A vacuum gripper for micro assembly

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Abstract

Assembly is a crucial part in the realization of a product. Compared to assembly in the macro world, the assembly in the micro world is influenced by scaling effects. These include surface forces, low placement uncertainties and small product dimensions. Conventional high-speed assembly often utilizes vacuum grippers. However, their large moving mass results in high collision forces during product placement. Therefore they are unsuitable for assembling micro products. This paper will discuss the problems during assembly in the micro world with an emphasis on the forces during the assembly process. A new design is proposed for a gripper with a low moving mass (less than 1 gram for a pickup needle with a 6 mm diameter). In the design friction and hysteresis are neglectable. The focus of the paper is on the design and realization of the gripper and experimental results.

Key words: Assembly systems, Miniaturization, Gripper

1 Introduction

The assembly of a product, both at the macro and micro scale, is often performed using a series of pick and place operations. During a typical pick and place action the assembler first moves the attached gripper to the desired pickup location. There the assembler positions the gripper to make contact with the component to be picked up.

The gripper then fixates the component to the gripper and the assembler moves the gripper and attached component to the placement location (e.g. a

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second component). When the component is positioned correctly it is released by the gripper and the assembler with gripper moves to the next pickup location.

The stiffness and mass of MEMS components under consideration is low compared to the macro scale equipment used to assemble them. Thus, when handling micro products, several problems arise at the interface, some of which will be discussed in the next section. Some assembly techniques are discussed in section 3. Then, in section 4, a new design for a vacuum gripper is proposed. Several experimental results with the gripper are discussed in section 5 and finally some concluding remarks are given.

2 Aspects of micro assembly

The assembly of components with dimensions below 1 mm, often referred to as micro assembly, has several opportunities and challenges compared to its macro scale counterparts. Important challenges are the collision and static forces during assembly and surface forces [1].

First the influence of the collision forces will be discussed using the example of a perfectly smooth spherical component with radius r that is placed on a perfectly smooth planar base. The admissible speed is calculated using Hertze contact theory [2]. Compliance of the components, which results in a higher admissible speed, is not taken into account. The maximum occurring Von Mises stress in the plane p_0 and the indentation δ are given by:

$$p_0 = \left(\frac{6F_{Hz}E_{red}^2}{\pi^3 r^2} \right)^{\frac{1}{3}} \tag{1}$$

$$\delta = \left(\frac{9F_{Hz}^2}{16rE_{red}^2} \right)^{\frac{1}{3}} \tag{2}$$

Where F_{Hz} is the contact force and E_{red} is the reduced Young's modulus [2]. During a collision the kinetic energy is absorbed by the elastic deformation of both bodies:

$$\frac{1}{2}mv^2 = \int_0^{\delta_Y} F_{Hz}(\delta)\, d\delta = \frac{\pi^5 r^3 \left(1.61\sigma_{0.2}\right)^5}{60E_{red}^4} \tag{3}$$

Here $\sigma_{0.2}$ is the yield strength of the component and δ_Y is the indentation at which plastic deformation begins, using the Tresca criterion [3]. The mass m

is the equivalent mass of the sphere, i.e. the mass that is 'felt' when trying to accelerate the sphere.

From equation 3 it can be seen that the admissible approach speed v decreases with decreasing component dimensions. This can also be seen in Figure 1 where we assume that the gripper is rigidly connected to the component. The equivalent mass in this case is the mass of the component and gripper combined. The figure shows the admissible approach speed to prevent plastic deformation as a function of the mass of the gripper for several component radii.

