Analysis of the Effect of Clearances in the Kinematics of Adaptive Structures

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Abstract: The analysis of the effect of the clearances in the kinematics of a prototype adaptive structure is presented. A tubular truss has been built equipped with three actuator bars (in phase of extension to twelve) that allow varying the structure geometry with great displacements. Photography techniques are used in order to study the effect of clearances in the structure movement with load and without load. Also the structure movement is simulated by means of a numerical model with the code Adams.

Key-Words: Adaptive, Structures, Instrumentation, Clearances, Error, Analysis, Mechanisms.

1 Introduction

The adaptive structures of variable geometry are able mechanical systems of modifying its geometry and mechanical properties in order to adapt themselves to different loads and operation conditions. An adaptive structure must be endowed of actuators that permit the controlled variation of its states and characteristics.

There are very various types of adaptive mechanical systems, between those that emphasise the VGT (Variable Geometry Truss). These structures are composed generally of a great number of articulated bars, forming a complex truss. Some of these bars are active elements, that is to say, that these can vary their length in a controlled way in order to correct small deformations. The causes of these deformations can be thermal distortions, static or dynamic forces, vibrations of the base, etc. These systems have a sensors system in order to register the deformation to correct.

The adaptive structures of variable geometry [1, 2] are a case more complex and less studied. These structures are mechanisms in those which the movement is composed of a part of rigid solid and other deformed part due to the elastic deformation of its components. These systems are endowed of actuators, usually with movement of translation or rotation, that are used to accomplish the global displacements. The number of these actuators is equal to the number of degrees of freedom. In the other hand, each one of its components can be also endowed of actuators, as those of the simple adaptive structures, in order to reduce the deformation effects of those components.

These structures are very light and are made of truss components. These are moved to low speed with high precision.

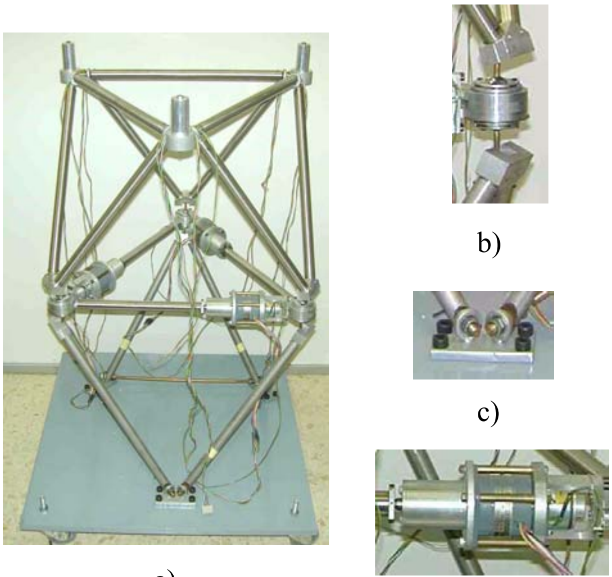
Since the first studies in the field of the adaptive structures, it has been made a great effort to the study of the position and effects of the corrector actuators located on them [3, 4, 5, 6, 7]. In this study, part of the obtained results in the tests of a prototype of adaptive structure is presented. This prototype is equipped with several actuators to change the structure geometry. Several authors [8, 9, 10, 11, 12] have studied the effect of clearances on the position of mechanisms using different techniques.

2 Prototype of the adaptive structure

A prototype equipped with three actuator bars has been designed and built, though it is planned shortly to endow it of twelve actuators. The structure is composed of articulated tubular bars made of stainless steel. The actuators have been designed to be fulfilled with several conditions. It must support a maximum load over the structure of 196 N. The ratio speed/load has to be able to open or close the actuator, being moved with the maximum load, in less than 30 seconds. It must have a resolution in terms of absolute displacement of less than 15 μm.

The maintenance has to be possible with the actuators assembled in the structure.

The actuator is composed of an electric step by step motor, a precision ball screw, a coupling, a brake and several connection elements. The motor has a maintenance torque of 0.4 N m, and it gives 200 steps/revolution. The ball screw has a pitch of propeller of 2.5 mm. Therefore a resolution of 12.5 μm is obtained. The ball screw has an extension length of 25 cm and a friction torque of 2.45 10^{-2} N m.



a) b) c) d)

Fig. 1. a) Prototype of the two modules adaptive structure and details: b) the cinematic joint, c) the joint to the base and d) the system motor-coupling-brake.

The bars of the prototype have a length of 0.54 m, included actuators (without extension). The bars sections have been calculated in order to obtain a maximum elastic deformation of 0.01 cm on each bar, when the structure supports a load of 196 N on each top vertex, in addition to own weight. This calculation has been accomplished through a finite element model using the code Cosmos.

