DESIGN AND ANALYSIS OF A SCALED-DOWN MODEL WITHOUT CHANGING THE STRUCTURAL DYNAMICS

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ABSTRACT

The design, prototype manufacturing, testing and certification processes of aircrafts and their components require long periods, and their high costs are one of the major tackles in the aerospace industry. Scaled-down models of actual parts are advantageous due to cost-effectiveness, as well as suitability for smaller testing beds. Nevertheless, there are some problems in reflecting the behavior of full-scale structures. To overcome this problem, different solutions are suggested in literature. One of the main solutions is to use of varying density materials or exploiting different inner structures that provide increased or decreased stiffness. In this study, first, the modal and flutter analysis of a full-scale, 1/10, and 1/5 length-scale models of a rectangular plate made of polycarbonate with dimensions of 423x30x6 mm were analyzed in commercial package Nastran, and a code written in Matlab. The results of both modal analysis Matlab were found to be comparable (3% difference only). It was noted that frequencies in the first 4 modes of the modal analysis were increased by the factor of inverse of the length-scale (e.g., 5x for 1/5 model). In the second phase of study, scaled-down, and 3-D printed parts with lumped masses were subjected modal analysis to achieve same response as in the case of full model.

INTRODUCTION

Time consuming and expensive process for designing of aircrafts and its components as well as verification activities are among the major challenges in aircraft industry. Design changes and updates are mostly based on structural dynamics-based analysis including scaled-model test results, and numerical analysis (e.g. finite element analysis). Furthermore, all the numerical analysis should be verified with the experimental data from ground vibration testing

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(GVT) and flight testing. For a design process to be regarded as viable, a modal analysis, the most basic of dynamics-based analyses, must reveal the natural frequency and mode shapes of the aircraft calculated under the specified conditions. There are quite a few studies in literature on the dynamic loading and natural frequencies for aircraft structures. Ersoy examined natural frequencies under different loading conditions, and then updating the finite element model [Ersoy, 2014]. The finite element model should be established as similar to the real structure as possible. Thus, it would be possible quickly to design aeronautics structures with optimum properties. Among the various researches available in the literature, Gibbs et al. studied the change of the flutter properties as a function of mass ratio, aspect ratio, and boundary conditions and they compared their results with previous research using alternative aerodynamic models [Gibbs, 2012]. Dimitrijević and Kovačević established the finite element model of the LASTA aircraft, and they obtained natural frequency and mode shapes of the aircraft through computational modal analysis. The results of the computational modal analysis were further imported into flutter analysis to calculate the aerodynamic forces and critical speeds of the aircraft [Dimitrijević and Kovačević, 2010]. Dalmış conducted flutter analysis of plate-like structures in an incompressible flow with the commercial flutter analysis program ZAERO ©. This analysis was carried out to obtain modal results that can be used in flutter analysis. It was noted that even if a perfect flutter analysis can be obtained, flutter experiments have to be performed [Dalmış, 2014]. GVT, which is one of the tools among the design verification activities, takes a few weeks, requires organization of a sufficient number of experts and a test team, fabrication of prototype models of original size (1/1 scale) for design verification, and GVT in wind tunnels. As far as authors' knowledge, dynamic behavior of scaled-down models and their wind tunnel tests either have been performed or not a common practice. This study, therefore, aimed to establish a basis for determining dynamic behaviors full-scale structures through scaled models protecting the dynamic properties of full-scale model. To this goal, different filling configurations will be adopted in 3-D printing of the scaled models in addition to lumped-masses added to the parts. A rectangular plate was used in this study and the modal analysis of the full scale and scaled models were firstly performed to determine structural dynamics properties in MSC. Nastran and MATLAB. As a second step, flutter analysis of the full-scale plate was carried out. After verification of the suggested approach, 3-D printed scaled down model parts were subjected to same procedure. Even though it needs further investigation, it was concluded that the dynamic behavior of full-scale model can be obtained via scaled-down models produced with additive manufacturing method along with lumped-masses added onto the parts.

