

## THE INFLUENCE OF SMALL CLEARANCES IN THE SPHERICAL JOINTS OF THE SYSTEMS ON THEIR DYNAMIC RESPONSE

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### ABSTRACT

*The paper highlights the influence of small clearances in the spherical joints on their natural frequencies and modes of vibration. Joints with bearings made of materials that involve low friction in the coupling (Teflon and HDPE polyethylene) were considered. Two cases of coupling by means of the spherical joints were considered, namely: the coupling angle of the bars in the spherical joint being of  $0^{\circ}$  and of  $90^{\circ}$ , respectively.*

*The size of the clearance influences the first natural frequency of the system in the sense of decreasing it, but also in the modification of the vibration modes of the system when even a small clearance appears in the joint.*

**KEYWORDS:** clearances in spherical joints, dynamic response, FEM analysis

### 1. INTRODUCTION

Spherical joints are important for their widespread use in mechanical structures.

The modification of the clearance affects the dynamic response of the entire mechanical structure through the nonlinearity introduced by the contact. There are concerns for making models of contact in the spherical joint in which there are large clearance [2], [4]. These models target traditional contact schemes and schemes based on the Winkler model and by modeling clearance using FEM [7].

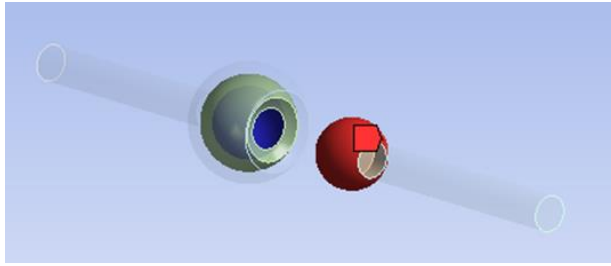
A computational methodology for analysis of spatial flexible multibody systems, considering the effects of the clearances and lubrication in the system spherical joints, is presented in the paper [5].

The results presented in [6] show that the joint clearance makes the mechanism performance worse; the flexibility of pivot has a clear suspension effect to minimize the negative outputs of joint clearance on mechanisms.

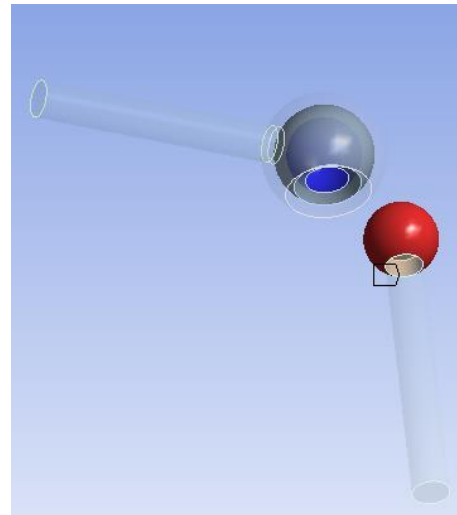
In this paper, the size of the clearance (GAP) is introduced practically by modifying the contact rigidity which also depends on the compression behavior of the joint materials. In the Ansys Workbench program within the contact conditions, there is the possibility of generating a GAP between the surfaces in contact (a negative offset) in Fig. 1.1a (a GAP of  $6e-006$  m) [1]. The contact surfaces (contact surface-red color and target surface-blue color) for the two types of angles of the bars in the spherical couple are given in Fig. 1.b and Fig. 1.c.

| Details of "Frictionless - Solid To Solid" |                          |
|--|--------------------------|
| Time Step Controls                         | None                     |
| Geometric Modification                     |                          |
| Interface Treatment                        | Add Offset, No Ramping   |
| <input type="checkbox"/> Offset            | -6.e-006 m               |
| Contact Geometry Correction                | None                     |
| Target Geometry Correction                 | Smoothing                |
| Target Orientation                         | Sphere Center Point      |
| Target Center Point                        | Global Coordinate System |

**Fig. 1.a.** Introducing the GAP in the spherical joint in Ansys Workbench



**Fig. 1.b.** Contact surfaces for the spherical joint angle of  $0^{\circ}$



**Fig. 1.c.** Contact surfaces for the spherical joint angle of  $90^{\circ}$

**Table 1.** Material properties for Modal analysis

|                   | Mass density [kg/m <sup>3</sup> ] | Young modulus in compression [Pa] | Poisson ratio |
|-------------------|-----------------------------------|-----------------------------------|---------------|
| Structural Steel  | 7850                              | $2.1 \times 10^{11}$              | 0.3           |
| Teflon            | 2160                              | $482 \times 10^6$                 | 0.42          |
| Polyethylene HDPE | 960                               | $110 \times 10^6$                 | 0.42          |

The spherical joint model was created in the Ansys Workbench program. The contact in the joint is made between the spherical head of a steel rod (Structural Steel) and a piece of Teflon / HDPE polyethylene as a bearing, fixed on the spherical wall of the head of the other steel rod. The one that will have the radial dimensions modified to create the radial play will be the piece made of Teflon / HDPE polyethylene; because the friction between steel and Teflon / HDPE polyethylene is small and the contact was considered frictionless.