The design of the cinematic joints has been made compact, though it should be changed when the structure is increased with more actuators, since each bar will have its own mobility. The design of the cinematic joint has a great difficulty due to the fact that there are six bars joined on it and with different cinematic pairs. This cinematic joint should be accomplished in a small space to maintain the theoretical dimensions of the prototype. In the Fig. 1 is shown the prototype of the adaptive structure and details of the cinematic joint, the joint with the base and the system motor-coupling-brake.

The motors are triggered through its controllers connected with a RS-232C cable to a computer. The orders are given through simple software to create a determinate sequence of movements of the structure. Figs. 2 and Fig. 3 show the assembly of the structure, the loads, the controllers and the connection with the computer.

Fig. 2. Assembly of the tests of the prototype: structure and its connection with the controller.

Fig. 3. Assembly of the tests of the prototype: connection with the computer.

3 Numerical simulation of the structure

A cinematic analysis of the structure has been carried out using the code Adams. The structure has been modelled with rigid elements and several cinematic pairs. The required angles in spherical bearings (part of the cinematic joints between bars) and the theoretical position of joints and elements have been calculated. Fig. 4 shows the numerical model of the structure. In each cinematic joint, it has been modelled two rotation pairs to join the actuators to the cinematic joint, and two spherical pairs to join the cinematic joint with the upper and lower part, being composed of two bars each of these parts. The actuator has been modelled with a prismatic pair and a mass.

In the study of the movement of the structure it can prove the limitation of the spherical pairs because of the displacement of the actuators.

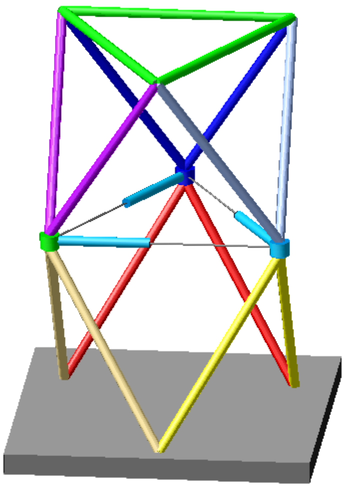


Fig. 4. Numerical model of the two modules prototype.

4 Photography tests

The photography tests have been carried out in order to analyse the clearances that are presented in the movement of the structure. Fig.5 shows the photograph equipment that consists of several elements: a camera Nikon D100 with CCD 3008x2000 pixels and with the mirror up option on (anti-vibration mirror elevation), an objective Nikon of 300 mm, a teleconverter of 1.4 (resulting in a focal distance of 420 mm), a flash, and a control program to shoot and register the picture (Nikon Capture Camera Control) connected to a computer. The camera is assembled on a very rigid tripod. The CCD is 1.5 times lower than a conventional negative of 35 mm. The distance between the camera and the structure is the same as a parallel projection without perspective distortion.

The measurements have been taken at a distance of 5 m from the objective of the camera to the base of the structure, and the vertical position of the objective is 1 m over the ground.

Several tests of movement have been made on the structure, corresponding to a displacement of the actuator of 1, 5, 10 and 15 cm (being a simultaneous displacement of the three actuators). The loads on the structure have been also different in the tests, considering four cases: without load, 58.8 N, 117.6 N and 176.4 N.

The tests have consisted of a return route, that is to say, it starts at initial position, and the structure is moved to the final position and returns to the initial position. A series of three measurements on each of the movements of the actuators is carried out. The number of measurements is a total of 48 for these tests.

Fig. 5. Photograph equipment.

The measurements have been accomplished on a calibrated grid (Fig. 6) using an optical microscope model Mitutoyo TM with micrometer heads on “x” and “y” directions. These measurements have been made in two points in order to calculate the mean value later.

The program Adobe Photoshop has been used to analyse the taken pictures with a zoom of the 1600 %. Afterwards, the relative error of the displacement has been calculated with the program Excel. These errors have been calculated dividing the absolute error in the initial position (the difference between the position before and after the movement of the actuators) by the total value of the displacement (difference between the initial and the final position). This has been repeated for the four cases of loads. Fig. 7 shows these relative errors in the “y” direction (vertical). On the other hand, in the "x" direction (horizontal), the study of the error has no interest because the obtained values of the displacement are very small (similar in magnitude to the precision in the measurement).

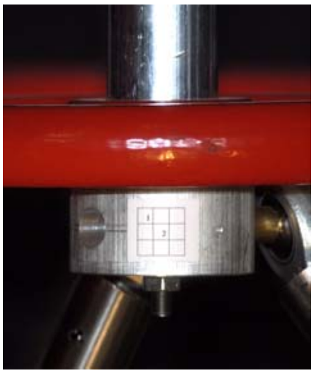


Fig. 6. Detail of the calibrated grid.