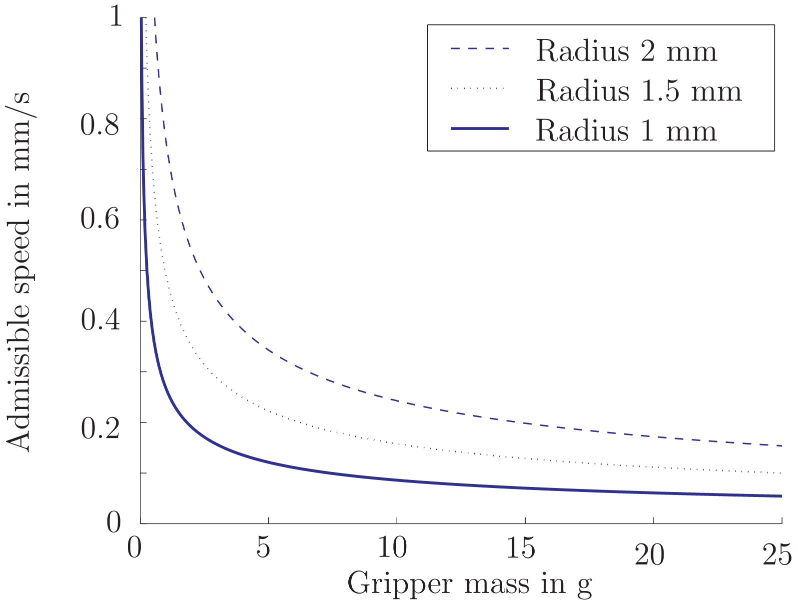

Fig. 1. The effect of the gripper mass on the admissible approach speed when placing a sapphire sphere on a planar aluminium workpiece.

The moving mass of traditional grippers is often more than 100 grams, resulting in high collision forces. To prevent permanent damage, the collision speed is therefore kept low, often well below 0,1 mm/s (also see Figure 1). As a result assembly time and its contribution to the total product cost are high.

After the collision of the two components and when the contact is detected a signal is provided to the assembly robot to stop the movement of its head. The distance between the point of contact and the point at which the movement of the assembler ends is referred to as the overtravel distance. The static force at the point of maximum overtravel depends on the overtravel of the assembler and the the stiffness c between both components, i.e. the stiffness of the loop through the assembly robot between both components.

The admissible speed regarding overtravel v_{ovt} depends on the reaction time t_r of the assembly robot and the deceleration a according to [4,5]:

$$v_{ovt} = -t_r a + \sqrt{t_r^2 a^2 + 170 \frac{r^2 \sigma_{0.2}^3}{c E_{red}^2} a} \tag{4}$$

From the viewpoint of dynamics a high stiffness of the assembler robot is advantageous. However, as seen in the above equation this also leads to a decreased admissible approach speed. This is also shown in Figure 2, where the admissible approach speed is shown as a function of the stiffness between the components for $t_r = 2$ ms and $a = 10\ mm/s^2$.

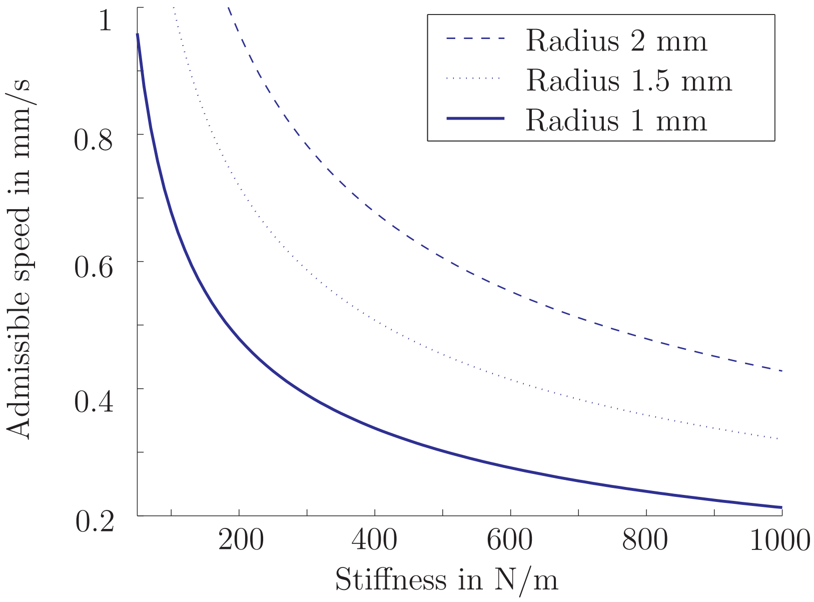

Fig. 2. Effect of stiffness on the admissible approach speed when placing a sapphire sphere on a planar aluminium workpiece.

To decrease the overtravel of the assembler an open loop placement can be used, where the gripper is moved to a predefined position. However, the position of the gripper is influenced by manufacturing and positional accuracies of both the components and the assembler. In the situation of a form closed loop [6], as can be found in many (semi)automated assemblers, this may result in high static forces during placement or release of the component when it is not in contact with the base component.

