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Experimental and Finite Element Studies on Free Vibration of Automotive Steering Knuckle

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ABSTRACT

The main aim of this research is to determine the best material for manufacturing of steering knuckle in order to reduce the weight using aluminum alloy and Metal Matrix Composite (MMC). To achieve this purpose, the Modal test has been performed to study vibrational behavior of steering knuckle. CAD Model has been prepared by using coordinate measuring machine (CMM). Finally, the Finite Element Analysis (FEA) has been performed to evaluate natural frequencies and mode shapes of knuckle. The results of the Finite Element Model (FEM) have been compared with experimental data to validate the simulation. Three groups of materials (iron, aluminum alloy and metal matrix composite with different fiber volume ratio) have been investigated to determine the best material for manufacturing. DIN 1.7035, unreinforced alumina and MMC-Al 15% Ti-C have been reported as the best materials in each groups. The MMC material has higher vibrational rigidity and by using it, about 63.65 percent weight reduction is possible. FEM results for different models including Coordinate-Measuring Machine (CMM) and smooth model have been compared with test data. The CMM model is closer to reality and it contains all details such as barcode, data and surface defects. It is obvious that meshing of smooth surface is easier than CMM model, but some details will be ignored which could affect the results. However, it has been shown that use of CMM model creates about 5.21% errors related to test data in comparison with 2.58% when the smooth model is used.

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1. INTRODUCTION

Suspension system detaches the body from road roughness and vibrations. It keeps the tires in contact with the road surface. In this way, a suspension system must be strong to endure loads during various maneuvers such as cornering, accelerating, braking, and road roughness [1]. Macpherson suspension system is a most common suspension utilized as a part of every commercial vehicles. The primary parts of Macpherson suspension system include Macpherson strut, tie rod, steering knuckle, wheel hub assembly, lower ball joint and brake caliper. There are various designs and sizes for steering knuckle of vehicle. The schemes contrast to fit a wide range of applications and suspension sorts. However, they can be separated into two principle sorts (with a hub and with a spindle) [2]. The steering knuckle links to the strut mount at the top, lower arm at the bottom and tie rod on the side. These connections for a Macpherson suspension system of a passenger car are shown in Figure 1 [3].

Several materials are utilized to produce steering knuckle including all kinds of cast iron. But, nowadays there is propensity to utilize aluminum alloy by automakers. Because of low weight of this material, it can decrease use of fuel and CO_2 production [4]. Material replacement which results in weight reduction and applying advanced materials are highly preferable [1]. In addition, some researchers have focused on different optimization methods as well as shape optimization to reduce the weight of the automotive components [5-7].

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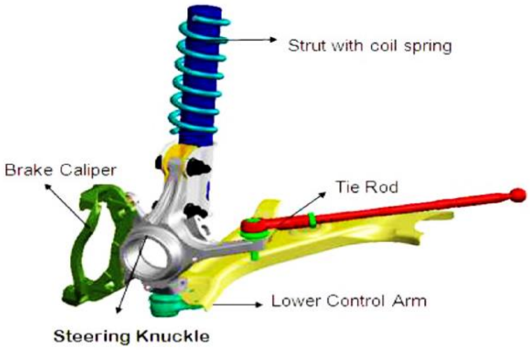


Figure 1. The connections of steering knuckle in Macpherson suspension system [3]

