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Numerical modal analysis of a domestic washing machine drum that is made of carbon fiber and steel

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Abstract: Washing machines are widely used among modern household appliances and play an important role in daily life. Carbon fiber composites stand out as an eye-catching material due to their high strength-to-weight ratio, excellent chemical resistance, and low thermal expansion properties. While traditional washing machine drums are usually made of steel or plastic, the use of carbon fiber composites increases the lightness of the drum and ensures its durability. In this article, the effect of using carbon fiber composite materials in washing machine drums on vibration and displacement is investigated. According to the results in the article, the average vibration decreased by 98.28% and the average displacement increased by 175.98% thanks to the use of carbon fiber composites.

Keywords: epoxy carbon fiber woven prepreg, drum, modal analysis, steel, washing machine.

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1. Introduction

Washing machine manufacturers focus their efforts on studies aimed at improving the functionality of these devices. An important aspect of research is related to noise and vibration reduction. The equipment for experimental benches is expensive, and the verification of new technical solutions is time-consuming. Therefore, numerical studies must be carried out before experimental analysis. Numerical models must be developed to find an effective way to minimize vibration. Thanks to the data obtained as a result of the analysis, noise reduction, performance improvement can be made, energy inefficiencies can be identified, and alternative solutions can be developed. As a result, vibration analysis of the washing machine drum can help both extend the life of the machine and reduce operating costs. When the studies on the washing machine drum are examined; Kolhar and Patel [1] studied the reduction of drum vibration in washing machine. For this purpose, they modelled the washing machine in SolidWorks. They proposed an improved drum design to reduce drum vibration. Based on the values obtained from the mathematical model, they performed the finite element analysis of the old and new model in SolidWorks Cosmos software and observed that the drum displacement in the new model was significantly reduced. Krishnaiah, K. [2] designed a washing machine drum in SolidWorks software and analysed it in ANSYS 14.5 software. He stated that the purpose of the analysis was to help conduct similar analyses for the production of high-capacity drums in the future and to reduce the experiments. Shihab, I. M. et al. [3] conducted a theoretical and experimental study of the drum-type vibration of a washing machine.

They also studied the effect of the stiffness of the isolators, the damping coefficient, and the drum mass on the laundry capacity. For this purpose, they experimentally investigated the effects of different velocities and unbalanced forces on vibration during the spinning cycle of the washing machine using Matlab. In this study, the vibration analysis of a steel and carbon fiber composite drum designed in different sizes, inspired by the drum designs in the literature [4,5], was numerically performed. As a result, the results of the drum made of steel and carbon fiber were compared.

2. Materials and method

Within the scope of the numerical study, the test elements were designed, the dimensions of which are shown in Figure 1. Steel and epoxy carbon-woven prepreg were used as drum materials. The mechanical properties of the materials used are given in Table 1.

Table 1. Mechanical properties of materials [6]

Material	E_x(MPa)	E_y(MPa)	E_z(MPa)	v_{xy}	v_{yz}	v_{xz}	G_{xy}(MPa)	G_{yz}(MPa)	G_{zx}(MPa)	Density (kg/m³)
Epoxy Carbon Woven Prepreg	91820	91820	9000	0.05	0.3	0.3	3600	3000	3000	$1.48\text{x}10^{-6}$
Structural Steel	200000	-	-	0.3	-	-	-	-	-	$7.85\ \text{x}10^{-6}$

In Table 1, E_x, E_y, and E_z represent the elasticity modules in the x, y and z directions; v_{xy} represents the Poisson ratio for the $x-y$ plane; v_{yz} represents the Poisson ratio for the $y-z$ plane; v_{xz} represents the Poisson ratio for the $x-z$ plane; G_{xy} represents the shear module in the $x-y$ plane; G_{yz} represents the shear module in the $y-z$ plane; G_{xz} represents the shear module in the $x-z$. The finite element model of the designed test elements, the boundary conditions applied to the model, and the number of elements and nodes of this model are given in Table 2.

