for a certain period of time.

Robustness: It has to be strong enough to avoid penetration by protrude obstacles or sharp edges as they are common on concrete surfaces.

High flexibility: To be able to overcome small steps the sealing has to be flexible enough to allow a working range of ±1 cm.

Highly leak-proof: The sliding surface has to remain smooth enough for leak-tightness even on structured surfaces.

The next section will introduce the used test stand for determining key characteristics of the materials. The materials itself and the experimental results will be shown in section 3, the conclusion follows in final section 4.

2. Dynamic Test Stand

The dynamic test stand itself consists of different parts as shown in figure 2. The *cartesian robot* can move its tool center point (TCP) in a total range of $1.7 \times 1.5 \times 0.5$ m with a velocity of up to 350 mm/s. At the TCP the *experimental platform* with the adhesion system is mounted. Beside the adhesion system as shown in figure 3 this platform consists of the necessary electronic components, integrated pressure valves and sensors for controlling the sealing pressure. Beside the *vacuum cleaner* which is used as suction engine for the adhesion force, also a *pressure pump* for inflating the sealings and a *personal computer* are not integrated into the platform but connected to the system from outside.

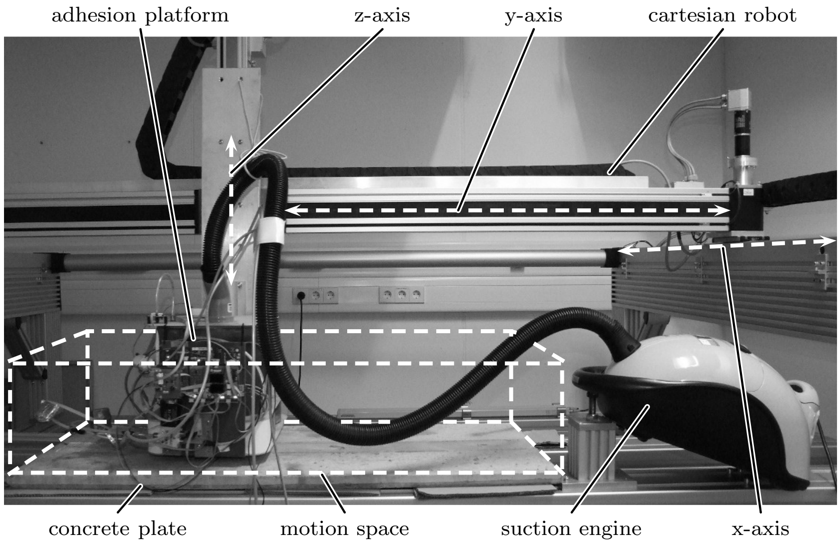

Fig. 2. The complete dynamic test stand with experimental platform (including the adhesion system), concrete surface, suction engine and cartesian robot with its three motion axes. The dashed box indicates the motion space of the platform.

The adhesion system (figure 3) is able to generate a desired adhesion force and to measure upcoming forces via a load cell connecting the system to the cartesian robot. The diameter of the round structures is 25 cm, the volumes are 4 l of the adhesion chamber and 10 l of the reservoir. The drawing also shows the air flow: Via leakage areas at the sealings ambient air enters the adhesion system (1). Of course, these leakages have to be reduced but as one can imagine the system would not be able to move on a concrete surface if the sealings are 100 % leak-tight. The negative pressure inside of the chamber is controlled by the valve opening (2) connecting pressure chamber and vacuum reservoir. The outer valve (3) allows the raising of reservoir pressure whereas the suction engine (4) lowers it.

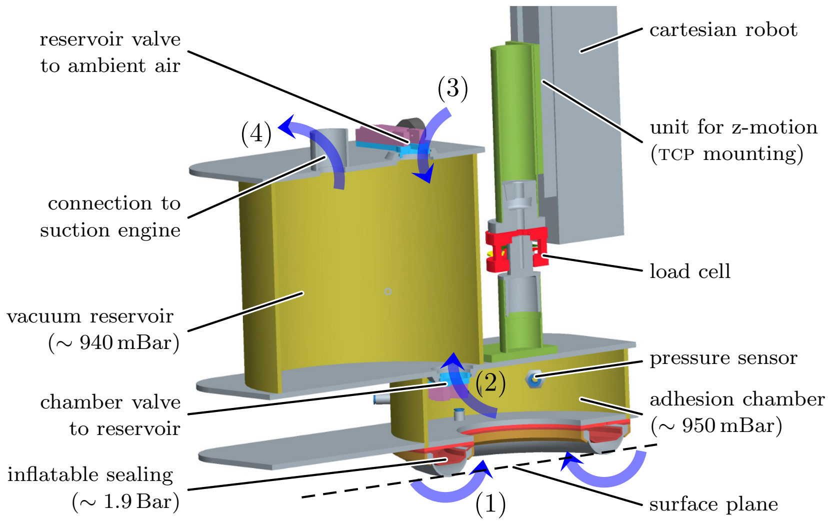

Fig. 3. Construction drawing of the adhesion system consisting of an adhesion chamber, a negative pressure reservoir and corresponding control elements.