Chavan and Patnaik [8] have analyzed the tie rod to obtain stiffness and stress distributions by using FEM. Theoretical calculation and finite element results are compared with experimental results. Natural frequencies are evaluated for different materials. It was found that the carbon steel tie rod is more suitable material to produce it. Finite element analysis has been used to determine critical area of tie rod which tends to fail [9]. Bhokare et al. [10] have predicted fatigue life of steering knuckle. The tests were performed to determine stress levels and deflection at the design locations. They reduced the weight of knuckle by material removal process to achieve savings in costs and materials. Sharma et al. [4] have done static analysis of steering knuckle and shape optimization. The different loads such as braking torque, longitudinal and vertical reaction and steering reaction were applied to analyze it. In this research, aluminum alloy 2011-T3 was reported as the best material for design of knuckle. Tagade et al. [11] performed static analysis of steering knuckle with two types of materials. The FEM results (total deformation and shear stress in XY plane) were compared with each material. Finally, the shape optimization is utilized to reduce mass of knuckle about 67%. Vivekananda et al. [1] have applied metal matrix composite to reduce weight of knuckle. The critical location was determined by performing structural and fatigue analysis during different maneuvers. Finally, knuckle's performance before and after the optimization are compared through fatigue, impact analysis and vibration test data. Shelar and Khairnar [12] have reduced weight of knuckle about 10% by utilizing optimization numerical methods. Dumbre et al. [2] performed structure analysis of steering knuckle for weight reduction. The targeted weight for this research was about 5% reduction without compromising on the structural strength. Babu et al. [13] have studied the stress analysis of knuckle under the actual load conditions as a time function. Kulkarni and Tambe [14] have optimized aluminum knuckle by utilizing topology and shape optimization methods to reduce weight.

The main aim of this research is to determine the best material for manufacturing of steering knuckle in order to reduce the weight amongst the candidates are aluminum alloy and metal matrix composite. Modal test has been performed to investigate vibrational behavior of steering knuckle. Computer-Aided Design (CAD) model has been prepared by using coordinate measuring machine (CMM). The finite element simulation has been used to get natural frequencies and mode shapes of steering knuckle. FEM results have been compared with experimental data to validate the simulation. FEM results also for different models including CMM and smooth model have been compared with test data. Thus, the effect of modelling accuracy and quality on the results have been studied and it was shown that the smooth model creates more real results than CMM model.

2. MATERIALS

Material replacement and applying advanced materials resulting weight reduction is highly preferable. One suggestion is the use of Metal Matrix Composite (MMC) which has higher strength to weight ratio and better performance than a metal [1]. So, mechanical properties for three categories of materials related to knuckle are reported in Table 1.

3. EXPERIMENAL ANALYSIS OF STEERING KNUCKLE

Modal test which is one of the essential tests to verify the construction and performance of components for dynamic applications is utilized to investigate dynamic characteristics of structures under vibrational excitation. The main goal of this test is to determine dynamic properties of mechanical objects such as natural frequencies, mode shapes and damping coefficient. This test for different components depends on various conditions, for example, installation conditions and geometry. Ordinary excitation signals include impulse, broadband, swept sine. The pulse software analysis has been used to measure the frequency ranges.

The impact hammer B&K8202 (Bruel & Kjaer) with B&K8200 force sensor has been used for excitation. Model hammer, Accelerometer, Portable pulse, Connectors, Specimen and Display unit were used in this test.

Steering knuckle has been put on a damper sheet to avoid the transmission of other vibrations from different sources. And Endevco 2235C accelerometer has been selected for better sensitivity. Frequency Data Logger with Dynamic Signal Analyzer (DSA) has been used to transfer signals to the portable pulse which was then converted to graphical form through the software. Hammer position is shown in Figure 2.

Fast Fourier Transform (FFT), autocorrelation function and cross spectrum can be calculated by the software. So, the first four modes that were top four peak amplitude modes of natural frequency have been taken into account in experimental FFT analysis test of steering knuckle, Table 2.

TABLE 1. Physical and mechanical properties of different group of materials for steering knuckle

Materials	Density [kg/m^3]	Elastic modulus [GPa]	Poisson's ratio	Yield stress [MPa]	Tensile ultimate stress [MPa]
Iron					
Cast iron [11]	7200	110	0.28	240	280
SG Iron [1]	7850	170	0.275	360	540
FCD500-7 [12]	7100	170	0.28	360	540
QT500-7 ferrite ductile iron [15]	7300	160	0.28	360	540
1.7035	7800	210	0.3	290	570
General Grey Cast Iron	7200	130	0.275	-	-
Aluminium					
Aluminium 2011 T3 alloy [11]	2770	71	0.33	280	310
Unreinforced Al Alloy [1]	2700	73	0.33	187	254
Metal matrix composite [1]					
Al-10%-Ti-C	2770	79	0.33	201	281
Al-12%-Ti-C	2800	84	0.33	213	289
Al-15%-Ti-C	2850	87	0.33	265	323

Figure 2. Hammer and accelerometer positions

TABLE 2. Result of modal test

Frequency set	1	2	3	4
Frequency of FFT analyzer (Hz)	1197	1523	1615	2018

4. FINITE ELEMENT SIMULATION

The CAD model of steering knuckle was prepared by 'cloud of points' file obtained by CMM, including the three-dimensional set of points describing the characteristics of the outer surface, as shown in Figure 3.

