Dynamic analysis of an off-road vehicle

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Abstract. *In this work the dynamic behavior of an off-road vehicle known as Mini-Baja is studied. For this analysis, the system cage's, which also takes into account the front and rear suspension, support engine and the mass of the structure welds as well were considered. The software Ansys 12 was used as a finite element solver in order to obtain the natural frequencies and their respective modal shapes. Several boundary condition configurations were considered aiming the evaluation of the structural behavior under different real physical situations. The natural frequencies and the modal shapes are presented for each boundary condition imposed to the system.*

Keywords*: Modal Shape, Natural Frequencies, Modal Analysis, Mini-Baja, FEM*

1. INTRODUCTION

For the last sixteen years a national competition is sponsored by SAE Brazil. Its main goal lies on developing an off-road vehicle by engineering students, known as Mini-Baja. Many Universities in Brazil are involved and represented by its own team, and international universities also take part. The technology involved in the automotive industry is always being improved. Many tests and analyses must be done in order to attain all specifications for a vehicle, especially when the design is changed. A conception of a vehicle is not a simple task, due to the many design variables involved. It is important to point out that the SAE Brazil rules are updated yearly to address new safety concerns. This means that, a new prototype design is always in course. This following paper outlines the dynamic analysis of the prototype built by the Piratas do Cerrado Team from Universidade de Brasília.

The main structure of an SAE Baja consists of the cage, front suspension, rear suspension and the engine support. Information about the natural frequencies of the vehicle are required, because the structure is always being excited by dynamic forces from the engine, irregular road and a possible impacts. It is well known the goal of modal analysis in structural mechanics consists in determining the natural mode shapes and frequencies of structure. Solution of the eigenvalue problem for the equations that describe the dynamic behavior of the structure leads to its mode shapes and natural frequencies. Generally the most important modes are those with corresponding low frequencies. In this work, the modal shapes and the frequencies of the Mini-Baja were obtained using the Finite Element Method (FEM).

The natural frequencies and the modal shapes may be used to optimize the structure strength, while taking into account weight minimization. Another issue, no less important, lies on avoiding the excitation of resonance frequencies. A brief survey of the results published by other teams on the dynamic analysis of their Mini-Baja "cages" was useful as a starting point for the boundary conditions and mesh size used in this work, and as well as to compare our results. A brief summary follows.

Candido et al. (2009) presented the dynamical results analysis done in a vehicle off-road built by the UFF Team. The modal shapes and the respective frequencies were obtained using ANSYS V10.0. The authors have used the element PIPE 16 to model the cage and had had dispensed a special attention to the maximum local strain. The five first models were presented and are listed in the Table 1.

Juras (2005) has focused on modal, harmonic and transient analysis of a previously manufactured cage by Piratas do Cerrado - UnB Team (2005/2006 prototype). An electronic device was used to register the cage's coordinates and as a next step the data to modeling the geometry in a computer were used. The author let the routine's code available in the manuscript. Some analyses were performed considering the existence or absence of bracings. The idea consisted in study the dynamic influence as the bars were being changed.

Freitas et al. (2004) presented the modal shapes of the cage designed by the UNESP-Ilha Solteira Team. All drawings were done in AUTOCAD 3D and after exported to ANSYS V7.0. The first five modes are listed in Table 1. The authors have also reported the number of elements and the degree of freedoms used, but they never indicated the boundary conditions applied to the structure.

Sousa (2006) showed the modal shape for the cage of the SAE Baja Maranhão State University-UEMA Team. The results were obtained using the software COSMOS/M. Two analyses were performed considering different materials, steel 1020 and aluminum 6065. The weight of the engine, pilot and the fuel were taken in to account in the analyses.

Summary Table 1 presents a comparative between results performed by the teams discussed above.

Table 1. Comparative between the final results by each team.

