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Gripping Compliant Systems Operated with Bellows Actuators Used in Biomedical Engineering

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Abstract: The purpose of this paper is to analyze a set of developed gripper prototypes operated by bellow actuators that can be utilized in biomedical engineering. The main role of these grippers is catching small and big objects, their main advantage being to remove the complexity of structures using flexible couplings. Experimental results will be compared with numerical results obtained by finite element method.

Keywords: compliant mechanisms, bellows actuators, grippers, finite element analysis.

1. Introduction

Nature is a real and inexhaustible source of optimal solutions for a variety of technical problems of great interest. Trends of miniaturization of compatible products with modern technology open new perspectives for micro grippers, for the manipulation of samples in mechatronics, robotics, biomedical engineering and other technical fields, where the required force is provided by micro actuators [1], [2].

This paper presents a structured set of grippers that can be miniaturized in the future, which highlights the multiple possibilities offered by compliant elements operated by corrugated tubular elements (bellows). The first part presents a few concepts about compliant mechanisms, followed by presenting flexible couplings which are having a major importance for the functionality of compliant structures. The importance of using bellow actuators in mechatronics/robotics and biomedical engineering is covered in chapter three, while chapter four is dedicated to the CAD model of proposed prototypes, which have two, three respectively four fingers (fasteners). The finite element method for the developed models is presented in the next chapter and finally, the comparing results obtained by numerical and practical methods are submitted.

Mini grippers are covered in various articles pertaining to specialty literature, such as [2], [3] and [4]. The authors create models and present aspects regarding robotic micro-manipulation systems, an artificial finger from polymer and metal composite used for micro gripping and debate about the control and the driver system for the proposed actuators.

2. Synthesis of mechanisms with elastic elements

Due to technological progress and the miniaturization of structure mechanisms that tend to get the best possible performance in terms of motion control, positioning systems were also part of the ongoing development and change. Transition from a positioning system based on mechanisms using couplings and classical elements to in one piece mechanisms with flexible joints is due to different material characteristics and related studies. Compliant mechanisms are those mechanisms that transmit the motion or force due to material elasticity, as shown *Fig. 1* [5].

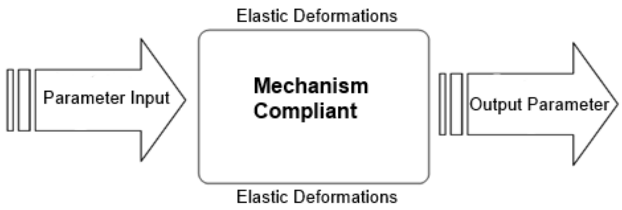


Figure 1: Principle of compliant motion mechanisms.

The elasticity of the material is exerted on the flexible coupling. A flexible coupling consists of a thin member that provides rotation between two members through bending, like in *Fig. 2* [6], [13].

Figure 2: Classical coupling (a), Flexure hinges (b).

The compliant mechanisms use elastic displacements due to forward movement, are reversible and remain within the validity limit of Hooke's law [12]. These mechanisms are designed for miniaturization and are accurate systems because they contain elements of rigid solid character, the connection between them being made by elastic type links which provide a certain unequivocally relative movement between elements [14].

Since the performance of compliant mechanisms is highly dependent on the characteristics of the materials from which they are made, the analysis of these unconventional mechanisms requires knowledge from several fields. Motions allowed by these mechanisms are more restrictive and highly dependent on the topology of the mechanism. Mechanisms with elastic joints have recently experienced a spectacular development due to advances in micro-technologies [7].

3. Bellows based actuators

Bellow elements are also called corrugated-tubes with thin walled shells of revolution, which are precision engineering constructive elements, frequently used as sensorial elements. They falls into the energy accumulation and signal translation categories. Bellows are curved on the side and can elongate or compress under axial force or internal/external pressure. Their activation is based on elastic deformation of corrugated elements, having high performances versus weight and they have a simple design and low cost [8].