It is clearly shown in Figure 3 that the geometric model is fully consistent with reality. Even the smallest details such as barcode, data, and screw of mold and surface defects are considered. The CAD model in STEP format was used for the finite element simulation. Solid elements with different grid sizes were used for meshed with equal grid size homogeneously according to the geometry. In order to use the lowest number of mesh and high accuracy, the convergence and sensitivity analysis carried out.

Natural frequencies for different number of elements (Table 3) have been achieved on free-free condition to determine the optimal mesh for knuckle. The six zero frequencies indicate the rigid modes for shift and rotate movement. The graph for the 7th frequency of all cases has been plotted in Figure 4 for comparison purpose. The steering knuckle has been made of DIN 1.7035 material.

Figure 3. CAD model of automotive steering knuckle by utilizing CMM data

TABLE 3. different meshes used to study mesh convergence

Case number	Nodes	Elements
1	48579	27508
2	7798	27905
3	37583	21419
4	35493	20024
5	24866	12198
6	24838	12163
7	84054	51858
8	134831	86190
9	266078	177437

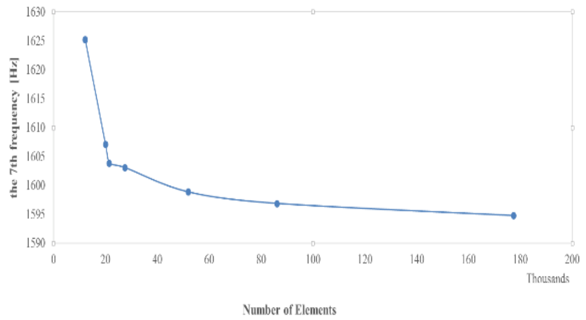


Figure 4. The 7th natural frequency for all studied cases vs. number of elements

Figure 4 show that after the number of elements of 50000, the results do not change significantly. So, the 7th case was chosen as the optimal finite element model of steering knuckle shown in Figure 5 with 51858 elements.

The same geometrical model and material were used for both of finite element simulation and FFT analyzer test of the steering knuckle. The knuckle material was general grey cast iron and the wheel hub has been fixed in all DOF. The modal analysis has been carried out, and the results are reported in Table 4.

The FEM results were in good agreement with the experimental data and the average error is less than 6 percent. In the next step, the effect of three groups of different materials will be studied on the vibration behavior of steering knuckle.

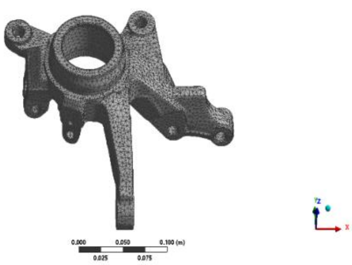


Figure 5. Finite element model of steering knuckle

TABLE 4. Frequency values of finite element simulation and FFT analyzer test

Frequency set	Experimental data	Finite element results	% of errors (Experimental data and present work)
1	1197	1194.8	0.18
2	1523	1455.7	4.41
3	1615	1558.9	3.47
4	2018	1759.7	12.79

5. RESULTS AND DISCUSSIONS

5. 1. Vibration Analysis of Steering Knuckle with Different Iron Materials

Different types of iron are used to manufacture steering knuckle, but grey cast iron is more popular. However, there is no obligation to use these materials because steering knuckles come in all size, geometries and materials. FEM results of vibrational behavior of different types of iron are illustrated in Figure 6. The mode shapes of steering knuckle with material DIN 1.7035 are shown in Figure 7.