TEAMS	SOFTWARES	MATERIAL	1º shape	2º shape	3ºshape	4ºshape	5ºshape
UFF – 2009	ANSYS V.10.0	Tubular (D = 25.4; w = 2)	1.37Hz	2.1Hz	2.6Hz	3.98Hz	4.26Hz
UEMA – 2006	COSMOS/M	Tubular (D = 25.4; w = 2.1)	45.74Hz	55.05Hz	58.51Hz	104.9Hz	143.58Hz
UNESP – 2004	ANSYS V.7.0	Tubular(D = 30; w = 2.125)	0.9432Hz	0.9479Hz	1.447Hz	2.412Hz	2.521Hz
UnB – 2005	ANSYS	Tubular (D = 31,75; w = 1,6)	0.359Hz	0.490Hz	0.721Hz	0.853Hz	0.906Hz

** Where D = diameter [mm] and w = width [mm]*

2. A BRIEF THEORETICAL FUNDAMENTALS

For linear elastic material the generalized equation of motion is given as:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\} \tag{1}$$

where $[M]$ is the mass matrix, $\{\ddot{X}\}$ is the vector acceleration, $[C]$ is a damping matrix, $\{\dot{X}\}$ is the velocity, $[K]$ is the stiffness matrix, $\{\dot{X}\}$ is the vector displacement and $[F]$ is the force vector. For vibrational modal analysis, if the damping is ignored, and the equation of motion is simplified as:

$$[M]\{\ddot{X}\}+[K]\{X\}=[0] \tag{2}$$

Equation (2) is the general form of the eigensystem. In order to represent the free-vibration solutions, a harmonic motion is assumed. Due to the $\{\ddot{X}\}$ is taken as $\lambda[U]$. The variable λ is an eigenvalue and the equation is rewrite as:

$$[M]\{\ddot{X}\}\lambda+[K]\{X\}=[0] \tag{3}$$

Now this is an eigenvalue/eigenvector problem. Solving this problem, the eigenvalues and eigenvectors are the frequencies and the modal vibration, respectively. Further details should be attained in the literature (Rao, 2008).

3. PROBLEM STATEMENT

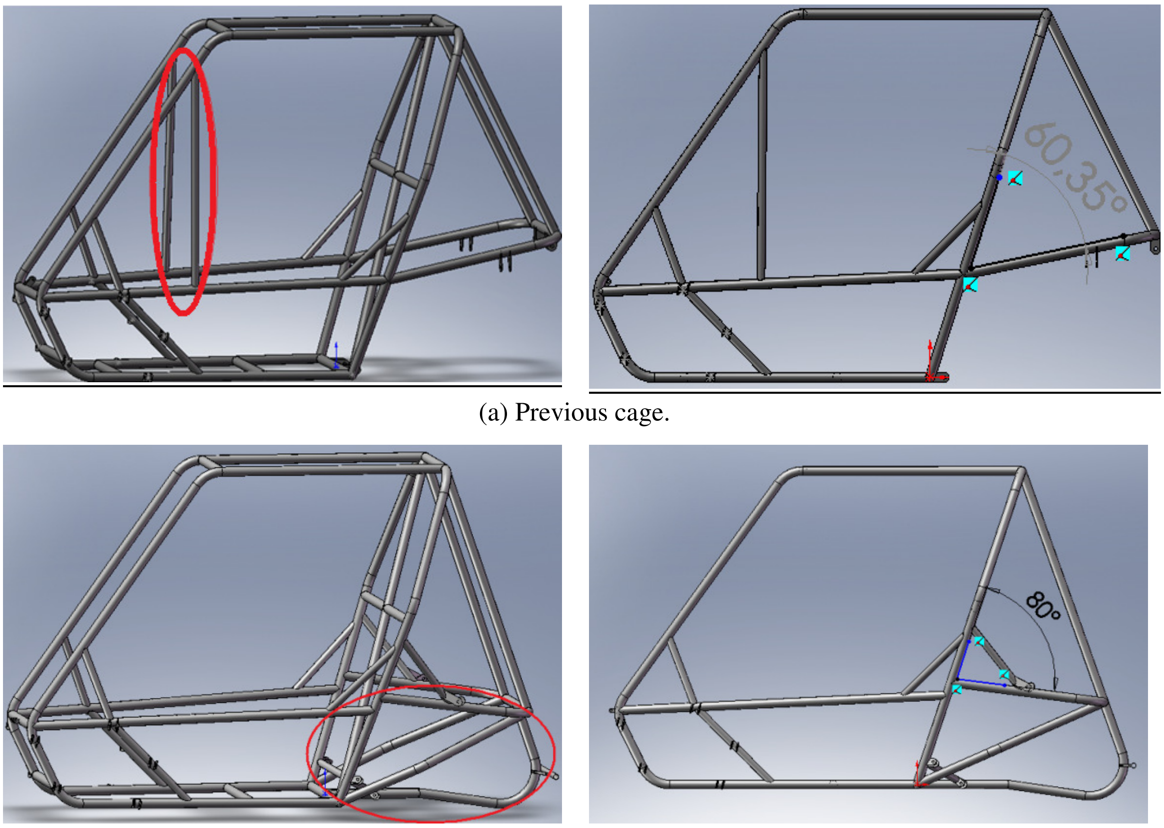
Every year SAE updates the rules and a new Mini-Baja design is required. As the prototype suffers some alterations a new set of decisions must be taken in account. In a car conception many issues should be considered, such as, break systems, structural analyze, fatigue and crack, power train, and dynamic analysis as well. A complete dynamic analysis considering all components involved should be done, but it is not a simple task even for the automotive companies. Minimal structural changes require a dynamic analysis, because the frequencies and modal shapes changes as the mass is added or reduced. The present work intends to consider a more complete analysis, than those which are performed only on the Mini-Baja's cage. As the new SAE 2010 rules came in to effect some changes in the angle of a group of bars was demanded. The difference between the previous and the current cage is depicted in fig.1. These changes have resulted in a great effort by the team to attend the new exigencies. A new geometric modification was performed in the front and back of the cage and consequently an innovator design is also a good new objective, afterwards this is a competition.