The length of the bars  $l = 120\text{mm}$ , and the outer diameter of the spherical cap is  $d = 50\text{mm}$ .

The matrix equation for the free vibration of the system is:

$$[M]\{\ddot{\Delta}\} + [K]\{\Delta\} = \{0\} \quad (1)$$

in which  $[M]$  is the mass matrix,  $[K]$  is the stiffness matrix,  $\{\ddot{\Delta}\}$  is the acceleration's vector, and  $\{\Delta\}$  is the displacement's vector.

Eigenvalues and eigenvectors of the equation were obtained from the Ansys Workbench program, using Subspace Iteration [1].

Although the introduction of contact elements involves a nonlinear approach, and the calculation of frequencies and eigenmodes is linear, the exclusion of friction allows the introduction of a GAP in the spherical joint by changing the contact stiffness that remains fixed.

The type of element used in discretization is SOLID187 (number of nodes 7485, number of elements 1981).

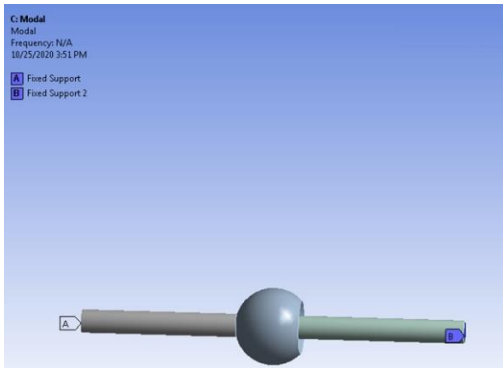
## 2. SIMPLIFIED MODEL OF A SPHERICAL JOINT WITH AXES AT $0^{\circ}$

The boundary conditions for the joint in which the angle of the bars in the coupling is  $0^{\circ}$  is represented in Fig. 2.a, and the components of the joint are represented in Fig. 2.b. The ends of the bars are fixed to highlight the influence of the change of contact rigidity on the dynamic response of the assembly.

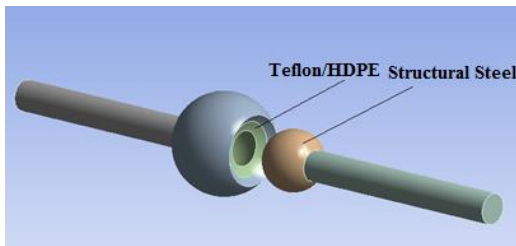
The first five natural modes of vibration of the spherical joint with the system bars at  $0^{\circ}$  are shown in Fig. 3-Fig. 7 (Teflon as a bearing material and GAP = 0).

The first five natural modes of vibration of the spherical joint with the system bars at  $0^{\circ}$  are shown in Fig. 8-Fig. 12 (Teflon as a bearing material and GAP = 1mm).

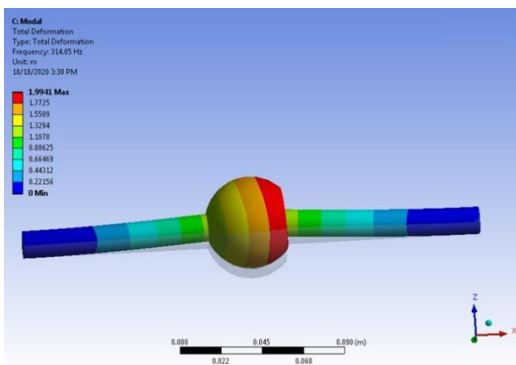
The influence of the size of the radial GAP in the spherical joint on the first 5 natural modes of vibration can be followed in Table 2 and Fig. 13. In Fig. 13 also appears the curve of linear approximation of the influence of the GAP in mm on the first natural frequency of the system in Hz.