METHOD

Every object in nature has a natural frequency. For example, when constructing a bridge, the natural frequencies of the structure are taken into account. Because the natural frequency of the structure has a destructive effect when combined with other frequencies. Similarly, knowing the natural frequencies of the aircraft wing is crucially important. In this study, a plate was used to represent an airplane wing. Then, a finite element model of the plate was established to find mode shapes and frequencies. It must be noted that the structural model of the plate is not enough for the flutter analysis. For this reason, two different models have been prepared: the structural model and the aero model. Unlike the structural model, aeroedynamic model is constructed as doublet panel which are used in Doublet Lattice Method. The aero model and the structural model were independent of each other when they were first created, and then the "MSC.PATRAN FlightLoads and Dynamics" module defined in the infinite plate spline was connected. Splines carry the displacement in the structural model to the aero model and the loads in the aero model to the structural model. In this way, the effect of aerodynamic forces was included in the analysis. The mode shapes and natural frequencies were determined with SOL103 in the MSC Nastran/Patran software for full-scale plate,1/10, and 1/5 scaled models. Full-scale plate flutter analyses were carried out using SOL145 PK-method in MSC Nastran / Patran. In the second stage of the study, the plate was reduced to 1/3 scale. Several numerical analyses with different filling ratio values for the 1/3 scaled model were performed to obtain the the natural frequency of the full-scale plate. As a final step, numerical analysis were verified with the experimental modal analysis on the 1/3 scaled and 3D printed part.

NUMERICAL ANALYSIS

Modal analysis of the full-scale model

A rectangular plate that represents the wing of an aircraft, and 423x30x6 mm in dimensions, was assumed to be made of polycarbonate, and modeled firstly for modal analysis to obtain its natural frequencies and mode shapes in Nastran. The FEA model of the plate is given in Fig.1 and the first 4 mode shapes of the plate are given in Fig.2. The natural frequencies and mode shapes obtained are given in Table 1. Modal analysis results obtained through Nastran and Matlab code are listed and compared in Table 2.