Bellows are frequently used in pneumatics and hydraulics, their geometrical dimension, shape and material determining a clear dependency between the inside or outside installed pressure and deformation produced by it [9].

The performances of different mechatronic systems are influenced by their actuators which convert the input energy into controllable motion. The actuation effect is achievable by: induced limited strains, interactions of the magnetic field, electrical current and electrical charges, respectively, mechanical interaction. The last one involves the presence of a liquid or gas, whose pressure or flow determines the movement and/or deformation of the active elements. The actuators based on inflatable elements may be classified as: variable stiffness actuators, actuators with asymmetrical pressurization, artificial muscles and other types, including bellow actuators [10].

The bellows which will activate the grippers are made from nickel alloy with 20 mm length in normal state and 0.08 mm wall thickness, a number of 24 convolutions powered with pneumatic pressure at a maximum value of 20 bar for the FC-1 bellow (*Fig. 3*) and 27bar for the FC-9 bellow. Tensile Strength for these types of bellows is 930 MPa and Yield strength is 910 MPa, according to Servometer manufacturer's catalog [11].

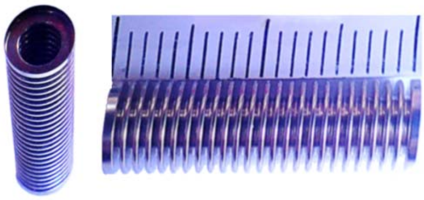


Figure 3: *FC-1 bellow.*

4. Constructive variants of grippers used in biomedical engineering

Fig. 4 presents CAD gripper models, each one being operated by only one bellow. For the constructive models presented in *Fig. 4* a), c) and d), the role of the corrugated tube element is to spread the clamps of the gripper. Their return into the initial position is achieved by releasing the pressure from the transducer. *Fig. 4* c) presents the structure of a gripper with three arms disposed at 120^0 from each other, which are operated simultaneously by one bellow disposed along the axis of the structure. In *Fig. 4* d) the fingers are disposed at an angle of 90^0 for bigger objects and better grasping.

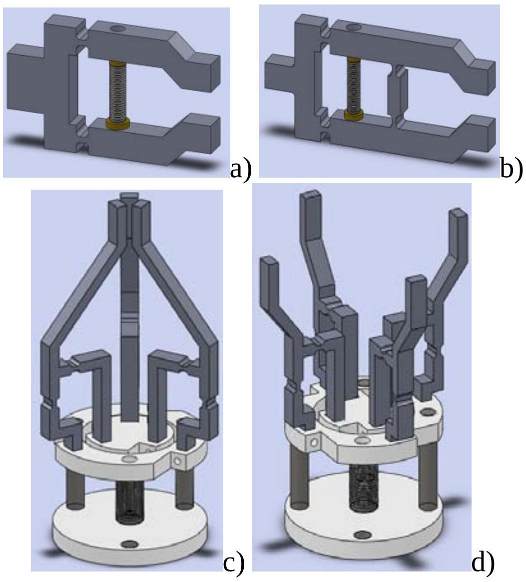


Figure 4: a) Normal gripper, b) Reverse operated gripper,
c) Gripper with three fingers, d) Gripper with four fingers.

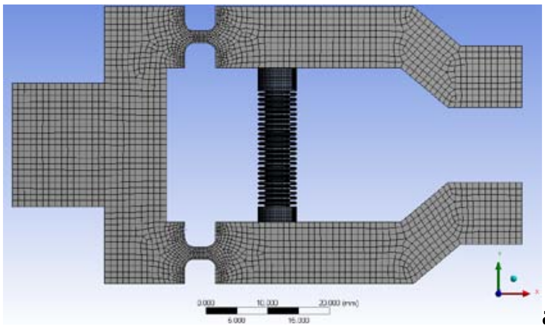
The model from *Fig. 4* b) differs from the previous one by introducing an element between the bellows and the gripping claw. Introducing an internal pressure inside the bellow will lead to the closure of the gripping claws.