Generally most of all analyses consider only the cage in the modal analysis. But it is well known that a simple fact of adding mass changes the frequencies signature. This work is concerned on determining the dynamic behavior due to the components insertion

During the prototype manufacturing, the weld process employed was the MAG (Metal Active Gas). One of the many questions was: How much mass is added during a weld process and how it could have an effect on the dynamic behavior? It was checked after the welding process the structure weight increasing by 11 kg, resulting in a significantly mass insertion. The question bout the mass effect it will be answered after the computational analysis run.

The suspension system was also considered. It is important to notice that both rear and front suspension with its respective shocks absorbers were taken into account in this study. The arm suspension was connected to the cage by a joint. As discussed earlier some changes in the bars angles were required and this action resulted in a new support engine development. This support was manufactured with square profiles and fixed to the structure by screwed union.

It is important to point out the place of the connection between the rear suspension and the cage was changed due to the new geometry. The suspension arms are connected to the cage by the screw joints allowing their movement. The suspension arms are structures which connected the tires and the shock absorbers to the cage.



(a) Previous cage.

(b) Current cage.

Figure 1. Geometrical modifications: (a) previous cage, (b) current cage.

Seven analyses were performed. Initially the modal analysis was performing only on the cage, but it is a current practice. On the next steps the analysis took into account the cage as the components were gradually added one after one in the structure. In this way it was allowed determining an historical of the modal shapes as the components were being added. In order to carry out a design check of the preliminary design developed in this work using Finite Element Analysis a finite element model was developed using the package ANSYS. The geometric model in SolidWorks was converted onto IGES format which was then imported in ANSYS. The analysis chronological order and the elements used to mesh each component added are presented in Tab.2.

Table 2. Chronological order for adding the components.

# Analysis	Code	Components Added to the cage	ANSYS - Element
1	E1	Single Cage	PIPE20
2	E2	Engine support	BEAM4
3	E3	front suspension arm	PIPE20
4	E4	Rear suspension arm	PIPE20
5	E5	Front shock absorbers	COMBIN14
6	E6	Rear shock absorbers	COMBIN14
7	E7	Weld mass added	MASS21
*** The connections between suspension arm and the cage were meshed using COMBIN7*			

It is possible to see the structural evolution as the components were being added during the analyses. This picture illustrates the same order presented in Table 2.