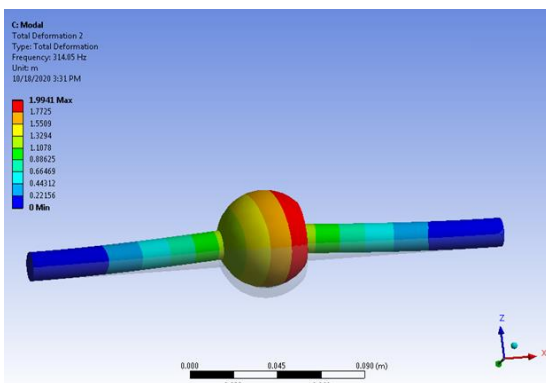
**Fig. 2.a.** The boundary conditions for the coupling angle in the spherical joint is  $0^\circ$



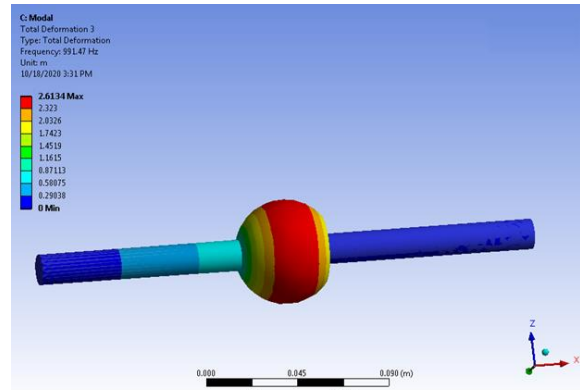
**Fig. 2.b.** Joint components (Teflon piece (sleeve) and spherical steel head)



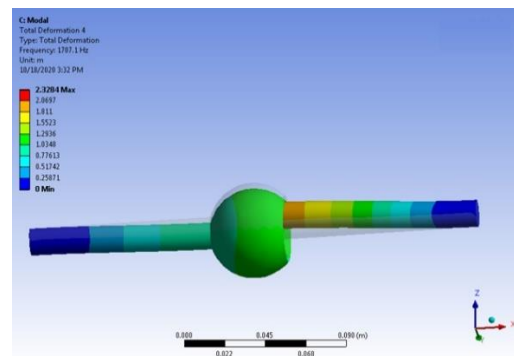
**Fig. 3.** The vibration mode 1 (GAP=0, angle of  $0^\circ$ )



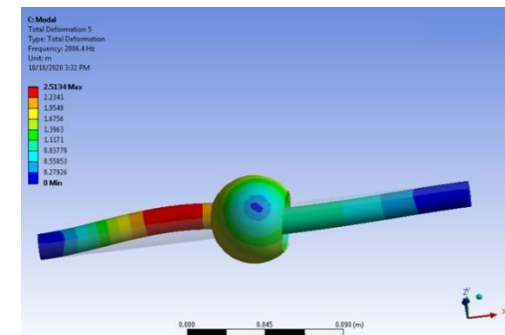
**Fig. 4.** The vibration mode 2 (GAP=0, angle of  $0^\circ$ )



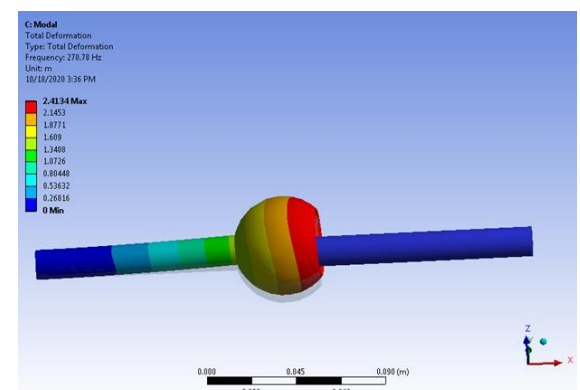
**Fig. 5.** The vibration mode 3 (GAP=0, angle of  $0^\circ$ )



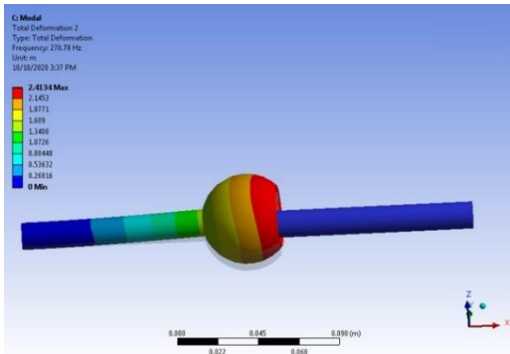
**Fig. 6.** The vibration mode 4 (GAP=0, angle of  $0^\circ$ )