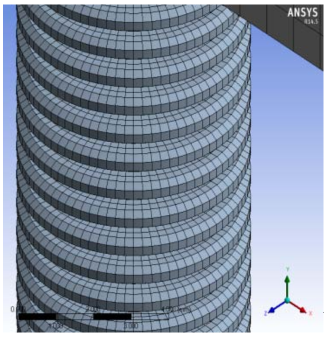
5. Finite element analysis for the compliant mechanisms

FEA begins with CAD modeling within the Design Module of the Ansys software. Ansys offers a suite of arithmetical and logical operations with the purpose of obtaining fast, efficient and approximate results and provides access to almost any field of engineering simulation which requires a design process [15].

The main advantage of FEM is reducing the complexity of the studied problem, making possible different types of analyses (linear and nonlinear static, dynamic, buckling, and fatigue). Also the shape and material optimization can be studied.

Analysis starts with establishing of the boundary condition and the material properties of the parts and is continued with the discretization of the models using different specific methods for each obtained element. *Fig. 5* shows the discretization of the normal gripper. Within this meshing the hex dominant method was used for the gripping claw. Size of the used elements does not exceed 2 mm for the gripping claw (exception: maximum size of the joints is 0.5 mm) and 0.2 mm shell elements for the corrugated tube.


a)



b)

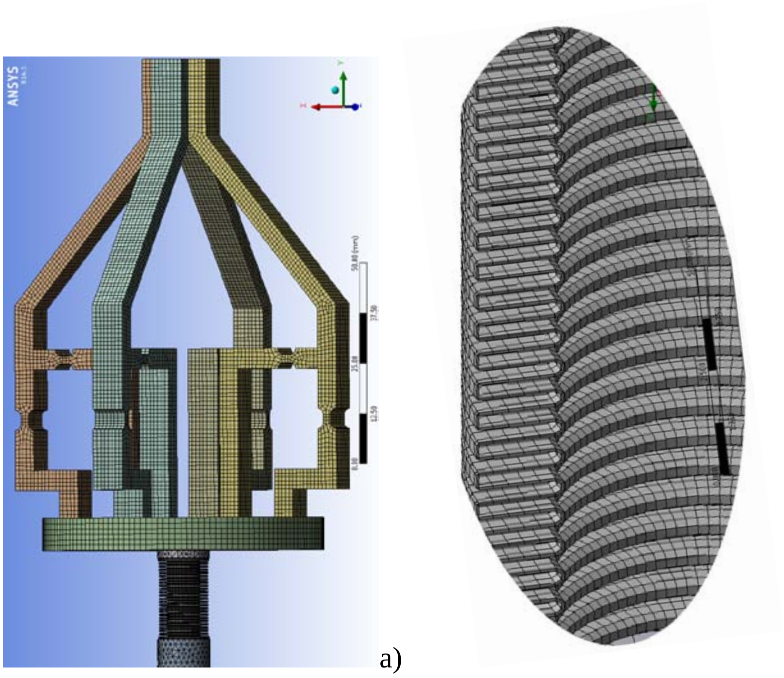
Figure 5: Discretization of the: a) normal gripper, b) FC-1 bellow.

Fig. 6. Presents the discretization for grippers with four fingers and details about FC-9 meshing with shell elements.

The discretization of the other structures was done in the same manner, the total number of obtained nodes and elements being shown in *Table 1*.

Table 1: Number of Nodes and Elements obtained by FEM method.

	Normal gripper	Reverse actuating gripper	Gripper with 3 fingers	Gripper with 4 fingers
Number of Nodes	240786	346016	226214	269707
Number of Elements	83575	107400	75110	83393



a) b)

Figure 6: a) Mesh of the gripper with four fingers; b) Detail view regarding discretization of the FC-9 bellow.