In this group, DIN 1.7035 and FCD500-7 demonstrated to be the best material for manufacturing steering knuckle. The difference is low in the first frequency set and it gradually increases.

5. 2. Vibration Analysis of Steering Knuckle made of Different Aluminum Alloy

There is a tendency to use aluminum alloy to produce some parts of car. So, the VA was performed for steering knuckle by assuming aluminum materials and the results are reported in Table 5.

The unreinforced alumina shows better performance for manufacturing of steering knuckle. The mode shapes of steering knuckle by assuming current material are shown in Figure 8.

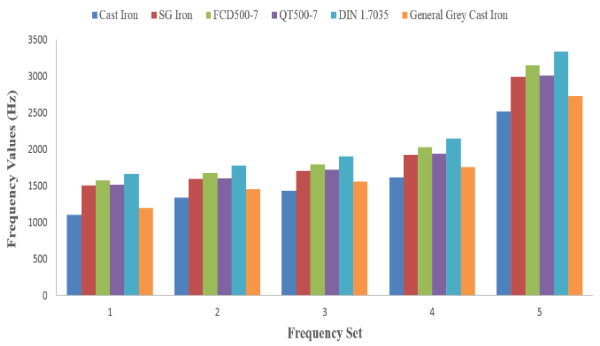
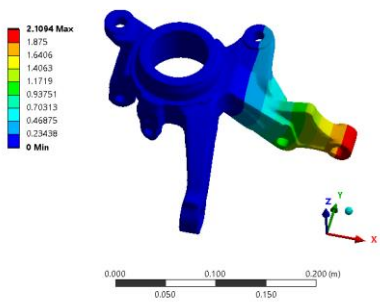
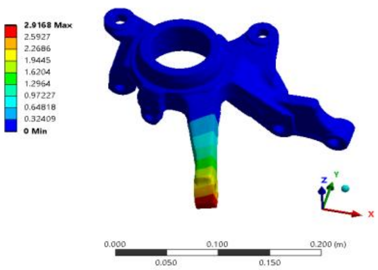


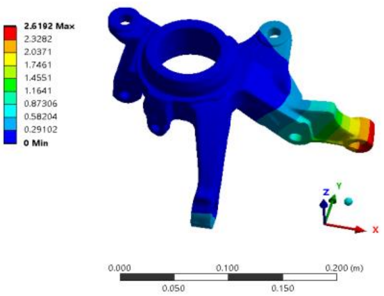
Figure 6. Frequency values of steering knuckle with different iron materials



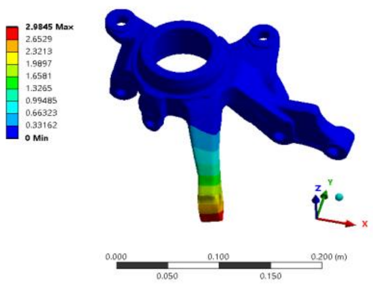
(a) The first frequency set (1461.6 Hz)



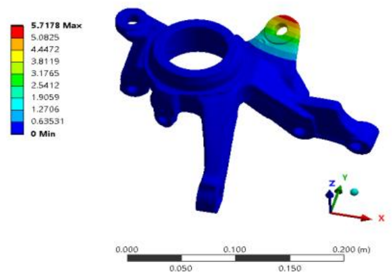
(b) The 2th frequency set (1779.9 Hz)



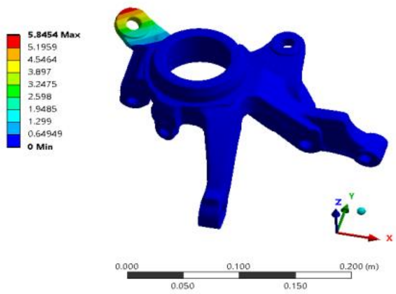
(c) The 3th frequency set (1902.0 Hz)



(d) The 4th frequency set (2149.6 Hz)



(d) The 5th frequency set (3337.5 Hz)