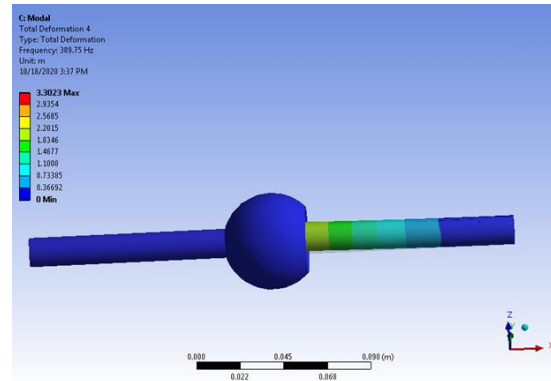
**Fig. 7.** The vibration mode 5 (GAP=0, angle of  $0^\circ$ )



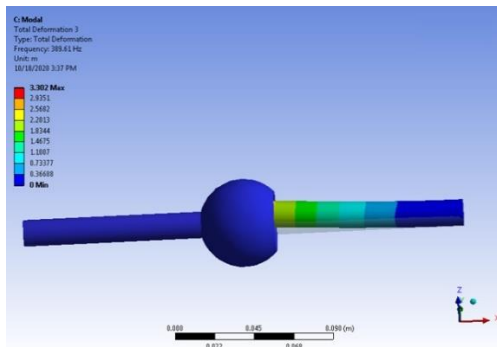
**Fig. 8.** The vibration mode 1 (GAP=1e-3m, angle of  $0^\circ$ )



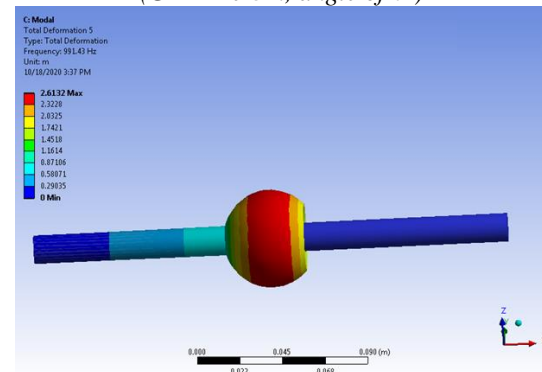
**Fig. 9.**The vibration mode 2 (GAP=1e-3m, angle of 0°)



**Fig. 11.**The vibration mode 4 (GAP=1e-3m, angle of 0°)



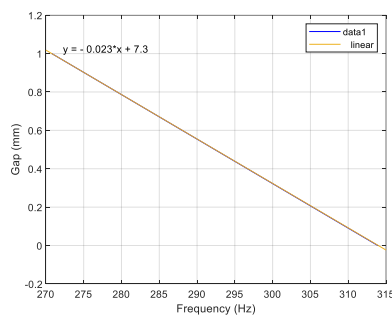
**Fig. 10.**The vibration mode 3 (GAP=1e-3m, angle of 0°)



**Fig. 12.**The vibration mode 5 (GAP=1e-3m, angle of 0°)

**Table 2.**The first five natural frequencies in the spherical joint with bars coupled at an angle of 0° (Teflon as a bearing material)

| Mode number | Natural frequencies in [Hz] |            |           |
|-------------|-----------------------------|------------|-----------|
|             | GAP=0                       | GAP=10e-6m | GAP=1e-3m |
| 1           | 314.05                      | 312.69     | 270.78    |
| 2           | 314.45                      | 314.28     | 270.91    |
| 3           | 991.47                      | 991.43     | 389.61    |
| 4           | 1707.1                      | 1060.4     | 389.75    |
| 5           | 2086.4                      | 1967.1     | 991.43    |



**Fig. 13.**Joint GAP vs the first natural frequency for the coupling angle in the spherical joint of 0° (Teflon as a bearing material)  $y = p1 * x + p2$ ; Coefficients:  $p1 = -0.023148$ ;  $p2 = 7.268$ ; Norm of residuals = 0.0022869

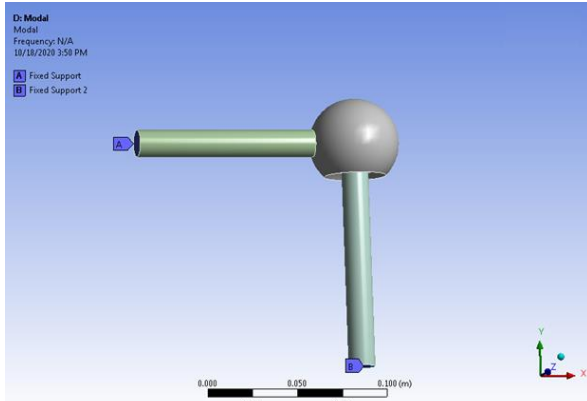
### 3. SIMPLIFIED MODEL OF A SPHERICAL JOINT WITH AXES AT 90°

The boundary conditions for the joint in which the angle of the bars in the coupling is 90° is represented in Fig. 14a, and the components of the joint are represented in Fig. 14b. The ends of the bars are fixed to follow only the influence of the change of contact rigidity on the dynamic response of the spherical joint.