All models have been tested using pressures between 0.1 and 0.7 MPa, with the purpose of studying joints' and bellows' behavior, total displacements, equivalent elastic strain and equivalent stress, of the model's structures.

Fig. 7 a) presents the total displacement of the normal gripper's claw, the bellow being pressurized with 0.2 MPa. The value of the equivalent elastic strain of the gripper joint can be observed in *Fig. 7* b). Details regarding values of equivalent stress of the FC-1 bellow are in *Fig. 7* c). *Fig. 7* d) presents a comparison between the initial position and the total displacement of the gripping elements at the pressure of 0.7 MPa. 7 e) and 7 f) show the values obtained for the equivalent elastic strain of all four fingers of the gripper and also for the equivalent stress of the FC-9 bellow which activates the gripper.

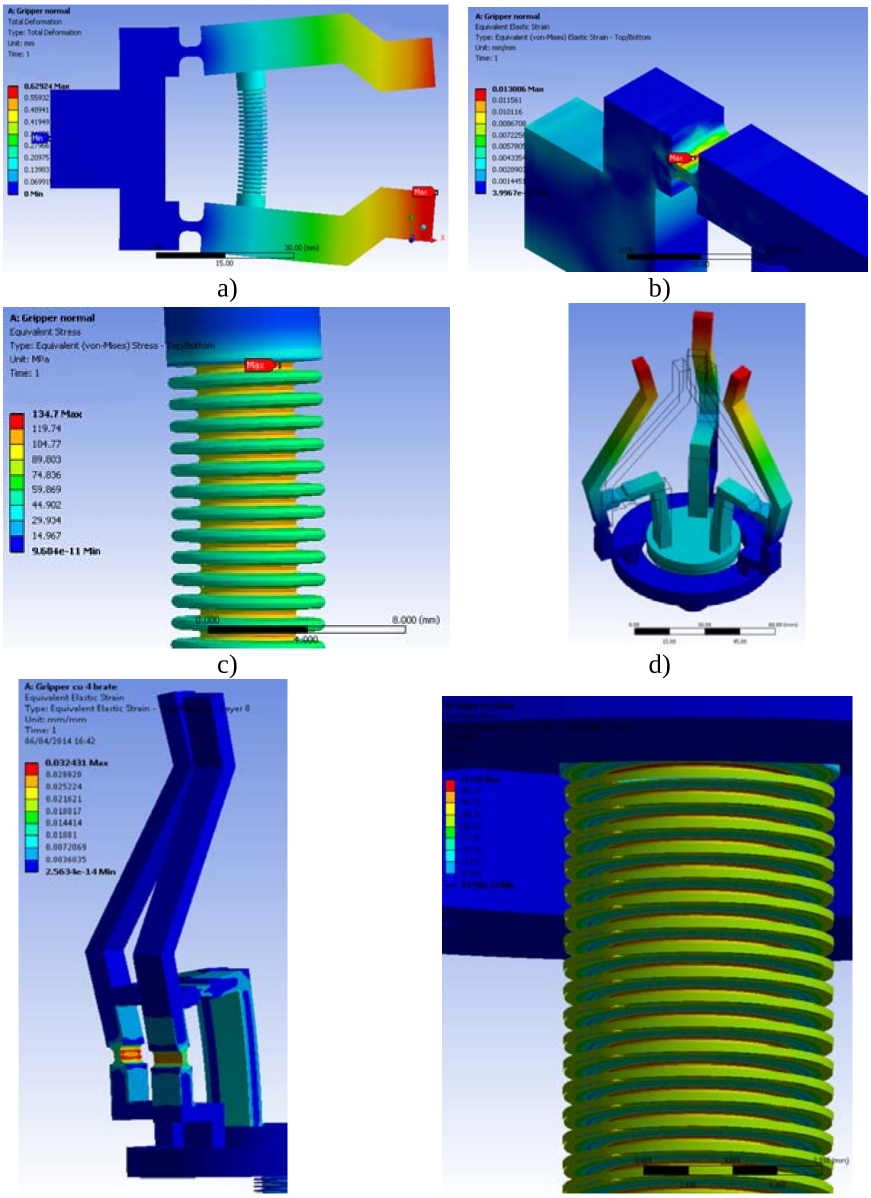