Fig. 7 shows the relative errors on the vertical displacement (position). These errors decrease progressively when the displacement of actuators is greater. This is due to the precision of the measurements (variation of the position) is one given, and when the displacement is increased in the vertical direction, the relative error can be calculated with greater precision. The obtained errors with great displacements confirm the good precision in the position of the structure.

It is observed that the most of position errors are due to clearances in the cinematic joints and the way the bars were built. This leads to the fact that the decrease of the position error of this prototype will be based fundamentally on the change of the design of the cinematic pairs.

On the other hand, it is observed that the relative error is decreased when there are large displacements of the actuators. This indicates that the error due to the movement of the motor is probably very small and is not accumulative.

With relation to the influence with the load, Fig. 7 shows that the smallest errors are obtained with the structure without load. However, it has obtained a lower value of the error with 117.6 N than 58.8 N. This is due to the non-linear behaviour that influences on the system (prototype).

Other measurements have been carried out also at a distance of 10 m between the camera and the prototype. The obtained results do not present hardly variation with the previously presented.

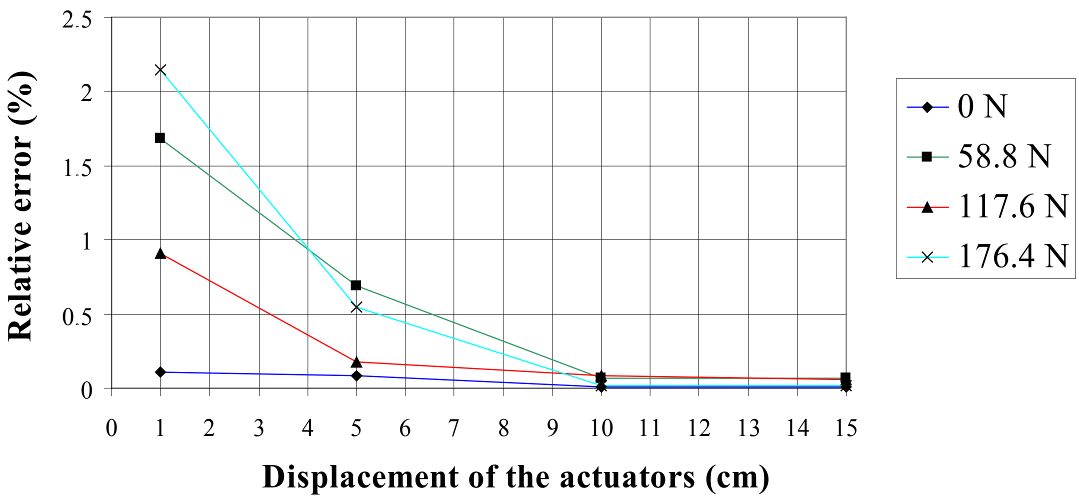


Fig. 7. Relative error (%) on the vertical displacement.

5 New developments

A new design of the cinematic joints has been carried out in order to improve the precision of the position of the structure. This design is more compact. The old spherical bearings have been replaced by others bearings with a better quality and a smaller size, as shown in Fig. 8.

With this improvement, the prototype gets closer to the theoretical model.

A new series of measurements is carried out in this structure. The obtained results are better than the old ones in almost all the cases. The results are not included in this paper because of the necessary validation with more tests.

a) b)

Fig. 8. Spherical bearing: a) old and b) new.

On the other hand, the next step is the extension of the prototype from two to three modules. An additional study of the new design of the cinematic joints has been accomplished because of different mobility of the bars. In the joint the six bars are joined in a different way that in the case of the prototype of two modules. Fig. 9 shows the prototype of the three modules adaptive structure.

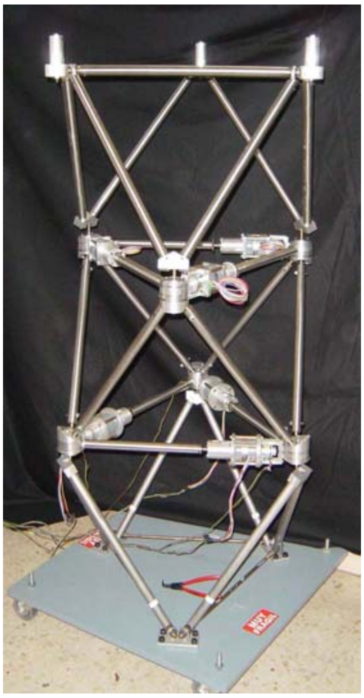


Fig. 9. Prototype of the three modules adaptive structure.