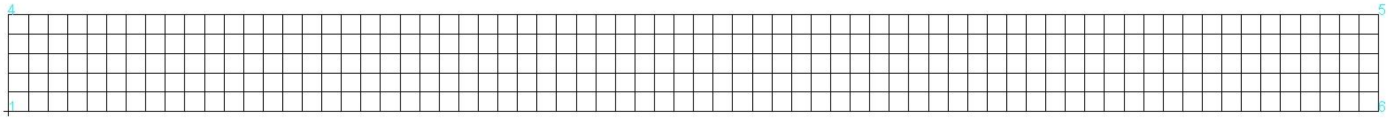


Figure 1. The FEA model of the plate

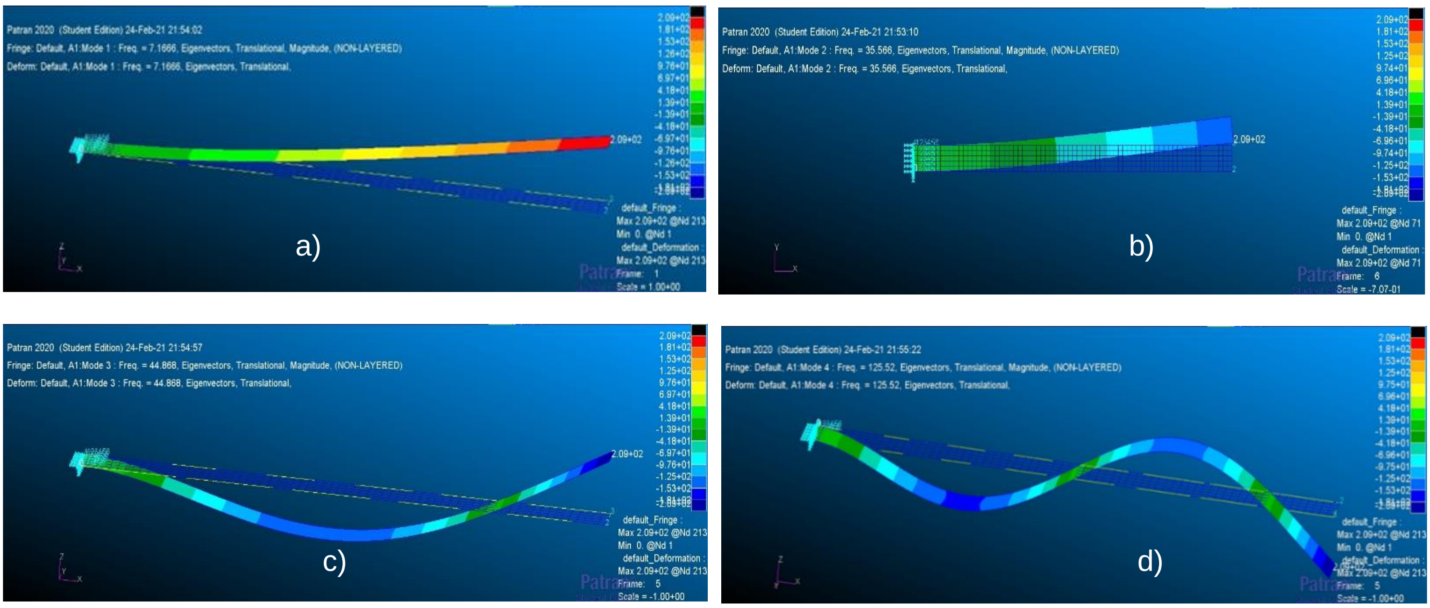


Figure 2. The first 4 mode shapes of the plate investigated a) Mode 1, b) Mode 2, c) Mode 3, d) Mode 4

Table 1.The natural frequencies and mode shapes of the full-scale model

Mode shape	Frequency (Hz)
1.Bending mode (Mode 1)	7,20
1.Lateral bending mode (Mode 2)	35,73
2.Bending mode (Mode 3)	45,08
3.Bending mode (Mode 4)	126,11
1.Torsional mode (Mode 5)	175,79
2.Lateral bending mode (Mode 6)	218,79
4.Bending mode (Mode 7)	246,89
5.Bending mode (Mode 8)	407,64
2.Torsional mode (Mode 9)	528,47
3.Lateral bending mode (Mode 10)	591,86

Table 2. Comparison of modal analysis results

Mode	MATLAB	MSC. Nastran	Difference (%)
1	7,20	7,20	0,03
2	N/A	35,73	N/A
3	45,12	45,08	0,07
4	126,30	126,11	0,15
5	180,51	175,79	2,61
6	N/A	218,79	N/A
7	247,53	246,89	0,26
8	409,29	407,64	0,4
9	542,89	528,47	2,66

According to Table 2, the maximum difference between the numerical two numerical results was 3% only (in mode 9). Lateral bending motion is observed in mode 2 and mode 6. However, since this motion is not defined in MATLAB code, the corresponding value was noted as N/A.

Flutter analysis of the full-scale model

The results of the first 4 modes were obtained by using the PK method for 3% and 1% damping ratios of the plate in MSC.NASTRAN. The velocity-dependent damping values of the first 4 modes are given in Table 5 and Table 7, and frequency values depending on the velocity are given in Table 6 and Table 8. The frequency-velocity graph of the first 4 modes is given in Figure 3 while the damping-velocity graph is given in Figure 4.