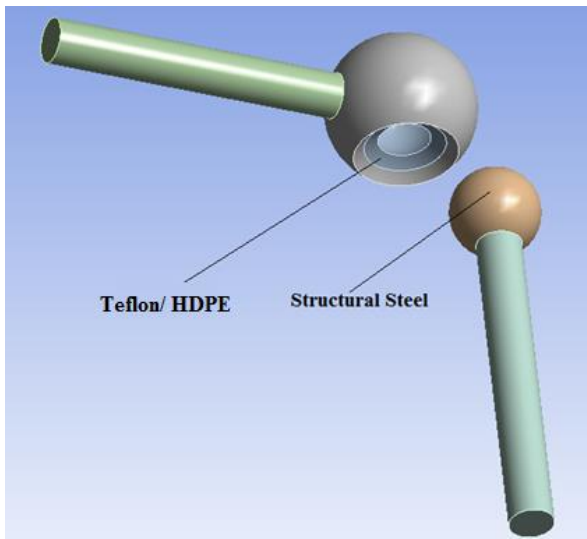
The first five natural modes of vibration of the spherical joint with the system bars at 90° are shown in Figs. 15, Fig. 19 (Teflon as bearing material and GAP = 0).

The first five natural modes of vibration of the spherical joint with the system bars at 90° are shown in Figs. 20, Fig. 24 (Teflon as bearing material and GAP = 7.5e-6m).

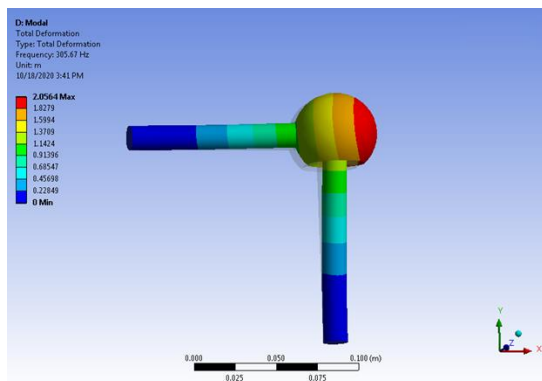
The influence of the size of the radial GAP in the spherical joint on the first 5 natural modes of vibration can be followed in Table 1.3 and Fig. 25. Also, in Fig. 25, the curve of linear approximation of the influence of the GAP in mm on the first natural frequency of the system in Hz appears.



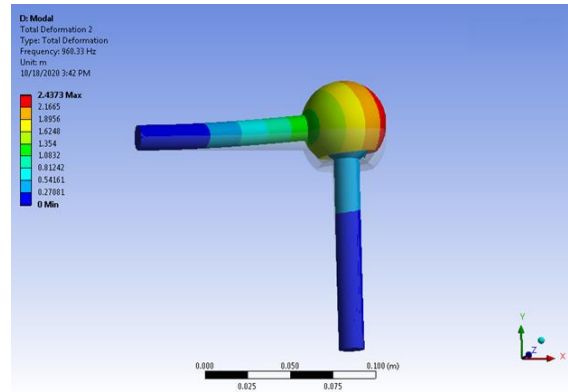
**Fig. 14.a.** Boundary conditions for the coupling angle of  $90^\circ$



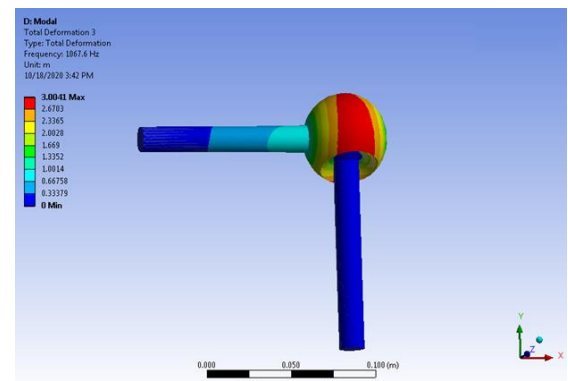
**Fig. 14.b.** Joint components (Teflon piece (sleeve) and spherical steel head)