Firstly, a numerical simulation with the code Adams has been required for the development of this new prototype of three modules. The study of the maximum required rotation angle in spherical bearings has been carried out. This study is made according to the multiple combinations of the displacements of the actuators. In the extreme position, with a maximum displacement of the actuator, the maximum permitted angle is obtained. The spherical bearing has to be able to reach this angle.

The numerical simulation has proved another problem. A new degree of freedom in the cinematic joint is presented when the structure is formed of three modules. This degree of freedom is a rotation that distorts the movement of the prototype and affects to the stability of the structure. Therefore the precision of the position is missed. To solve this problem, a modification of the joint is accomplished. This modification consists of removing the redundant degree of freedom. Afterwards, the cinematic joint was modified in the actual structure. Fig. 10 shows the numerical model of the structure of three modules.

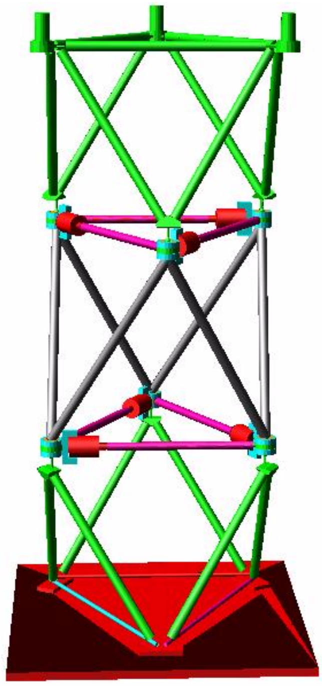


Fig. 10. Numerical model of the three modules prototype.

6 Conclusions

In this work, a study of the clearances of a structure of variable geometry using photography techniques (without contact) has been made. The results show the good precision in the position of the structure, and the load on the structure has a little influence on the position error. The study of the clearances using this procedure has proved to be an effective method because the results agree with those obtained with a conventional system of dial gauges for the same movements.

In next studies, the analysis of the clearances with great displacements will be approach in order to obtain a better precision. The study will be made with more actuators in order to check their influence in the position error of the structure.

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References:

[1] K. Miura, H. Furuya, Adaptative Structure Concept for Future Space Applications, *AIAA Journal*, Vol. 26, No. 8, August 1988, pp. 995-1002.

[2] M. Subramaniam, S.N. Kramer, The Inverse Kinematic Solution of the Tetrahedron Based Variable-Geometry Truss Manipulator, *Journal of Mechanical Design*, Vol. 114, September 1992, pp. 433-437.

[3] R. Avilés, M.B.G. Ajuria, J. Vallejo, C. Angulo, Un procedimiento de resolución de problemas estáticos en estructuras adaptativas, *Anales de Ingeniería Mecánica*, Vol. 1, 1997, pp. 109-116.

[4] J. Agirrebeitia, R. Avilés, I. F. de Bustos, G. Ajuria, A Method for the Study of Position in Highly Redundant Multibody Systems in Environments with Obstacles, *IEEE Transactions on Robotics and Automation*, Vol. 18, No. 2, 2002, pp. 257-262.

[5] R.A. Burdisso, R.T. Haftka, Statistical Analysis of Static Shape Control in Space Structures, *AIAA Journal*, Vol. 28, No. 8, August 1990, pp. 1504-1508.

[6] A.K. Dhingra, B.H. Lee, Optimal Placement of Actuators in Activelly Controlled Structures, *Engineering Optimization*, Vol. 23, August 1994, pp. 99-118.

[7] R.T. Haftka, H.M. Adelman, Selection of Actuator Locations for Static Shape Control of Large Space Structures by Heuristic Integer Programming, *Computers & Structures*, Vol. 20, No. 1-3, 1985, pp. 575-582.

[8] K. Ting, J. Zhu, D. Watkins, The Effects of Joint Clearance on Position and Orientation Deviation of Linkages and Manipulators, *Mechanism and Machine Theory*, Vol. 35, No. 3, March 2000, pp. 391-401.

[9] R.T. Haftka, H.M. Adelman, Effect of Sensor and Actuator Errors on Static Shape Control for Large Space Structures, *AIAA Journal*, Vol. 25, No. 1, 1987, pp. 134-138.

[10] J. L. Stein, C. Wang, Automatic Detection of Clearance in Mechanical Systems: Experimental Validation, *Mechanical Systems and Signal Processing*, Vol. 10, No. 4, July 1996, pp. 395-412

[11] J. Zhu, K. Ting, Uncertainty Analysis of Planar and Spatial Robots with Joint Clearances, *Mechanism and Machine Theory,* Vol. 35, No. 9, September 2000, pp 1239-1256.

[12] R. Gonzalez, R. Cibrian, A. Pino, J. Soler, Y. González, Displacement Measurement in Structural Elements by Optical Techniques, *Opt Laser Eng*, No. 34, 2000, pp. 75-85.