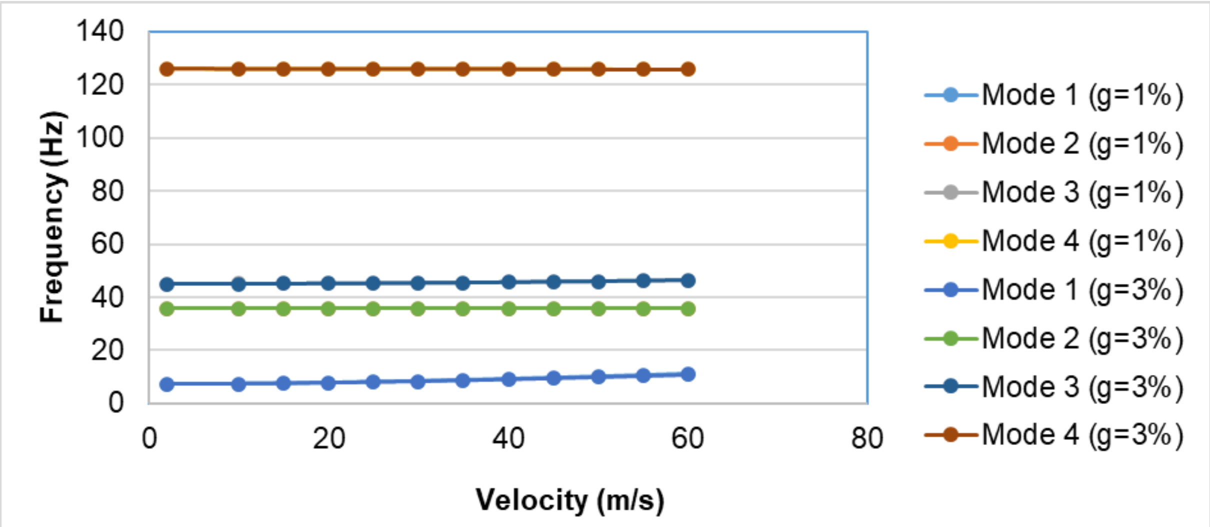


Figure 3. The frequency-velocity relation for varying damping ratios

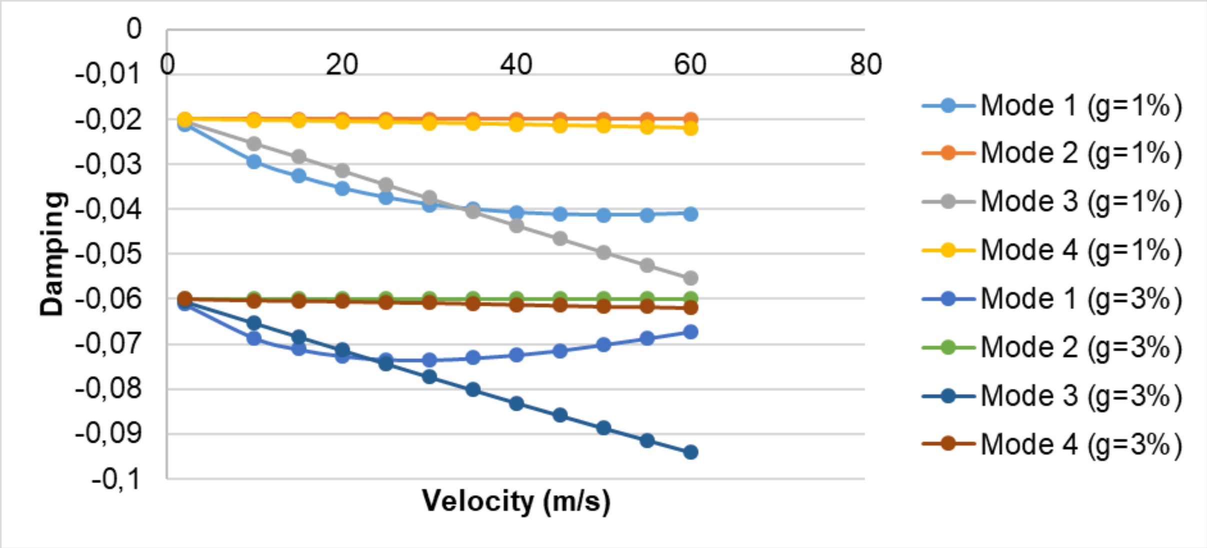


Figure 4. The damping-velocity variation for different damping ratios

From Fig. 3 and Fig. 4, no flutter occurred for 1% and 3% damping values on the plate. The reason for this is that the plate is very light, and the natural frequencies are quite high.

Modal analysis of the 1/10 and 1/5 scaled models

In this stage, the original model dimensions was scaled down to 1/10 and 1/5, and modal analysis was performed again in MSC NASTRAN and MATLAB, and the results were compared for 1/10 and 1/5 scaled models in Table 3 and Table 4, respectively.

Table 3. Results of the 1/10 scaled model

Mode	MATLAB	MSC Nastran	Difference (%)
1	72,03	72,01	0,03
2	N/A	357,34	N/A
3	451,15	450,81	0,07
4	1263,01	1261,14	0,15
5	1805,11	1757,91	2,61
6	N/A	2187,97	N/A
7	2475,26	2468,85	0,26
8	4092,96	4076,44	0,40
9	5428,90	5284,70	2,66
10	N/A	5918,63	N/A

Table 4. Results of the 1/5 scaled model

Mode	MATLAB	MSC Nastran	Difference (%)
1	36,01	36,00	0,03
2	N/A	178,67	N/A
3	225,57	225,41	0,07
4	631,51	630,57	0,15
5	902,56	878,95	2,61
6	N/A	1093,99	N/A
7	1237,63	1234,43	0,26
8	2046,48	2038,22	0,40
9	2714,45	2642,35	2,66
10	N/A	2959,32	N/A

As it can be seen in Table 3 and Table 4, the maximum difference was again 3% between the results of modal analyses performed in MATLAB and NASTRAN. As it was noted in the literature, the natural frequencies of scaled-down models are equal to the multiplication of full-scale model frequencies by a length scale [Wasserman].