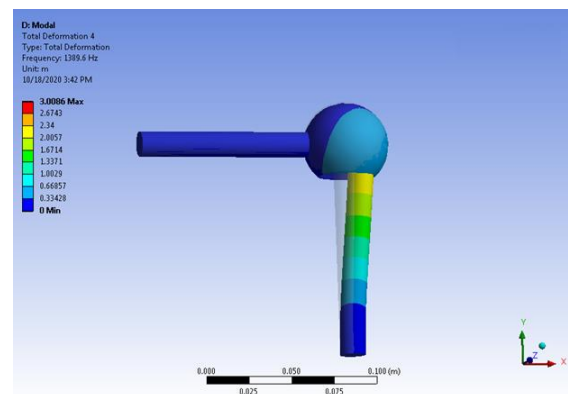
**Fig. 15.** The vibration mode 1 (GAP=0, angle of  $90^\circ$ )



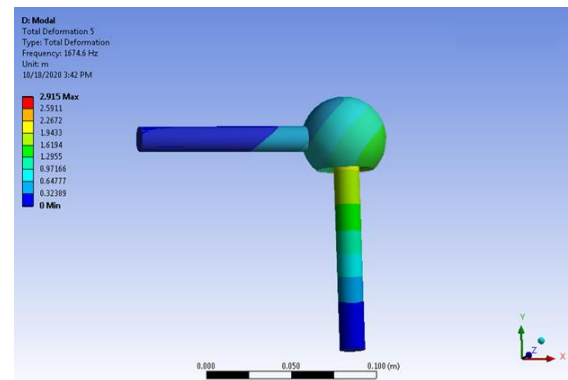
**Fig. 16.** The vibration mode 2 (GAP=0, angle of  $90^\circ$ )



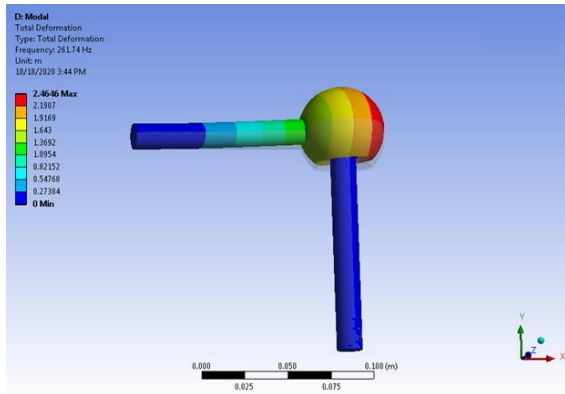
**Fig. 17.** The vibration mode 3 (GAP=0, angle of  $90^\circ$ )



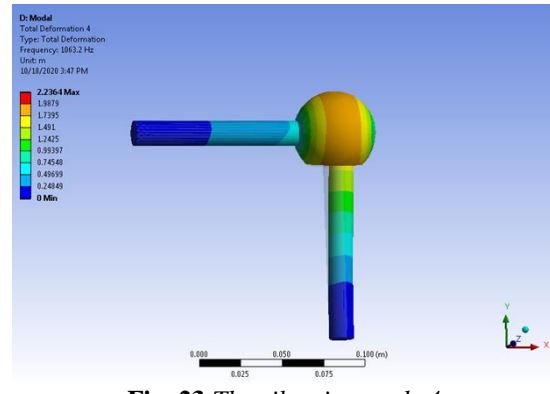
**Fig. 18.** The vibration mode 4 (GAP=0, angle of  $90^\circ$ )



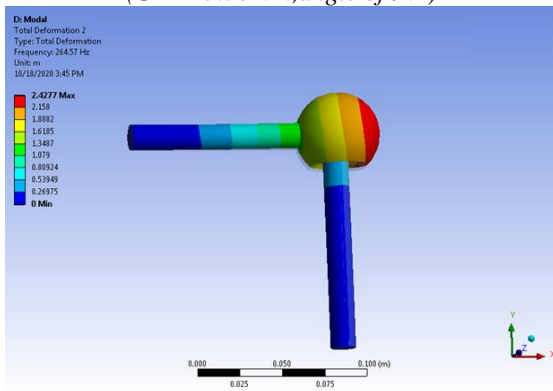
**Fig. 19.** The vibration mode 5 (GAP=0, angle of  $90^\circ$ )