For both the open as closed loop systems it is therefore preferred to create a loop which is closed using a predefined force, often referred to as a force closed loop [6]. When locally decreasing the loop stiffness to decrease the static force it is preferred to do this as close to the component as possible to minimize the negative effect on the dynamics of the system. One possibility is to realize this in the gripper, as discussed in section 4.

Another issue in microassembly are surface forces as they are dominant over gravitational forces in the micro regime [1]. There are possibilities to decrease the surface forces between a gripper and component, including the use of conductive materials, decreasing the contact area, use hard materials, use a hydrophobic coating and work in a dry atmosphere or in ionized air [1]. If the gravitational forces are not dominant over surface forces for a specific placement operation, an active release mechanism is needed.

3 Micro assembly techniques

There are several techniques to assemble micro components. In general these can be categorized as parallel or serial assembly techniques (ref bohringer???). Parallel techniques include wafer-to-wafer transfer of parts, assembly using an array of micro grippers and stochastic microassembly (often referred to as self assembly) [1,7,8].

The abovementioned techniques often result in a high throughput and good placement accuracy. However, they are often only useful for a limited number of assembly operations and systems [7]. Therefore serial assembly techniques in which components are picked up and placed individually are still used in a wide range of micro assembly operations. The gripper used to handle micro components during the assembly should meet several functional requirements.

- the gripper should be able to pickup a component
- the gripper should be able to release a component
- the contribution of the gripper to the positional uncertainty during assembly should be well below the placement uncertainty of the assembly robot
- the components should not be damaged during assembly

As discussed in section 2 these requirements are not as trivial as they may seem when assembling micro components with macro scale equipment.

Several actuation principles can be used to pickup a component, including suction, electrostatic, magnetic, surface tension and friction forces. Tichem et al. [9] provide an overview of grippers suitable for micro assembly, categorized by their actuation principle. Each actuation principle has its advantages and limitations. The best actuation principle thus depends on the part to be manipulated, the environment and the requirements to the assembly operation (e.g. cycle time).

As mentioned in section 2, the effects of surface forces are an important challenge during the handling of micro components. For a large number of components these surface forces are dominant over gravitational forces, making it more difficult to release them. Therefore care must be taken to minimize these forces during assembly and it is thus needed to use an active release mechanism.

An actuation principle that is widely used in both macro and micro assembly, is the suction gripper [1,9]. The design of this gripper usually consists of a thin tube or pipette connected to a vacuum pump and is thus cheap to manufacture and easy to replace. Also the cycle time is very low, often well below 1 second. Furthermore it has the option to release components using a puff of air and the gripper is usable on a wide range of materials.

The main limitation of a suction gripper is the physical contact between gripper and component. As discussed in section 2 this leads to high collision and static forces during the pickup and placement of components, possibly damaging them. Other limitations are the handling of certain kinds of porous materials and the possibility that small particles obstruct the tube. The presence of particles is a common issue during micro assembly, which is therefore often performed in a cleanroom environment.

To decrease the collision forces during assembly and thereby decreasing plastic deformation of the components Höhn et al. [10] developed an aerostatic gripper. Here the component is suspended on an air cushion which prevents physical contact between gripper and component. The preload force is, similar to a vacuum preloaded air bearing, supplied by a suction nozzle. However, mechanical stops are needed to secure the lateral position and the rotation of the part around the gripper axis. Also, the stiffness of the gripper in axial direction is still high, which may result in high static forces during assembly, as discussed in section 2. A force closed loop would decrease the static forces caused by the overtravel of the assembly robot.

4 Design of the gripper

The design of the gripper should fulfill the functional requirements as stated in the previous section. It is also mentioned that a suction (or vacuum) gripper is usefull to pickup and fixate a wide variety of material. Also it is fast, widely used and when the component is placed it can be released using a puff of air, thereby fulfilling the first two functional requirements.

The third functional requirement: 'the contribution of the gripper to the positional uncertainty during assembly should be well below the placement uncertainty of the assembly robot' depends on the assembly robot used. A quick survey of assembly robots [refs ???] yields an achievable placement uncertainy of 5-100 micrometers. For the gripper to be usefull in these assemblers the contribution to the placement uncertainty should therefore be well below 5 micrometers.