NUMERICAL ANALYSIS VERIFICATION OF SCALED- MODEL

Modal analysis of the 1/3 scaled models

Since it is difficult to approximate the frequency values of the 1/10 and 1/5 scaled models to the ones for full-scale model and to support these data with experimental one, the plate scale was set as 1/3. Modal analysis were repeated according to the plate with new dimensions of 141x10x2 mm. In addition, PLA, which is one of the commonly used 3D printer filament, was used in manufacturing of the plate model to compare the numerical analysis results with the experimental ones. The numerical results obtained are given in Table 5.

Table 5. Modal analysis results of the 1/3 scaled model

Mode shape	Frequency (Hz)	
	Full-scaled Model	1/3 Scaled-model
Mode 1	5,8	17,4
Mode 2	28,9	86,7
Mode 3	36,4	109,2
Mode 4	101,5	305,4
Mode 5	145,2	435,7
Mode 6	176,9	530,9

As it can be noted from Table 5, the frequency increase was also confirmed with the 1/3 scaled model, depending on the reduction scale as it was also obtained in the 1/5 and 1/10 scaled models. However, it has been observed that the plate has a frequency quite far from its natural frequency.

This study aimed to approximate the natural frequency of the down-sized model to the natural frequency of the full-scale model. For this reason, additional studies were carried out to reduce the obtained frequency of 17.4 Hz to 5.8 Hz. First of all, the 1/3 scaled plate is completely emptied so that it has a wall thickness of the 3-D printing system nozzle tip of a 3-D printer. Then, the emptied plate was filled starting from the wingtip to the half-length of the plate (Figure 5).

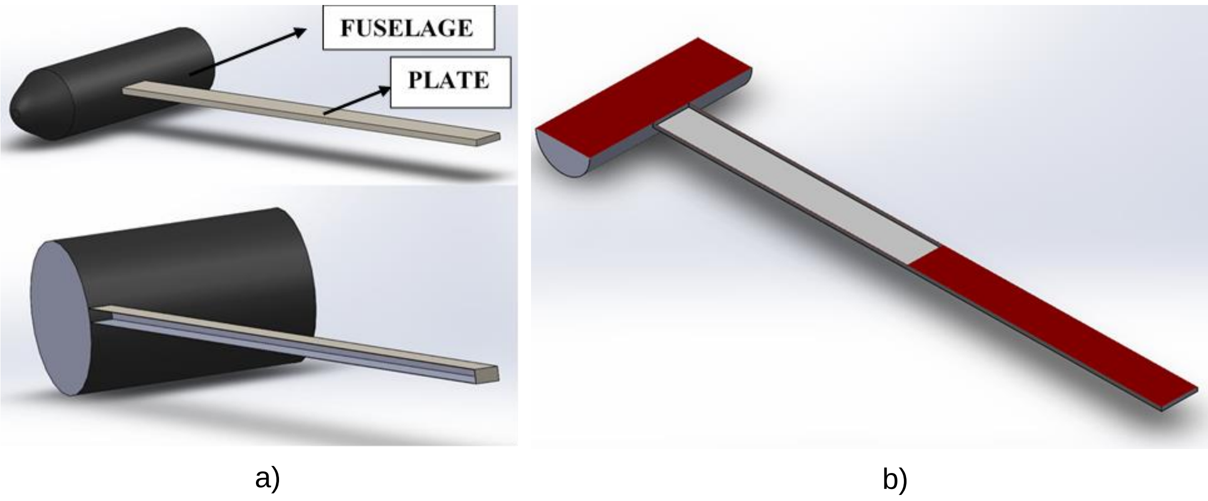


Figure 5. 1/3 scaled model with different filling scenarios, a) Emptied model (Model A), b) Model filled to the half-length (Model B)