3. Material Characteristics

The presented test stand is used for different static and dynamic experiments to determine a couple of material characteristics as presented in sections 3.1 and 3.2. Nevertheless, some additional trials on common industrial test stands become necessary to get more information. These experiments will be described in section 3.3.

3.1. *Static Experiments*

In the first experiments on the test stand some static values of the different sealing materials are determined. This includes leakage values and pressure force induced by the sealing depending on the distance between test stand and concrete surface. Table 1 sums up the examined rubbers. Sealing pressure (1.9 Bar) and negative pressure for adhesion (−50 mBar compared to ambient pressure) are set fix during these experiments. The graphs in figure 4 represent the leakages of the used materials at different heights (set via the z-axis of the cartesian robot) of the adhesion system while it is not in motion. Here one can test the static leakages (the lower the better) as well as the flexibility (the wider the range the better). It is obvious that the leakage increases with growing distance between adhesion system and ground surface. Furthermore, the softest sealing (MVQ-30) with SH 30 has the highest flexibility (±1.2 mm) and is highly leak-proof, whereas sealing NBR-S-40 with a steal coating was leak-proof only in a very small range (±0.4 mm). Very interesting are the results of neoprene (CR-40) which is of the same hardness as MVQ-40 and NBR-40 but much more leak-tight. Materials with a SH above 50 are not tested on this test stand since the needed pressure for inflation would be too high.

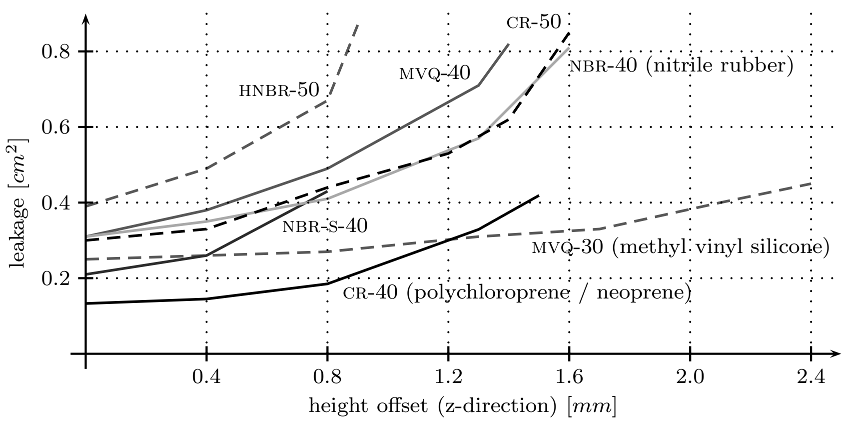

Fig. 4. Static leakages at varying distances between adhesion system and concrete plate with different sealing materials and shore hardnesses.

3.2. *Dynamic Experiments*

In a second test series the adhesion system is moved by the cartesian robot in y-direction (compare fig. 2) back and forth with a velocity of about 100 mm/s to retrieve the dynamic parameters. Figure 5 shows an excerpt of the logged data with materials of SH 40 on top and the others below. In this cutout one motion from left to right of the adhesion system is depicted – except MVQ-30 which had its turning point at about $t = 10$ s as it can be seen by the ratio value going down. This ratio of sideward forces $F_{xy} = \sqrt{F_x^2 + F_y^2}$ and pressure force F_p, which are measured by the integrated load cell, allows a conclusion on the friction value. In an optimal case it would be exactly the friction value, but so far it only allows a relative statement.