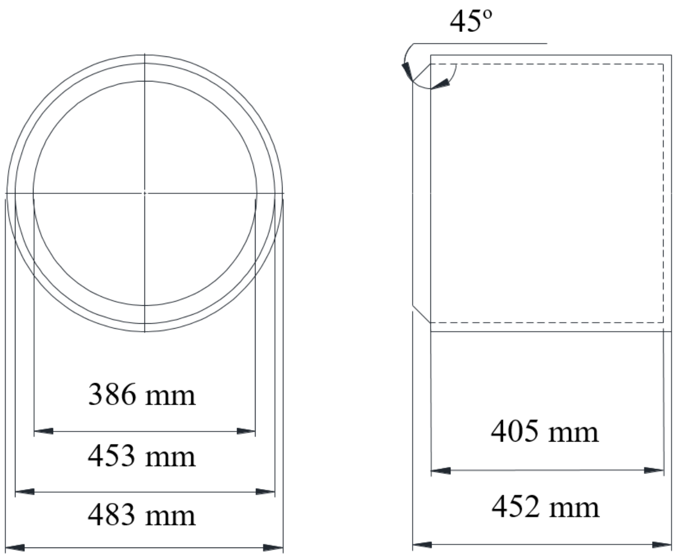
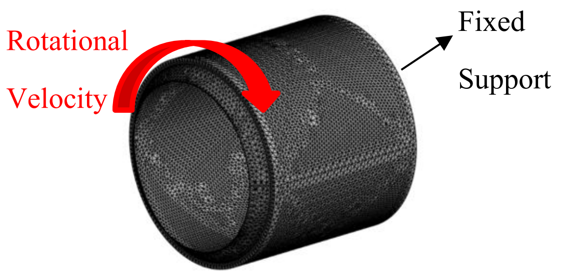


Fig 1. Dimensions of designed test elements.

Table 2. Finite element model of the designed test elements, boundary conditions applied to the model, number of elements, and number of nodes belongs to this model

Finite Element Model with Boundary Conditions	
Number of Elements	90532
Number of Nodes	163688

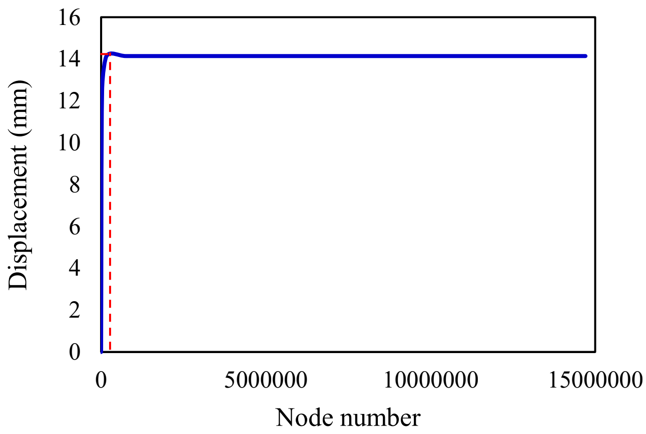


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Fig. 2. Mesh convergence analysis

As a boundary condition, the drum is fixed from the rear area, and the rotation velocity values of 0, 314, 628, 1256, and 2512 rad/s are given to the drum in the program. A mesh convergence study was performed to obtain the optimum values (Figure 2). In the mesh convergence graph, when it was observed that the displacement value remained constant with the increase in the number of nodes, it was decided that it would be appropriate to use the mesh size value. ANSYS analysis settings were made to determine the natural frequencies and displacements at given velocities for 10 mode shapes and to display the Campbell Diagram of the results.

3. Results and discussion

In the analysis, the frequencies at different rotation velocities for 10 different mode shapes were found as given in Table 3.