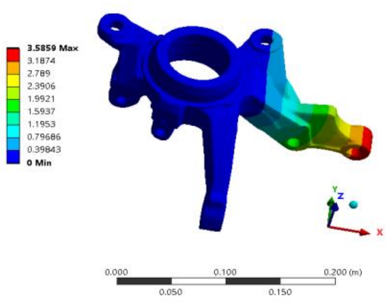
(e) The 6th frequency set (3361.3 Hz)

Figure 7. Mode shapes of steering knuckle with material 1.7035

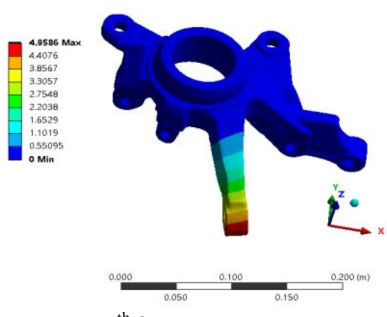
5. 3. Vibration Analysis of Steering Knuckle of Metal Matrix Composite Metal matrix composite has higher strength to weight ratio and better performance than a metal. Al–Ti-C with better properties than Aluminum and SG Iron is suitable for this application. Although its yield strength is less than SG Iron.

TABLE 5. Frequency values of the steering knuckle with different aluminum alloys

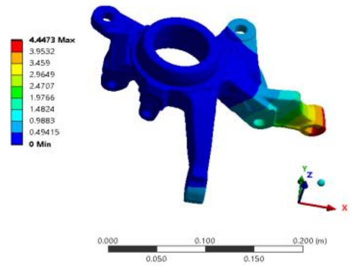
Materials	Frequency set	1	2	3	4	5
Al	Aluminium 2011 T3 alloy	1429.7	1739.8	1854.3	2098.7	3262.4
	Unreinforced alumina	1468.3	1786.8	1904.4	2155.5	3350.7



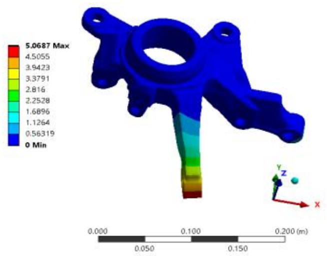
(a) The first frequency set (1468.3 Hz)



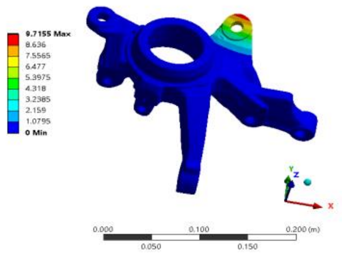
(b) The 2th frequency set (1786.8 Hz)



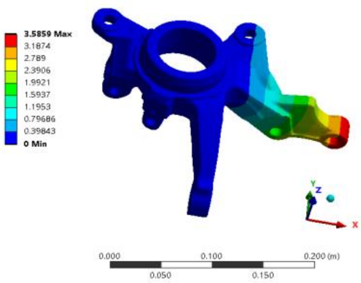
(c) The 3rd frequency set (1904.4 Hz)



(d) The 4th frequency set (2155.5 Hz)



(e) The 5th frequency set (3350.7 Hz)



(f) The 6th frequency set (3380.4 Hz)

Figure 8. Mode shapes of steering knuckle with material unreinforced alumina

The modal analysis was done for different ratio of fiber volume to composite volume such as 10, 12 and 15%. The results were compared with each other and other published data.

It is clear that MMC with aluminum fiber volume 15% has better performance. However, the difference is little. Figure 10 shows the mode shapes of steering knuckle made of Al 15% Ti-C.

5. 4. Effect of Modelling Accuracy and Quality
The geometric model plays an important role on the vibration analysis affecting the frequency values. To create 3D Geometry model drawings are commonly used which contains smooth surfaces. But, if the drawings are not available, the reverse engineering methods should be applied to create model. This model contains all details such as barcode, data and surface defects. It is obvious that the smooth model can be meshed easier than CMM model. The real results can be obtained when a regular mesh is used. However, some details will be neglected which could affect the results. In other words, CMM model is closer to reality, but there are different problems to mesh the unexpected surface roughness. The vibration analysis of steering knuckle was performed on two types of models (CMM and smooth). The finite element results were compared with experimental data (see Table 7) to determine which model exhibits minimum errors.