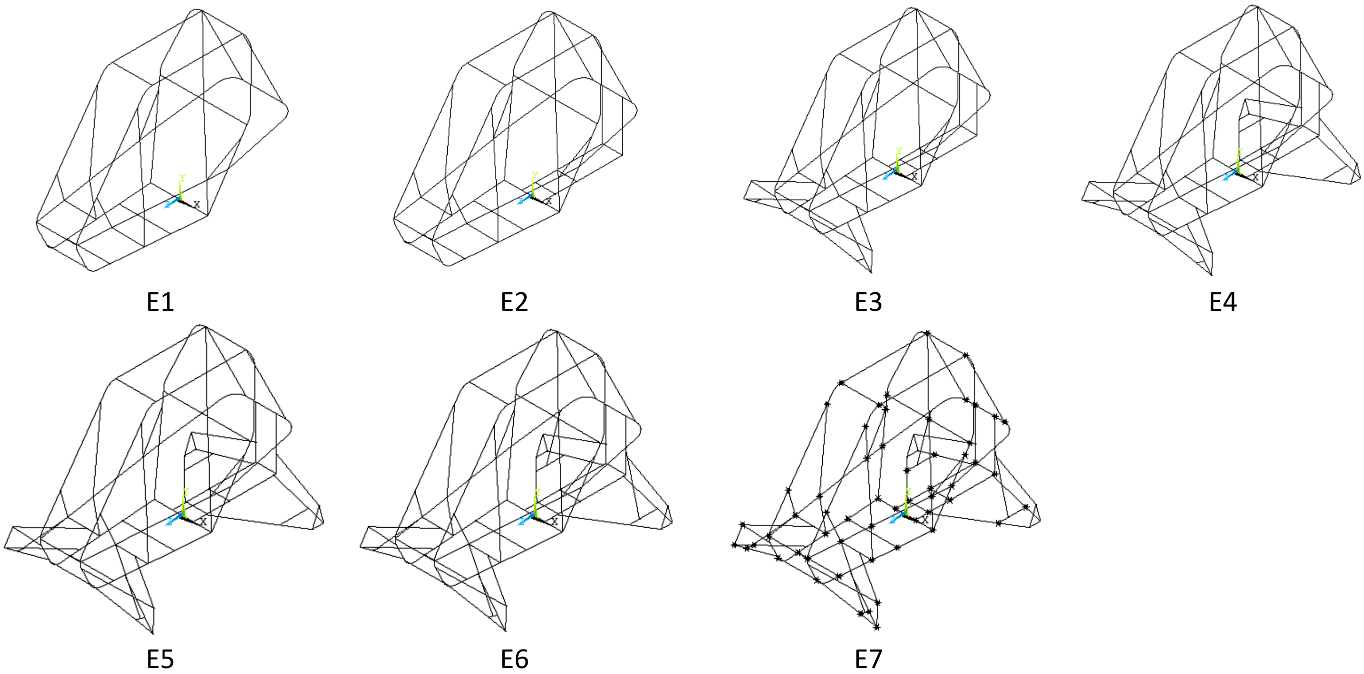


Figure 2. SAE Baja evolution analysis.