The fourth functional requirement: 'the components should not be damaged during assembly' as stated in the previous section can be made explicit by specifying that no plastic deformation should occur when a sapphire sphere with a 1 mm diameter is placed on a planar aluminum workpiece ($\sigma = 300\ 10^{-6} N/m^2$, $E_{red} = 70\ 10^9 Pa$) with an approach speed of 1 mm/s. The assembly robot is assumed to decelerate with 10 mm/s^2 after a reaction time t_r of 2 ms. With these values a maximum equivalent mass of 1.4 gram and a maximum stiffness of the placement loop of 2.5 N/mm is obtained using equations 3 and 4.

The functional requirements from the previous section thus lead to the following specifications for the new gripper design:

- the components are gripped and fixated using suction
- the total positional deviation introduced by the gripper should be less than 5 micrometers
- the equivalent mass which is rigidly connected to the component should be less than 1.4 gram
- the stiffness of the gripper in axial direction should be less than 2.5 N/mm

The proposed design is shown in Figure 3. In this design the needle of the vacuum gripper (10) is suspended using a radial porous air bearing (5). During a movement of the assembler, with attached gripper, the axial position of the needle is constrained using a mechanical stop (2). This mechanical stop is preloaded using a bellow (8), as shown in Figure 3. The bellow is also used to prevent rotation of the needle around its axis. As a result the needle is constrained in 6 degrees of freedom (DOF) during movement of the assembler.

During a pickup operation the assembler positions the gripper to make contact with the component to be picked up. When the gripper collides with the component the needle moves in axial direction into the gripper housing (6), guided by the porous air bearing (5). The equivalent mass during this collision is therefore limited to the mass of the needle and the equivalent mass of the bellow, resulting in a low collision force.

As soon as the needle is moved from its zero position, the resistance of an electrical circuit between the mechanical stop and the needle is altered. A signal is given to the (robotic) assembler, which stops its movement. As discussed in section 2, the forces as a result of the overtravel of the assembler are caused by the stiffness of the loop between both components and thus by the bellow stiffness. Since the equivalent mass is limited, a low bellow stiffness is sufficient for a good dynamical behaviour of the gripper, resulting in low overtravel forces.

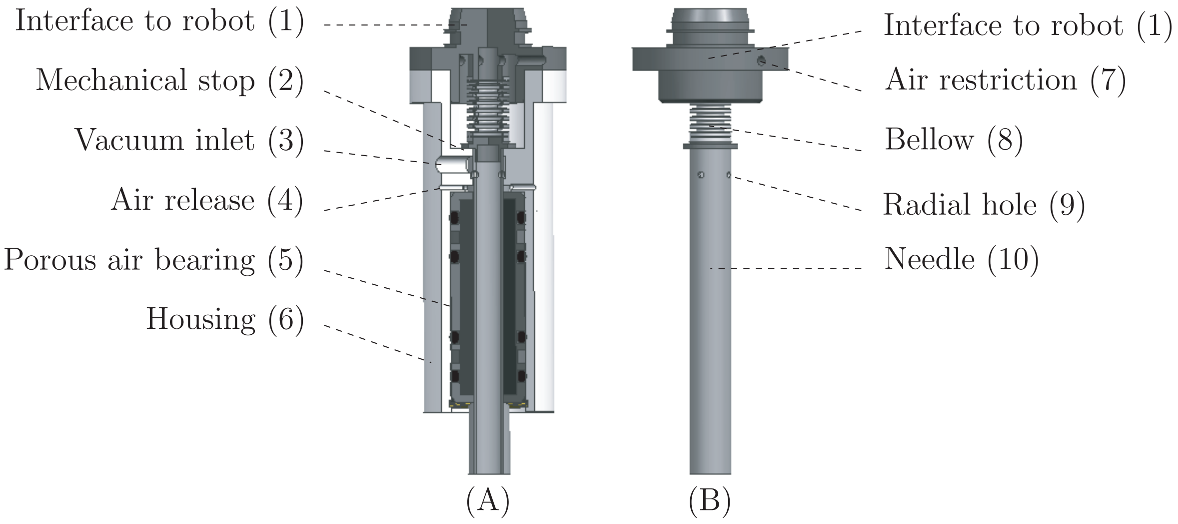

Fig. 3. Schematic of the new gripper design, (A) frontview of the gripper with a cutout section, (B) subassembly of the needle, bellow and interface to the robot.

After contact between gripper and component a vacuum is supplied to the vacuum inlet (3) to secure the component. The lateral position of the component is fixated via physical contact between the needle and component. The vacuum is supplied to the gripper needle using a vacuum inlet chamber in the gripper housing and radial holes in the needle (9), as shown in Figure 3. By measuring pressure variations in the vacuum supply, contact with the component is detected. When the component is fixated, the assembler moves to the placement position.