TABLE 6. Validation of simulation by using metal composite material (MMC-Al 15% Ti-C)

Frequency set	Finite element results [1]	Present work	% of errors (present work and finite element results [1])
1	1827.6	1560.2	14.63
2	1872	1898.6	1.42
3	1918	2023.6	5.50
4	1958	2290.3	16.97
5	3857.8	3560.3	7.71

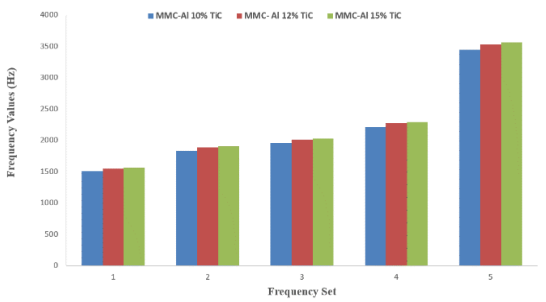
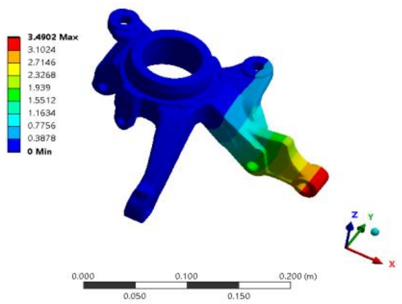


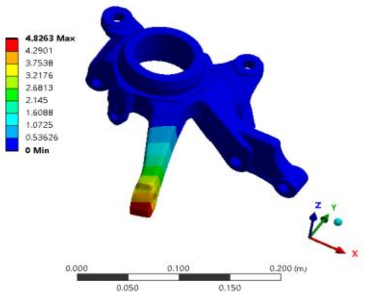
Figure 9. Frequency values of steering knuckle with different volume ratio of MMC

TABLE 7. Comparison of frequency values of two different finite element model and FFT analyzer test

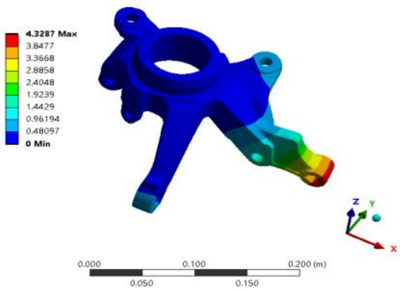
Frequency set	Test data	CMM model	Smooth model	% Error between experimental data and CMM model	% Error between experimental data and smooth model
1	1197	1194.8	1195.4	0.18	0.13
2	1523	1455.7	1519.4	4.41	0.24
3	1615	1558.9	1713.6	3.47	6.1
4	2018	1759.7	1940.1	12.79	3.86



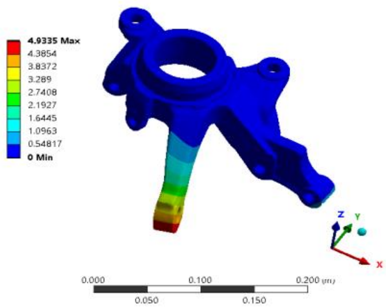
(a) The first frequency set (1560.2 Hz)



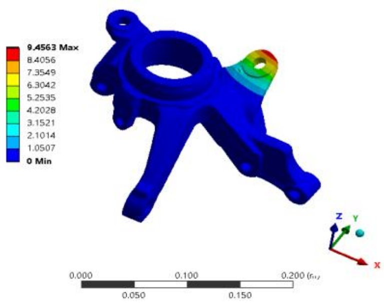
(b) The 2th frequency set (1898.6 Hz)



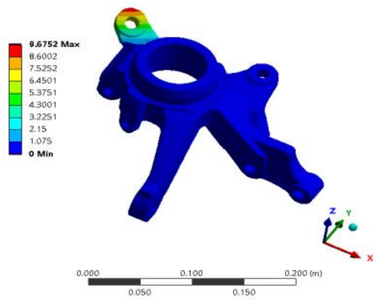
(c) The 3th frequency set (2023.6 Hz)