Table 3. Frequencies at different rotation velocities according to modes

Mode	Rotation velocity, rad/s										
	0		314		628		1256		2512		
	Steel	Carbon Fiber	Steel	Carbon Fiber	Steel	Carbon Fiber	Steel	Carbon Fiber	Steel	Carbon Fiber	Frequency, Hz
1	625.73	256.51	622.9	255.62	620.07	253.45	614.44	247.67	603.33	235.1	
2	625.77	269.65	628.61	270.58	629.85	272.89	623.82	279.21	611.94	293.91	
3	635.45	332.74	632.86	332.38	631.48	331.35	637.27	327.45	648.99	314.38	
4	636.47	385.54	639.07	385.76	642.13	386.39	648.32	388.69	660.91	395.61	
5	984.38	445.06	973.47	444.45	962.21	442.68	940.08	436.39	897.41	417.91	
6	985.38	521.71	996.42	522.43	1008.1	524.54	1031.8	521.29	980.57	457.16	
7	1134.9	576.03	1130.4	569.31	1125.8	554.88	1116.8	532.2	1080.9	556.02	
8	1134.9	630.3	1139.5	637.74	1144.	645.64	1144.4	624.02	1099.1	586.46	
9	1338.	663.3	1288.4	656.51	1238.3	654.36	1153.3	696.64	1171.9	792	
10	1343.4	679.42	1395.1	686.77	1451.5	699.35	1570.7	727.74	1833.1	795	

When the data in Table 3 is examined, it is seen that the highest frequency in the drums occurs in the 10th mode. This situation is due to the fact that the smallest frequency obtained as a result of the ordering of natural frequencies from smallest to largest is called the fundamental frequency, and the mode shape corresponding to this frequency is called the first mode shape [7, 8]. For each rotational velocity, it was seen that the average vibration number per unit time occurring in carbon fibers was lower than that of steel. This rate is 98.28% according to the average vibration number. The vibration changes from mode to mode with the increase in rotational velocity. Kim, M. et al. experimentally investigated the vibration analysis of a 3D printed carbon fiber composite material used as a chuck adapter. For this purpose, they compared the vibration results of carbon fiber and steel chuck adapters. The products were rotated at 10, 500, and 1000 rpm, and the rotation velocity and displacement values were obtained. As a result, they stated that the vibration in the material made of carbon fiber was 5.6–18.2% lower than that of steel [9].

It was observed that increasing the velocity caused a decrease in the average displacement values for both types of materials [9]. The average displacement amount in carbon fiber is 175.98% more than in steel. Campbell Diagrams shown in Figure 3 were created in order to determine the critical velocities below 2500 rad/s. According to the graph of the carbon fiber drum (Figure 3b), the design has four critical velocities. These critical velocities are shown in Table 5. There is no critical velocity in the steel drum.

Table 4. Displacements at different rotation velocities according to modes

Mode	Rotation velocity, rad/s										
	0		314		628		1256		2512		
	Steel	Carbon Fiber	Steel	Carbon Fiber	Steel	Carbon Fiber	Steel	Carbon Fiber	Steel	Carbon Fiber	Displacement, mm
1	14.143	34.96	10.043	33.977	10.026	32.296	10.02	30.098	10.019	28.748	
2	14.2	46.894	10.09	45.333	20.626	42.642	20.194	38.983	20.026	36.47	
3	28.047	84.794	21.389	84.763	10.107	84.686	10.051	84.561	10.044	85.321	
4	28.134	89.451	21.454	89.057	20.693	87.935	20.294	84.164	20.1	74.967	
5	51.62	16.165	37.299	16.093	36.914	15.895	36.731	15.3	36.722	14.479	
6	51.803	19.21	37.414	19.152	37.027	19.003	36.848	134.19	72.324	126.59	
7	6.2531	163.4	4.4235	155.41	4.4224	145.06	4.4201	18.578	36.737	19.179	
8	6.257	230.66	4.4266	217.44	4.4263	120.29	72.673	109.59	4.4273	96.321	
9	102.07	151.98	74.059	132.33	73.15	200.91	4.513	184.26	4.4239	106.92	
10	100.72	131.61	72.947	115.99	72.06	108.27	71.618	104.84	71.407	175.61	