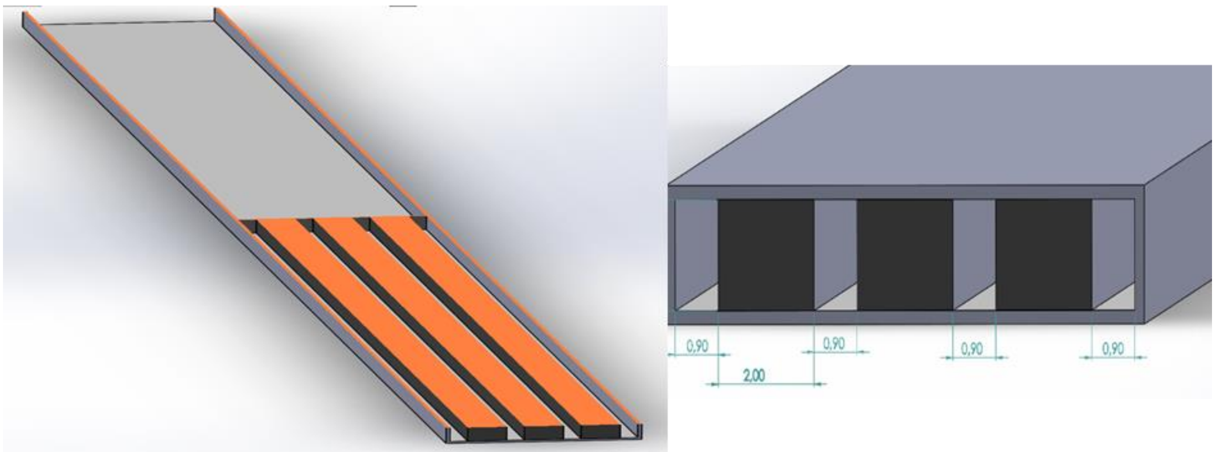
The modal analysis results of the two models given in Figure 5 are given in Table 6. At the same time, the filling strategies continued until the body of the plate and analyzes were performed until 100 % filling was obtained. However, the best results were obtained by filling the plate up to half its length.

Table 6. Modal analysis results of the Model A and Model B

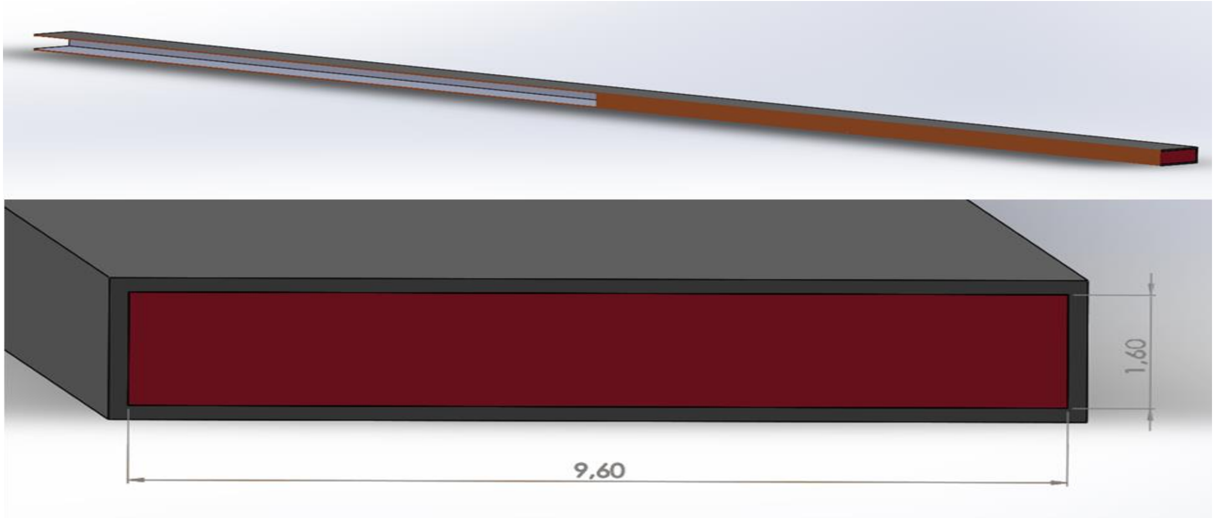
Mode shape	Frequency (Hz)		
	Full-scaled Model	Model A	Model B
Mode 1	5,8	23,3	7,6
Mode 2	28,9	94,6	31
Mode 3	36,4	143,9	90,3
Mode 4	101,5	394,3	237,4
Mode 5	145,2	517,3	368,1
Mode 6	176,9	576,6	528,4