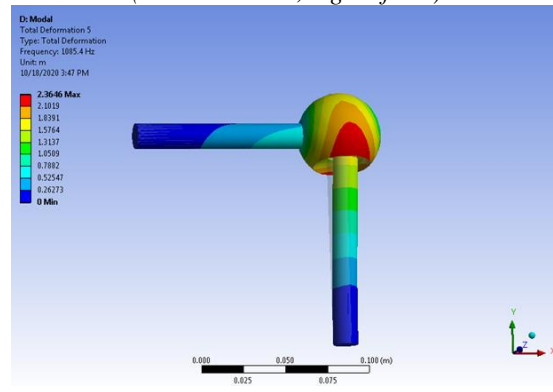
**Fig. 20.**The vibration mode 1 (GAP=7.5e-6m,angle of 90<sup>0</sup>)



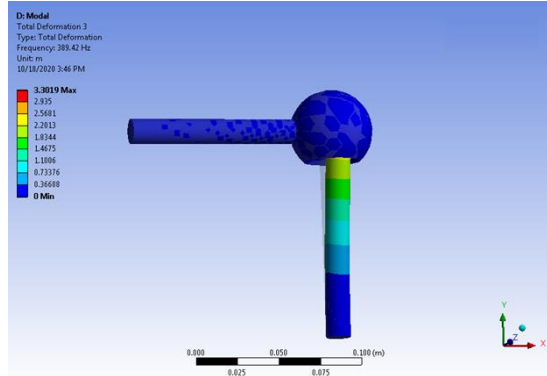
**Fig. 23.**The vibration mode 4 (GAP=7.5e-6m,angle of 90<sup>0</sup>)



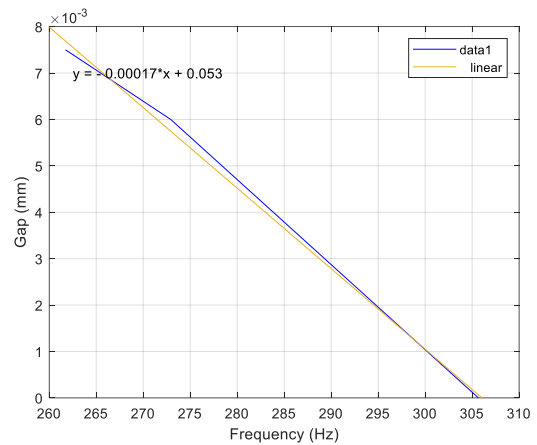
**Fig. 21.**The vibration mode 2 (GAP=7.5e-6m,angle of 90<sup>0</sup>)



**Fig. 24.**The vibration mode 5 (GAP=7.5e-6m,angle of 90<sup>0</sup>)



**Fig. 22.**The vibration mode 4 (GAP=7.5e-6m,angle of 90<sup>0</sup>)



**Fig. 25.**Joint GAP vs the first natural frequency for the coupling angle in the spherical joint of 90<sup>0</sup> (Teflon as bearing material) $y = p1*x + p2$ ;Coefficients: $p1 = -0.00017353$  $p2 = 0.053108$ Norm of residuals = 0.00032223

**Table 3.**The first five natural frequencies in the spherical joint with bars coupled at an angle of 90<sup>0</sup> (Teflon as a bearing material)

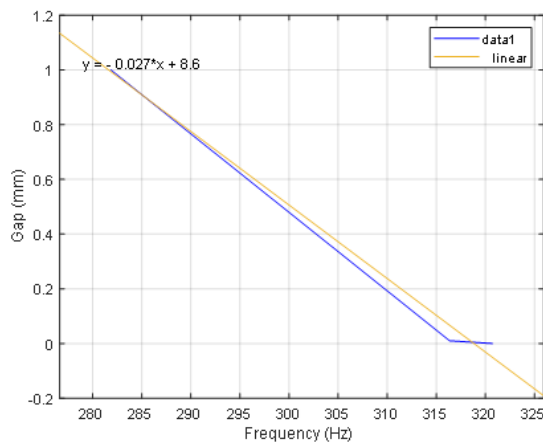
| Mode number | Natural frequencies in [Hz] |            |             |
|-------------|-----------------------------|------------|-------------|
|             | GAP=0                       | GAP=6 e-6m | GAP=7.5e-6m |
| 1           | 305.69                      | 272.93     | 261.74      |
| 2           | 960.33                      | 384.12     | 264.55      |
| 3           | 1067.6                      | 567.49     | 389.42      |
| 4           | 1389.6                      | 1072.9     | 1063.2      |
| 5           | 1664.5                      | 1275.3     | 1085.4      |