Figure 7: a) Total deformation of the normal gripper; b) Equivalent elastic strain of the joint; c) Equivalent stress for the FC-1 bellow; d) Normal vs. Total deformation of the gripper with three fingers; e) Equivalent elastic strain of the gripper with four fingers joints; f) Equivalent stress for the FC-9 bellow.

6. Experimental results

Compliant grippers made of PMMA, with aid of a CNC 3 axis mill (ISEL – CPM 2018) are presented in *Fig. 8*.

a) b)

Figure 8: Compliant grippers: a) Normal and reverse actuating grippers
b) Gripper with three and four fingers.

Fig. 9 shows the components of the experimental stand where the measurements were performed on each gripper with a high speed camera and with VEDDAC software used for digital images correlation. The points of reference and arrows that show the starting and the final position of the fingers' free ends can be observed in *Fig. 10*.

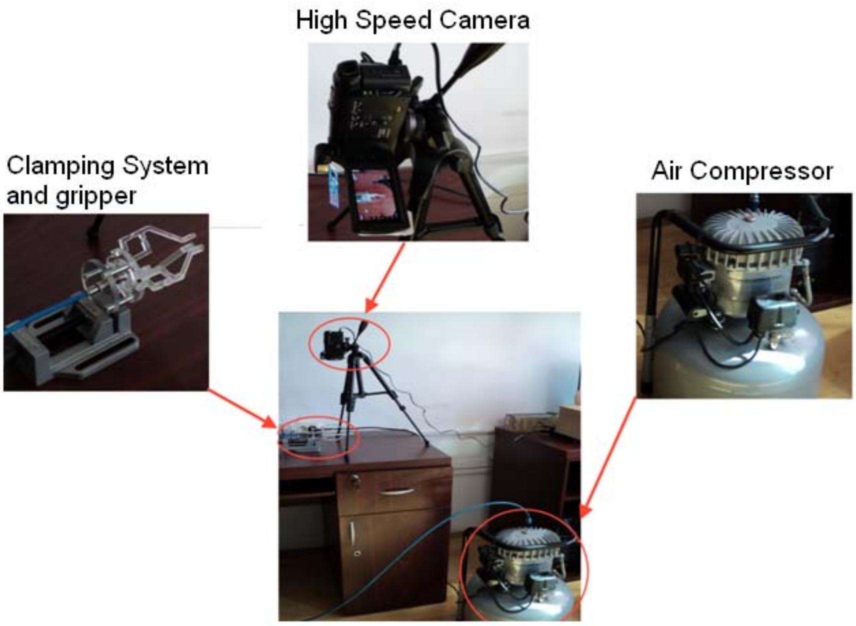
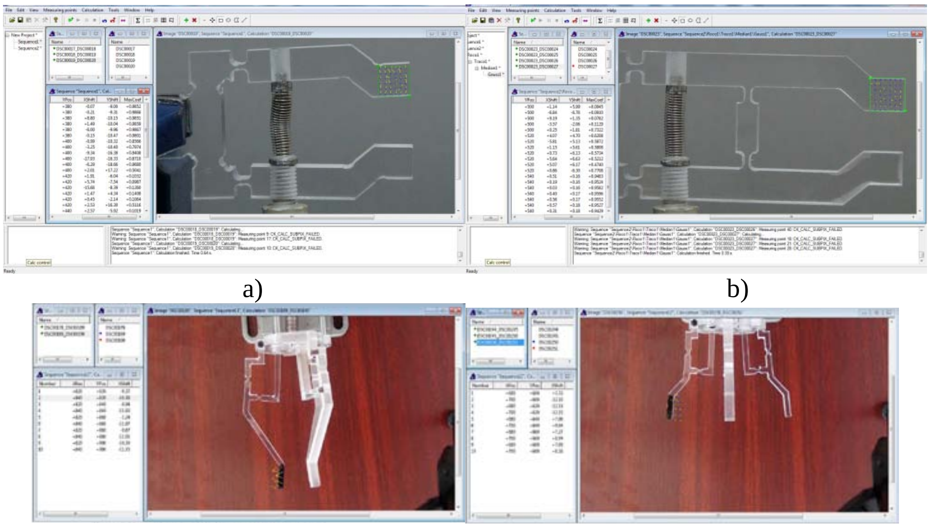