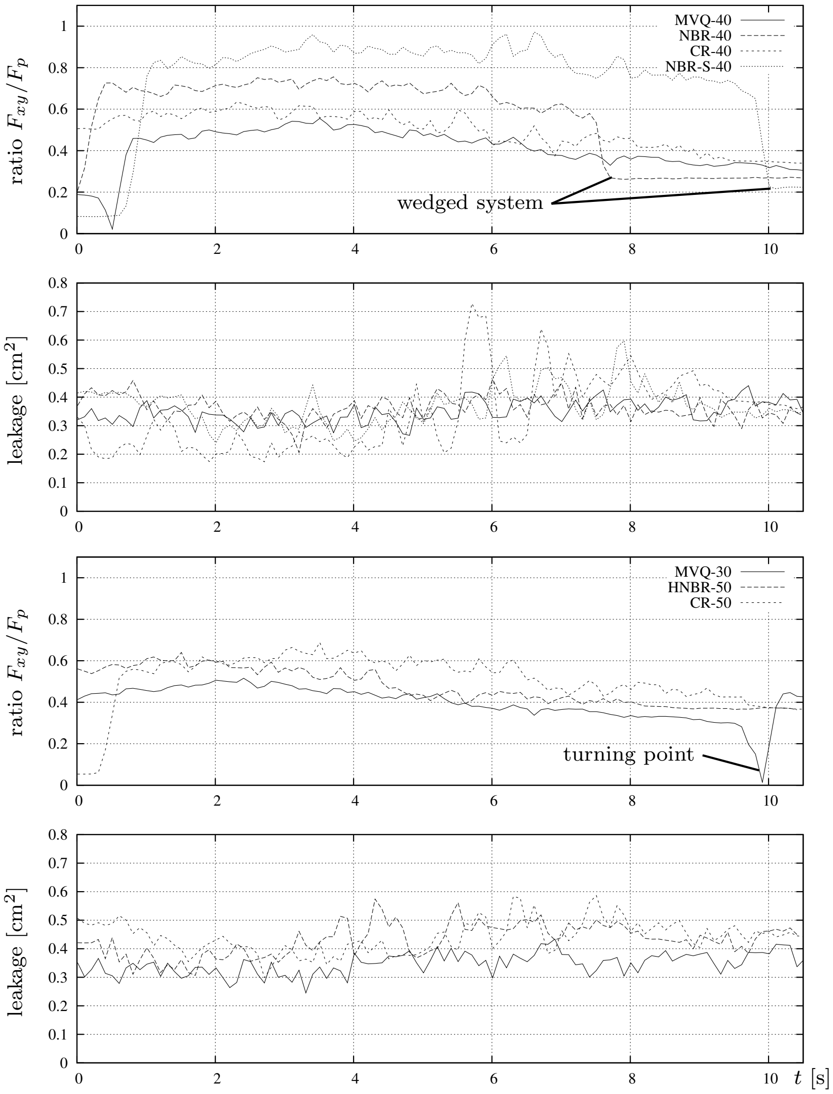

Fig. 5. Results of the dynamic experiments with adhered and moved platform using seven different materials.

In the graphs one can notice a surprisingly high difference in these ratio values although the shore hardnesses are (nearly) the same. Unfortunately, it is not possible to perform a large number of test cycles automatically because the adhesion system wedges itself if sideward forces are high. This problem occurs because of irregularities on the ground and results in an emergency stop of the motors which have to be reactivated manually. In the final application this problem does not exist since the distance between robot chassis and ground is set fix via the wheels.

3.3. *Additional Experiments*

In addition some more key data are examined on separate test stands: The abrasion has been analyzed on a test bench with a rotating barrel and abrasive paper. The values given in table 1 show the reduction of material weight in percent after 20 m. The elasticity is illustrated in needed air pressure to expand the sealing 1 cm on a separate test stand. The tensile strength as given in the last column has been determined on an universal testing machine as it is commonly used in industrial applications. Table 1 sums up the average values of all experiments, the best values are highlighted.

Table 1. Characteristics of the used materials: static flexibility, dynamic leakage and force ratio and finally common industrial key data.

material – abbreviation-SH	flexibility [± mm]	leakage [cm^2]	force ratio	abrasion [%]	elasticity [Bar]	tension [N/mm^2]
fluorocarbon rubber						
– FPM-50	-	-	-	21.4	-	5.8
methyl vinyl silicone						
– MVQ-30	**1.20**	0.34	**0.46**	**3.0**	**0.9**	5.7
– MVQ-40	0.70	0.34	0.48	4.4	1.3	6.7
– MVQ-50	-	-	-	10.8	1.6	9.9
natural rubber						
– NR-40	-	-	-	16.1	**0.9**	18.4
– NR-45	-	-	-	14.9	1.3	10.4
nitrile rubber						
– HNBR-50 (hydrogenated)	0.45	0.43	0.51	5.9	1.6	**22.6**
– NBR-40	0.80	0.36	0.70	12.9	1.0	5.8
– NBR-50	-	-	-	12.2	1.7	8.6
– NBR-S-40 (steel coated)	0.40	0.35	0.88	-	1.1	-
polychloroprene						
– CR-40	0.75	**0.30**	0.59	8.4	1.2	12.3
– CR-50	0.80	0.42	0.60	11.9	1.5	10.3

4. Conclusion

The sealing material is very essential for robust operability and economic application of the developed inspection system. A malfunction of the sealings caused by abrasion or penetration can lead to severe damages or a total loss of the system. So far, the results are very promising and give hints on the feasability of the different rubber materials for the sealings.

Nevertheless, a final decision can not be taken since a one-fits-all material does not exist. It seems as if a combination of materials like a soft and flexible sealing (e.g. MVQ-30) with a more robust sliding surface (e.g. HNBR-50) might be the best solution. The next steps are now to produce compound material probes and to perform additional test series to find the optimum in flexibility, leak-tightness and robustness with these combinations.

Acknowledgements

This research was funded by the german *Bundesministerium für Wirtschaft und Technologie* (BMWi) under the program *Zentrales Innovationsprogramm Mittelstand* (ZIM) and took place in cooperation with *Fraunhofer Institute for Industrial Mathematics* (ITWM), Kaiserslautern, Germany.

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