A prototype version has been manufactured, as shown in Figure 4. The gripper needle has a length of 45 mm and an outside diameter of 6.3 mm. To decrease its mass, the needle is manufactured from magnesium. As a result its weight is approximately 0,8 grams, well below the specification of 1,4 grams.

(??? mention specification and literature of magnesium ???)

A bellow with an axial stiffness of 50 N/m is used in the prototype gripper. It can be shown that a preload distance of 50 micrometers results in a vibration frequency of the needle of 180 Hz. Also, when the needle moves in the gripper housing (during a collision), air from within the bellow and the top chamber is forced out via several air restriction holes (indicated by (7) in Figure 3). This functions as an air damper and further improves the dynamical behaviour of the gripper.

Force variations on the needle will result in positional deviations of the component with respect to the gripper housing. The vacuum supply hose is usually rigidly connected to the gripper needle. A displacement of the needle thus

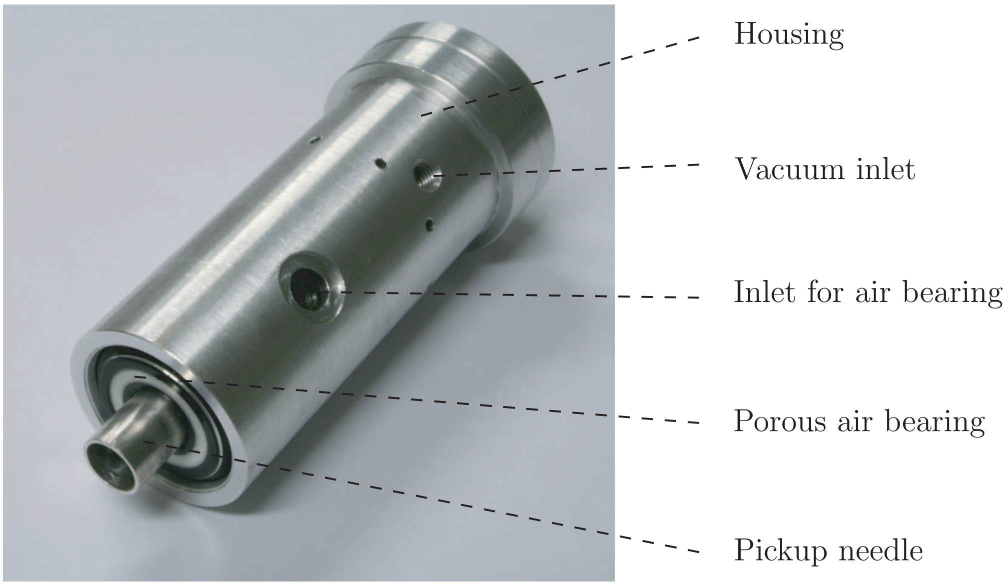

Fig. 4. Picture of the assembled gripper.

leads to a deformation of the hose and forces on the needle. Another factor of influence is pressure variations in the hose.

In the proposed design the vacuum hose is connected to the gripper housing. The vacuum pressure is supplied to the gripper needle using a vacuum inlet chamber and radial holes in the needle, as discussed earlier. There is no physical contact between the vacuum hose and the needle. The needle itself is suspended using a radial air bearing. As a result, friction and hysteresis in the design are neglectable. The absence of friction also decreases the formation of particles. To prevent crosstalk between the air bearing and the vacuum inlet chamber an intermediate chamber is manufactured. This chamber is connected to the environment using several holes (indicated by (4) in Figure 3) in the gripper housing.

Positional deviations of the needle with respect to the housing have been calculated to be less than 1 micrometer for accelerations up to 20 G and components up to 1 gram. The dimensions of the gripper can be greatly reduced using a custom air bearing. The equivalent mass and stiffness can thus be further reduced, making it even better suited for the assembly of small components.

5 Experimental results

As discussed in the previous section a vacuum chamber and radial holes in the needle are used to create a pressure in the needle. However, since the flow restriction between the vacuum chamber and the environment is limited, air will flow from the environment to this chamber or vice versa, depending on the pressure inside the chamber. A high flow loss is an indication of a poor flow resistance and may cause the gripper to blow away small components.