Table 5. Critical velocities for carbon fiber drum

Mode	Critical Velocity, rad/s
1	1538.4 rad/s
2	1793.9 rad/s
3	2008.3 rad/s
4	2484.8 rad/s

If the carbon fiber drum is designed as specified, it will have four critical velocities. If the drum rotation velocity of the washing machine is 600 rpm, the angular velocity is calculated with the formula $\omega=2\pi n/60$, and $\omega=62.8$ rad/s is found. Similarly, for the rotation velocity of 1200 rpm, $\omega=125.66$ rad/s is obtained. According to these calculations, it is understood that the vibration modes of the drum are far from creating resonance in terms of the operating velocities of the washing machine in daily life, and the drum design is made appropriately in this respect. The displacement shapes occurring in the carbon fiber drum in the critical mode shapes are as seen in Table 6. In addition, the displacement shapes in the steel drum corresponding to these modes are also given.

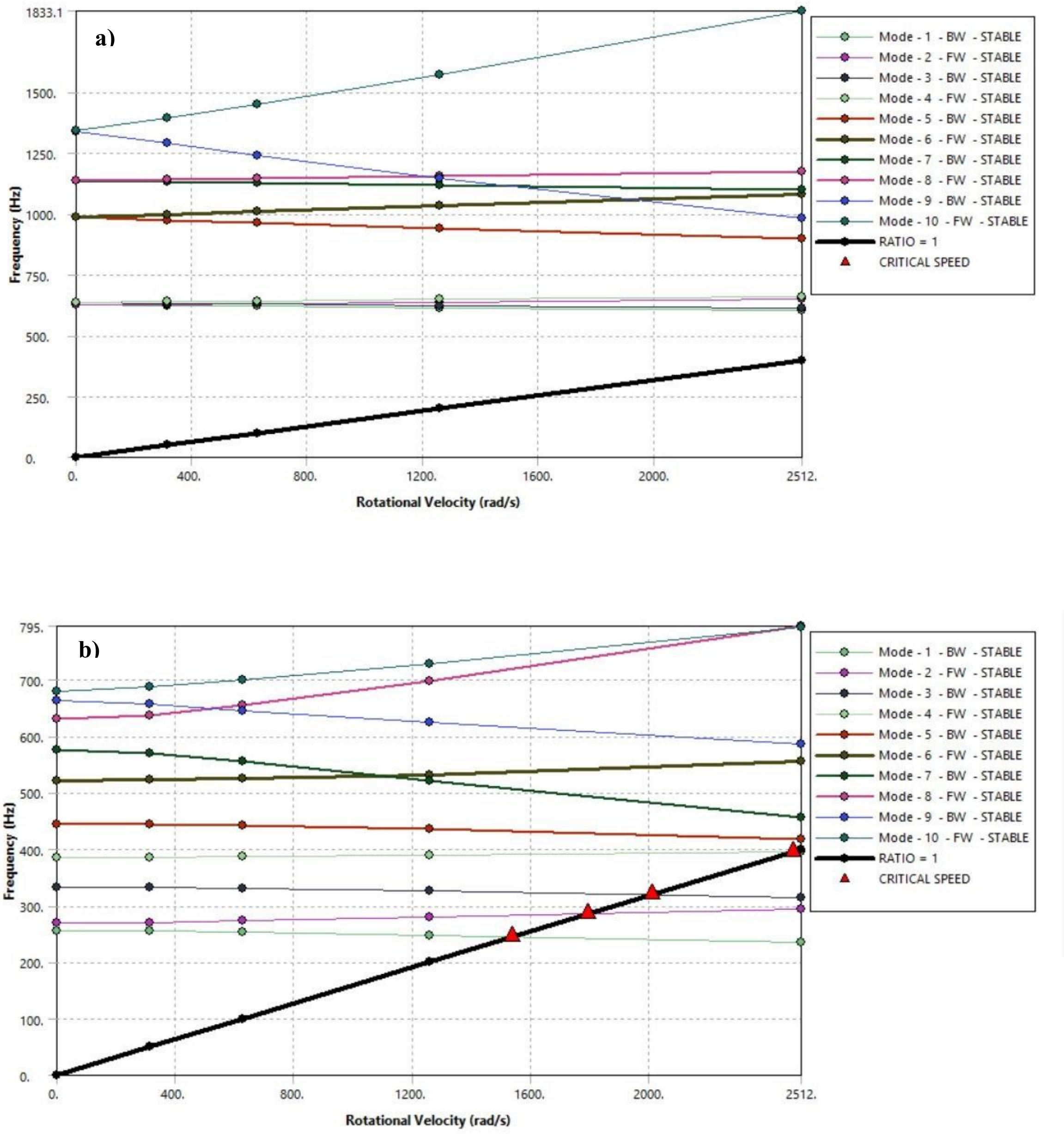
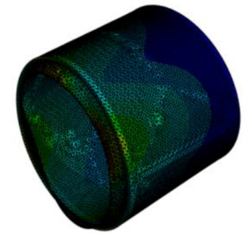
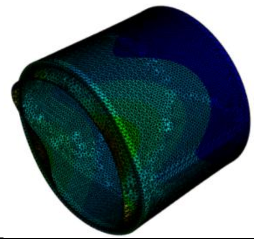
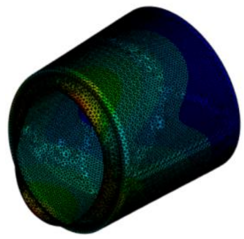
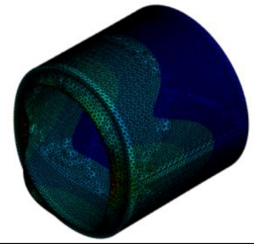
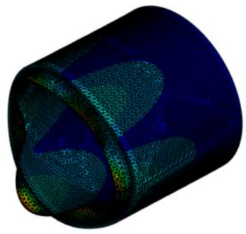
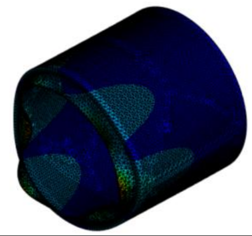
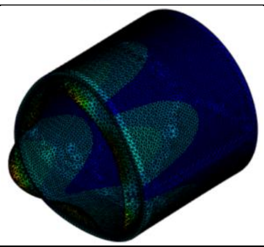
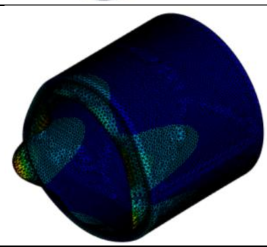


Fig. 3. Campbell Diagram for Drums

Table 6. Deformation representation of critical mode shapes

Mode	Steel	Carbon Fiber
1		
2		
3		
4		

The largest deformations occurred in the front section of the drum, while the least occurred in the rear section. It was observed that the deformation patterns of the steel and carbon fiber drums were similar (Table 6).

4. Conclusions

The results obtained from the modal analysis performed for the drum designed within the scope of this study are as follows:

- There are 4 critical mode shapes that may occur in the carbon fiber drum. These are 1538.4 rad/s, 1793.9 rad/s, 2008.3 rad/s and 2484.8 rad/s.
- There is no critical mode shape that is likely to occur in the steel drum.
- Modal analysis of the drums in this study shows that the system will operate without entering into vibration resonance.
- The use of carbon fiber composite in the washing machine drum has been found to be advantageous in terms of reducing vibration.

This study was conducted on a drum with only one geometry. The modal properties of the drum can be better understood by conducting a study with the geometric variables of the drum. In addition, analysis can be performed by using different materials and considering the effect of the temperature on the drum during operation.

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