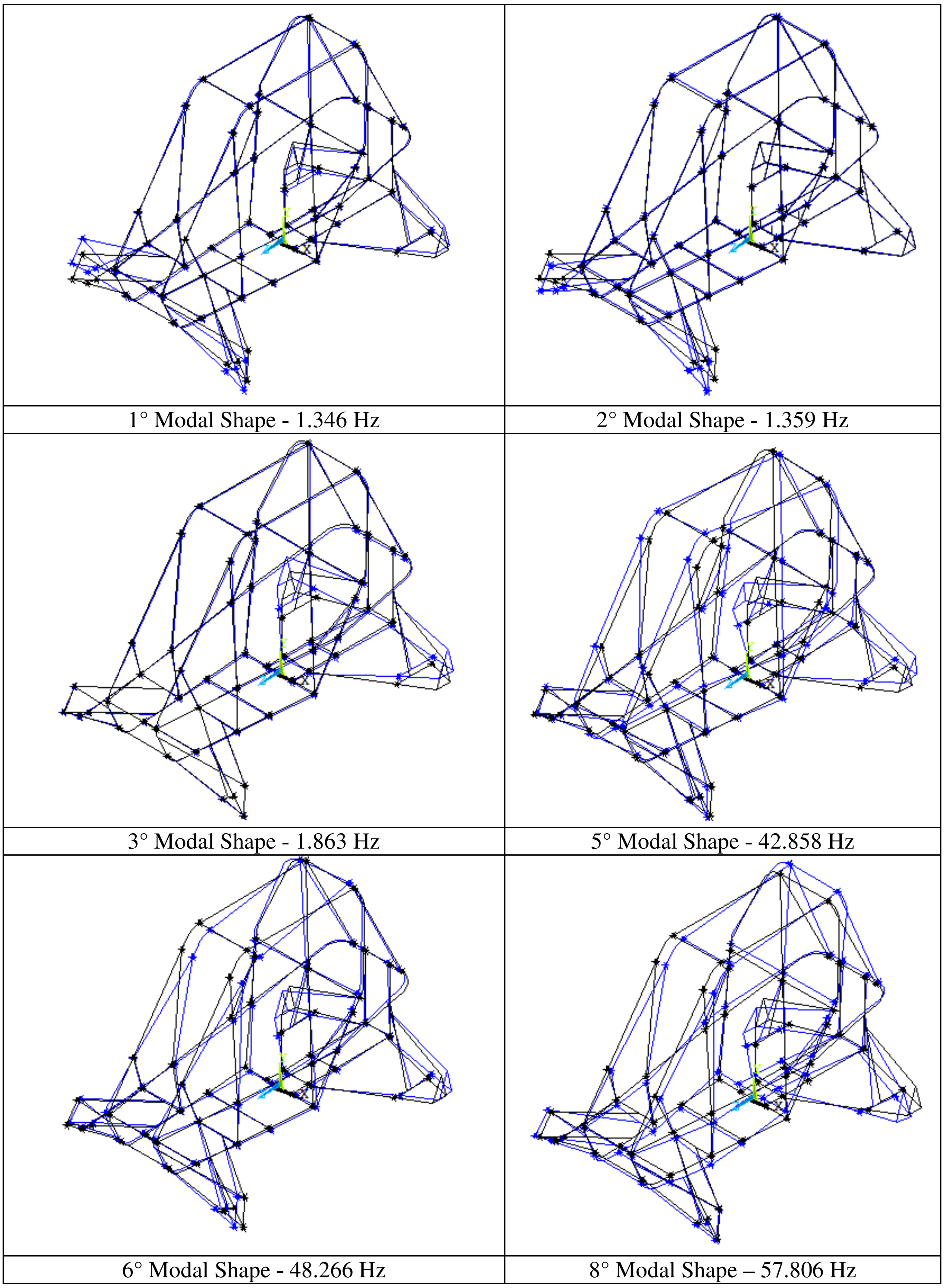
4. NUMERICAL RESULTS

Despite performing seven cases the discussion will be carried out only for the last case E7, which considers all components. However the frequencies for each case from E1 to E7 are showed in Tab.3. A color scheme was used to discriminate the modal shape that affects each component. Cells which were highlighted in blue refer to the structure frequencies as whole body, i.e., considering all components attached. The others cells highlighted in another colors represents the rigid body modes for each specific component, e.g., cells highlighted in yellow refer to frequencies of the front suspension arm mode while those highlighted in red are the rear suspension arm mode. These affirmatives are checked by inspection on fig.3 for the case E7. Note that the first mode has its occurrence at 1.3595 Hz and represents, physically, the movement of the front arm suspension. The third mode occurs at 1.8634Hz and represents the rear arm movement. Analyzing all cases in tab. 3, it is possible to see the influence of the components as they were being added, i.e., from E1 to E7.

Table 3. Frequencies as the components were being added to the Cage.