Figure 5 shows the flow loss in the gripper as a function of the pressure inside the needle. For this gripper a needle pressure of 20 kPa corresponds to a pickup or release force of approximately 0,5 N. The flow loss at this pressure is approximately 0,01 l/s. Another issue is the flow loss in the porous air bearing. This is specified to be less than 0,018 l/s. A displacement of spheres with a diameter of 100 micrometers or larger on a planar surface has not been observed due to this flow loss.

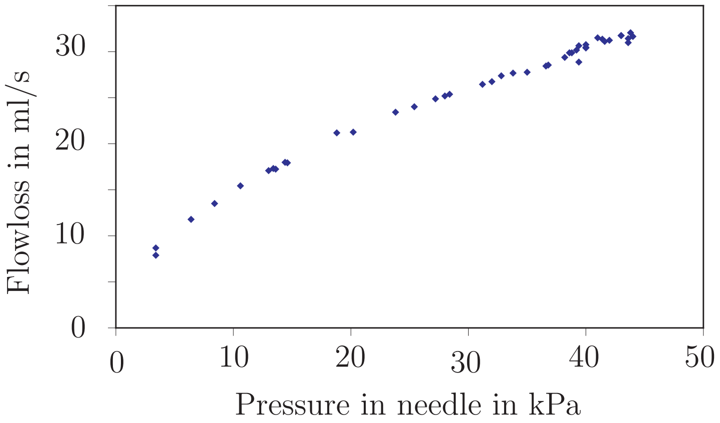

Fig. 5. Flow loss in the gripper as a function of the pressure inside the needle.

The force during a collision is measured using the setup shown in Figure 6. The gripper (2) is mounted on a column (1) using a clamp (4). The column is guided in vertical direction using roller bearings. A force sensor (5) is mounted under the gripper needle using a clamp (6). The column is risen so that the distance between the gripper needle and the force sensor is 1 mm. After release of the column gravity accelerates it with the attached gripper in the direction of the force sensor.

After a fall of 1 mm the gripper needle collides with the force sensor with a speed of approximately 130 mm/s. The gripper housing is connected to the column and the gripper needle is now in contact with the force sensor. Since the column continues its free fall after the collision, the needle is thus pushed inside the gripper housing. Finally the column comes to a stop when it collides with the sensor clamp (6). The forces between the gripper needle and the force sensor for the first 9 ms after the initial collision are shown in Figure 7. The second collision between the column and sensor clamp also results in vibrational forces between gripper and sensor. However, as this occurs at a later point in time, it is not shown in this figure.