(d) The 4th frequency set (2290.3 Hz)



(e) The 5th frequency set (3560.3 Hz)



(f) The 6th frequency set (3591.9 Hz)

Figure 10. Mode shapes of steering knuckle with material Al 15% Ti-C

6. CONCLUSION

For the case of steering knuckle, modal test was performed to extract natural frequencies. Then, the finite element technique was used to calculate modal analysis. Natural frequencies and mode shapes were extracted by fixing wheel hub. The results were in a good agreement with experimental data.

Material replacement is one of the common ways to reduce the weight of parts in the automotive industry. It causes to reduce fuel consumption and CO_2 emission. Three groups of materials (iron, aluminum alloy and metal matrix composite with different fiber volume ratio) were investigated to determine the best material for manufacturing. DIN 1.7035, unreinforced alumina and MMC-Al 15% Ti-C demonstrated best performance in each groups. If the aluminum material is used instead of Iron, then the mass reduction will be about 65%. However, it is better to use composite materials because of higher vibrational rigidity. In this case, the weight reduction will be about 63.65 percent.

Finally, the effect of modeling accuracy and quality was studied on the finite element results. The vibration analysis was done for both model of CMM and smooth surfaces. The results were compared with experimental data. The use of CMM model creates about 5.21% errors related to test data. However, it can be reduced to 2.58% when the smooth model is used.

However, both models can be used with very good approximation, if only the first frequency of the system is studied. The smooth model is more appropriate for other frequency sets albeit, the same mode shapes have been obtained for both smooth and CMM models.

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Experimental and Finite Element Studies on Free Vibration of Automotive Steering Knuckle

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چکیده

هدف اصلی این پژوهش، تعیین بهترین ماده برای تولید سگدست خودرو به منظور کاهش وزن آن با به کارگیری آلیاژ آلومینیوم و کامپوزیت زمینه فلزی است. به منظور دست‌یابی به این هدف، آزمایش مودال برای بررسی رفتار ارتعاشی سگدست انجام شده است. مدل هندسی با استفاده از دستگاه اندازه‌گیری سه بعدی CMM آماده شده است. سپس، تحلیل المان محدود به منظور استخراج فرکانس‌های طبیعی سگدست و شکل مودهای متناظر با آن‌ها انجام شده است. به منظور اعتبارسنجی شبیه-سازی، نتایج المان محدود با داده‌های تجربی مقایسه شدند. سه گروه از مواد (آهن، آلیاژ آلومینیوم و کامپوزیت زمینه فلزی با درصد حجمی الیاف متفاوت) به منظور تعیین بهترین ماده برای ساخت سگدست بررسی شدند. فولاد DIN 1.7035، آلومینیوم تقویت نشده و کامپوزیت زمینه آلومینیومی با درصد حجمی ۱۵٪ الیاف کاربید تیتانیوم به عنوان بهترین مواد در هر گروه گزارش شدند. کامپوزیت زمینه فلزی دارای صلبیت ارتعاشی بیشتری است و با به کارگیری آن، امکان ۶۳٫۶۵٪ کاهش وزن وجود دارد. نتایج المان محدود به دست آمده برای مدل‌های مختلف CMM و smooth با داده‌های تجربی مقایسه شدند. مدل CMM به واقعیت نزدیک‌تر بوده و شامل تمام جزئیات، اعم از شماره بارکد حک شده و عیوب سطحی در قطعه است. مشخص است که مش‌بندی سطوح هموار به مراتب راحت‌تر از مدل CMM است. اما، برخی جزئیات در آن نادیده گرفته می-شود که ممکن است در نتایج اثرگذار باشند. با این وجود، نشان داده شد که استفاده از مدل CMM منجر به خطای ۵٫۲۱٪ و استفاده از مدل smooth منجر به خطای ۲٫۵۸٪ در نتایج المان محدود در مقایسه با داده‌های تجربی می‌گردند.

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