Figure 9: Experimental stand for displacement measurements.



a) b) c) d)

Figure 10: Correlated images from VEDDAC software with the results in the left side of the image. a) Normal gripper; b) Reverse actuating gripper; c) Gripper with three fingers; d) Gripper with four fingers.

Table 2: Experimental results obtained using Veddac software.

Gripper Type	Test No.	Pressure [MPa]	Maximum displacement [mm]
Normal gripper	1	0.2	0.62
Normal gripper	2	0.3	0.93
Normal gripper	3	0.6	1.24
Reverse gripper	4	0.2	244×10^{-3}
Gripper with 3 fingers	5	0.2	7.8
Gripper with 3 fingers	6	0.3	13
Gripper with 3 fingers	7	0.4	14.52
Gripper with 3 fingers	8	0.5	15.44
Gripper with 3 fingers	9	0.6	18.16
Gripper with 3 fingers	10	0.7	20.4
Gripper with 4 fingers	11	0.2	1.5
Gripper with 4 fingers	12	0.3	3.5
Gripper with 4 fingers	13	0.4	8.5
Gripper with 4 fingers	14	0.5	9.5
Gripper with 4 fingers	15	0.6	11
Gripper with 4 fingers	16	0.7	13

In order to determine the values for the displacements, one must know the pressure corresponding to each gripper type, the size of the flexible couplings and the limits within which it moves its active elements. *Table 2* presents the experimental results for each gripper, having applied pressures between 2 and 7 bars by taking into account the gripper's structure.

Table 3 shows the total displacement, equivalent elastic strain and equivalent stress obtained using the FEM method for each gripper at 0.6 MPa The 10 mm thick PMMA has the following properties: Young's Modulus 1920 MPa and Poisson's Ratio 0.39, while the 8 mm thick one is characterized by: Young's Modulus 1811 MPa and Poisson's Ratio 0.38. These were determined by performing measurements on PMMA check bars on a servo hydraulic tensile testing machine.

Table 3: Results obtained by using FEM method.

	Normal gripper	Reverse actuating gripper	Gripper with 3 fingers	Gripper with 4 fingers
Total displacement [mm]	1,80	0,325	21	20,038
Equivalent elastic strain	0,005	0,016	0,038	0,036
Equivalent Stress [MPa]	230,68	120,14	682,08	657,28

7. Conclusions

The authors were able to combine and develop a set of grippers with elastic joints operated by bellow actuators and they made a comparison between the results obtained using the numerical method with FEM and experimental method with precise measuring. For the first types of grippers, actuated by FC-1 bellows, the difference between the obtained results are due to underestimating the stiffness of the elastic joints (the actuators start bending from the middle when being pressurized with more than 0.2MPa). Instead, the numeric results obtained for the grippers actuated by the FC-9 bellow can be improved by modifying the quality of the mesh elements.

One can state that the designed and tested prototypes present certain advantages in comparison with classical grippers, as they are more compact, do not require lubrication and the friction from couplings is missing. Due to miniaturization, they can work in special environments requiring high precision, accuracy reliability and small workspaces.

Gripper operation through elastic elements like bellows provides the desired control of the structure over the manipulated object, depending on input and output parameters of the bellow and the compliant mechanisms.

Acknowledgements

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