E1 - Single cage		E2 - Cage + support engine		E3 - Cage + support engine + front sunspension arm		E4 - Cage + support engine + front and rear sunspension arm		E5 - Cage + support engine + front and rear sunspension arm + front shock absorber		E6 - Cage + support engine + front and rear sunspension arm + front and rear shock absorber		E7 - Cage + support engine + front and rear sunspension arm + front and rear shock absorber + welds	
# Shape	Frequency [Hz]	# Shape	Frequency [Hz]	# Shape	Frequency [Hz]	# Shape	Frequency [Hz]	# Shape	Frequency [Hz]	# Shape	Frequency [Hz]	# Shape	Frequency [Hz]
1	59,441	1	56,233	1	1,409	1	0,00048232	1	0,00050866	1	1,554	1	1,346
2	73,508	2	74,934	2	1,445	2	0,0010331	2	0,0010413	2	1,602	2	1,360
3	77,042	3	77,430	3	53,209	3	1,407	3	1,602	3	1,949	3	1,863
4	86,147	4	92,328	4	65,578	4	1,433	4	1,640	4	1,987	4	1,871
5	96,936	5	96,803	5	69,876	5	47,368	5	47,221	5	46,631	5	42,858
6	99,895	6	99,596	6	73,047	6	54,355	6	53,974	6	53,600	6	48,266
7	124,530	7	123,680	7	87,632	7	63,957	7	62,676	7	62,329	7	54,969
8	135,670	8	131,270	8	92,347	8	64,561	8	63,747	8	62,992	8	57,806
9	139,290	9	138,010	9	103,330	9	76,102	9	74,719	9	74,057	9	67,365
10	151,430	10	150,440	10	105,450	10	76,699	10	75,302	10	75,106	10	67,761
11	156,880	11	151,960	11	117,160	11	91,965	11	91,684	11	89,773	11	82,478
12	168,360	12	163,170	12	125,520	12	93,872	12	92,646	12	92,521	12	84,910
13	174,600	13	168,990	13	129,960	13	104,820	13	102,190	13	101,960	13	91,234
14	178,210	14	175,320	14	130,890	14	107,490	14	106,550	14	104,470	14	95,021
15	186,970	15	181,030	15	142,100	15	108,230	15	107,630	15	105,940	15	96,308
16	202,860	16	189,290	16	146,560	16	116,260	16	115,050	16	111,820	16	102,070
17	212,030	17	194,480	17	153,950	17	118,530	17	116,150	17	114,310	17	105,540
18	219,490	18	204,980	18	155,890	18	121,130	18	120,880	18	117,340	18	109,450
19	225,370	19	210,770	19	160,440	19	122,700	19	122,370	19	118,800	19	109,550
20	237,520	20	219,350	20	167,010	20	129,870	20	124,930	20	124,920	20	110,470

From now on the discussion will be focused only on case E7. Figure 3 depicts the modal shapes for case E7, in which all components modeled are connected to the cage structure. It is possible to see the behavior for six modes of vibration. The modal shape selected were the first, second, third, fifth, sixth and eighth. The first mode is responsible for the movement of the front and rear suspension and second one affects predominantly the front suspension. The third mode affects especially the rear suspension. The fifth mode presents torsion in the cage and the movement of the rear suspension. It is important to notice that this mode occurs at 42.858 Hz which is in the region of the predominant rotation regime of the engine during the race. The sixth mode affects the all structure and a special attention must be focused on the torsion presented in front of the cage. The eighth mode is similar to the sixth one but with a pronounced torsion mode at the top of the structure. Special attention must be paid to the modal shapes in the range of 40 and 60 Hz. It is interesting to note that the addition of the mass of the welds which decreased the natural frequencies, as well expected.



1° Modal Shape - 1.346 Hz

2° Modal Shape - 1.359 Hz

3° Modal Shape - 1.863 Hz

5° Modal Shape - 42.858 Hz

6° Modal Shape - 48.266 Hz

8° Modal Shape – 57.806 Hz

Figure 3. Modal Shapes of the structure E7.

5. CONCLUDING REMARKS

The main goal of this work was to study the dynamic behavior of the Piratas do Cerrado Mini-Baja cage structure, by obtaining the natural frequencies and modal shapes of the structure. This was done considering the cage by itself, as well as when certain components were added to the structure. As a final result it was possible to conclude that the main modes to be considered were those which impose a pronounced torsion movement in the structure. Analyzing the modal shapes it was feasible to check that this event occurs between the fifth and eighth modes and the frequency range was 42.811 Hz to 57.806 Hz, respectively. This band is exactly the range of the engine regime and should be taken in account however it is not the unique source of vibration. Only an experimental test should determine the input of vibration due to the ground irregularities. Further work will be aimed to perform experimental measurements in field and a reverse engineering as well. Afterwards, it is recommended additional bracing at the top of the cage to avoid the torsion mode caused by fifth, sixth and eighth mode. A specific reinforcement might avoid possible failure during the race or even extend the cage's life. The authors hope the results presented in this work be useful to other teams.

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