**Table 4.**The first five natural frequencies in the spherical joint with bars coupled at an angle of 0° (HDPE as a bearing material)

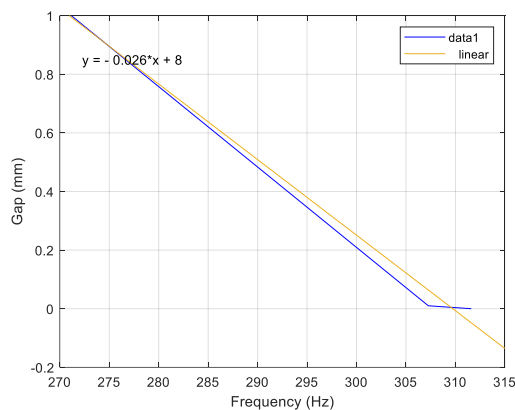
| Mode number | Natural frequencies in [Hz] |             |            |
|-------------|-----------------------------|-------------|------------|
|             | GAP=0                       | GAP=10 e-6m | GAP=1e-3 m |
| 1           | 320.71                      | 316.35      | 281.87     |
| 2           | 321.92                      | 321.46      | 282        |
| 3           | 905.94                      | 610.08      | 389.61     |
| 4           | 1017.9                      | 1017.9      | 389.75     |
| 5           | 1182.1                      | 1046.1      | 1017.9     |

**Table 5.**The first five natural frequencies in the spherical joint with bars coupled at an angle of 90° (HDPE as a bearing material)

| Mode number | Natural frequencies in [Hz] |             |            |
|-------------|-----------------------------|-------------|------------|
|             | GAP=0                       | GAP=10 e-6m | GAP=1e-3 m |
| 1           | 311.6                       | 307.26      | 271.17     |
| 2           | 544.6                       | 456.92      | 272.37     |
| 3           | 764.28                      | 592.58      | 389.41     |
| 4           | 878.52                      | 751.47      | 389.44     |
| 5           | 1110.2                      | 1105.2      | 1103.6     |



**Fig. 26.**Joint GAP vs the first natural frequency for the coupling angle in the spherical joint of 0° (HDPE as bearing material)  $y = p1*x + p2$  Coefficients:  $p1 = -0.02688$  ;  $p2 = 8.5704$ ; Norm of residuals = 0.076202



**Fig. 27.**Joint GAP vs the first natural frequency for the coupling angle in the spherical joint of 90° (HDPE as bearing material)  $y = p1*x + p2$  Coefficients:  $p1 = -0.02578$ ;  $p2 = 7.9849$ ; Norm of residuals = 0.07239

#### 4. CONCLUSIONS

The influence of the size of the radial clearance in the spherical joint with the bars at an angle of 0°, in which the bushing is made of HDPE polyethylene on the first 5 natural frequencies can be followed in Table 14. In Fig. 26 is presented the curve of linear approximation of the influence of the play in mm on the first natural frequency of the system in Hz.

The influence of the size of the radial clearance (the GAP) in the spherical joint with bars at an angle of 90°, in which the bushing is made of HDPE polyethylene on the first 5 natural vibration frequencies can be followed in Table 15. Fig. 27 presents the curve of linear approximation of the influence of the play in mm on the first natural frequency of the system in Hz.

The mechanical characteristics of the spherical joint bearing materials (Table 1) influence to a small extent the size of the fundamental frequency (Tables 2 and 3 for the Teflon and Tables 4 and 5 for the UHPE).

From the analysis of the natural modes of vibration of the systems with and without GAP, it results that the appearance of the GAP in the spherical joint decouples the movements of the bodies within the first natural mode of vibration. Also, the natural modes 2-5 are different for the cases without GAP and with a small GAP. The size of the GAP in the spherical joint "controls" the first natural frequency of the structure (the rigidity of the structure is reduced by changing the contact rigidity) [3].

As the size of the GAP increases, the fundamental frequency decreases. If the GAP has a considerable amount, some rigid modes appear (having natural frequency=0), which in real situations will generate a shock operation in the system.

The GAP in the spherical joint that appears from the wear of the bearing piece has a negative influence on the dynamic operation regime of the assembly.

Even a small GAP in the spherical joint changes its fundamental frequency and its associated mode.

The length of the bars has an influence on the flexibility of the structure and modifies the response of the system with GAP, i.e. it makes it sensitive to large GAP in the spherical joint.

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