It can be seen that even with an approach speed of 130 mm/s the forces during

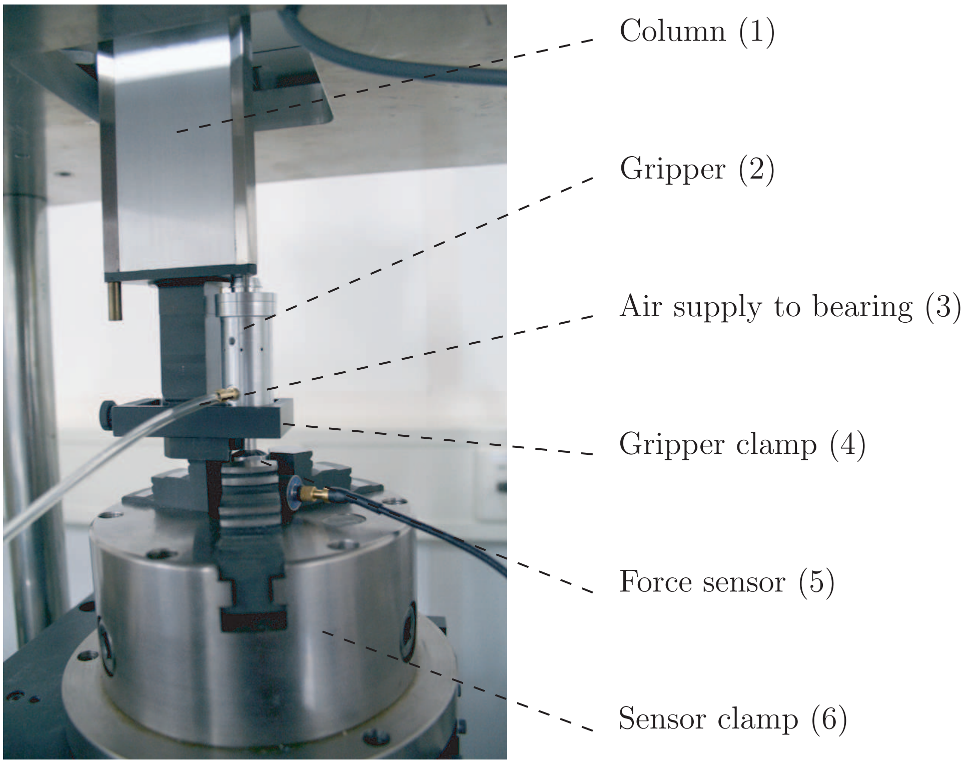

Fig. 6. Setup used to measure the collision force.

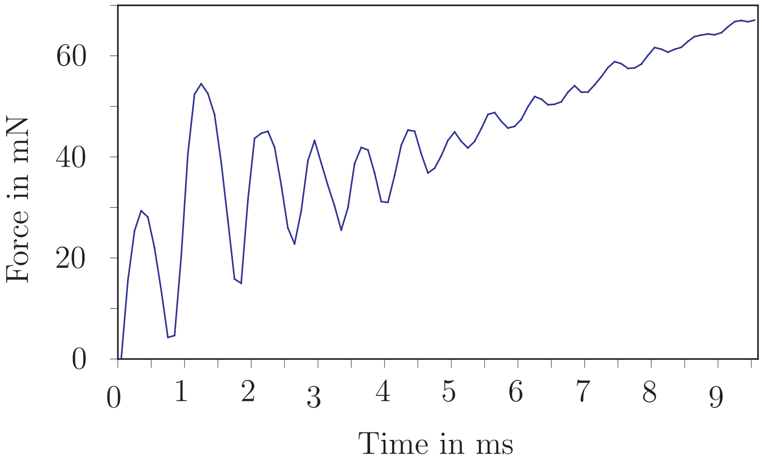

Fig. 7. Forces as measured during a collision with the gripper at an approach speed of 130 mm/s.

collision remain less than 60 mN. The initial build up of force is most likely caused by the preload of the bellow, as discussed in section 4. A preload force of 15 mN, indicates a preload distance of the bellows of approximately 300 micrometers. This is higher than required and as specified in the design. This may be caused by a poor length tolerance on the bellow. The preload force could be decreased by adjusting the internal dimension of the gripper housing after assembly.

Another point of interest are the peaks in the force curve. It can be seen that the maximum force is not achieved during the initial collision, but during the second collision. Most likely this is caused by the collision dynamics. The force sensor consists of a mass suspended on a spring. After the first collision, the gripper will bounce of the sensor. The sensor mass itself will also bounce of the gripper in the opposite direction. Since the column continues its movement, the relative speed during the second collision will be increased, resulting in a higher force. After the second collision the vibration is damped within several milliseconds, showing the good dynamic behaviour of the gripper as a result of the low moving mass and the air restriction holes.

Finally it can be seen that the build up of force continues after the collision. This is the result of the movement of the column and the stiffness of the bellow.

??????? ——————— What will be added: ———————

Additional measurements (to be done): * Of the plastic deformation when a spere collides with an aluminium workpiece at several approach speeds (picture of plastic deformation of the block and picture of the assembler used). * Friction force between the gripper and a component (with what force can components be held by the gripper?)

Have the specifications, as stated at the start of section 4 been met??? First give an overview of the specifications of the gripper as given in the paper, refer to the spefications and conclude that they have been met.

——————— ????

6 Conclusions

A new design for a vacuum gripper is proposed. In the design friction and hysteresis are neglectable. A prototype version is realised with a magnesium gripper needle with a length of 45 mm and a diameter of 6.3 mm. The needle is suspended using a porous air bearing, resulting in a moving mass of less than 1 gram. The needle is supported in axial direction by a bellow with a stiffness of 50 N/m. As a result the collision force for an approach speed of 130 mm/s is measured to be 60 mN or less.

Positional deviations of the needle with respect to the housing have been calculated to be less than 1 micrometer for accelerations up to 20 G and components up to 1 gram. Furthermore the gripper is used to pickup and release sapphire spheres with diameters of 0,3 mm or larger. The requirements as stated in section 4 have therefore all been met. Finally the gripper is used to place a sapphire sphere on a planar aluminium workpiece with an approach speed of ???? mm without damaging the workpiece or other components.

7 Acknowledgement

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