As it can be noted from Table 6, the complete emptying of the plate did not result in closer frequency values to full-scaled model one's. The desired result could not be achieved by filling the plate up to half its length yet better results were obtained compared to Model A. In the light of these results, it was concluded that filling the plate causes a decrease in the frequency values yet it is not sufficient to reach the frequency values of full model. Therefore, blocks with higher densities are placed on the scaled-down plate models. Accordingly, 3 different models were created, inspired by the spar structures in the aircraft wings. Structural steel material having a higher density (7.85 g/cm^3) compared to the density of the plate were used in these models.

In the first model created, 3 longitudinal parts with the dimensions of 2x1.6x70.4 mm were added to the plate at equal intervals (Figure 6.a). In the second model, the distance between the added 3 parts was closed and 1 beam was formed (Figure 6.b). In the final model, parts in 2x1,6x9,6 mm dimensions were disposed transversely so as to be adjacent to each other starting from the free end of the plate. In the third model, the best results were obtained by placing 18 parts in transversely placed configuration (Figure 6.c).



a)



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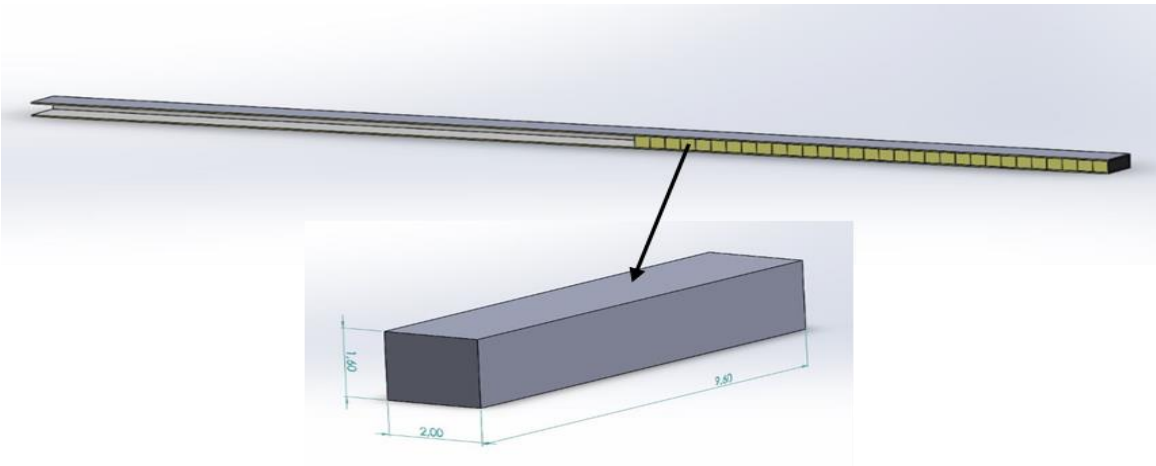

c)

Figure 6. Different filling configurations a) Filling with 3 pars (Model C), b) Filling with 1 big part (Model D), c) Filling with transverse parts (Model E)

Modal analyzes were repeated for the three models created. The modal analysis results of Model C and Model D, which consists of parts placed longitudinally, are given in Table 7, and the modal analysis results of Model E, which consists of parts placed transversely, are given in Table 8.

Table 7. Modal analysis results of models with longitudinal beams

Mode shape	**Frequency (Hz)**		
	Full-scaled Model	**Model C**	**Model D**
Mode 1	5,8	6,7	5,4
Mode 2	28,9	25,2	20,2
Mode 3	36,4	88,7	72,1
Mode 4	101,5	235,9	171,8
Mode 5	145,2	313,4	260,5
Mode 6	176,9	587,1	472,3

As it can be noticed from Table 7, the Model D gave closer results to the frequency values of the full-scale plate. This indicates that natural frequencies can be better approximated by filling the plate with a different material up to a length of 70.4 mm (which is half the length of the plate).

Table 8. Modal analysis results for the model in which the parts placed transversely

Mode shape	Frequency (Hz)	
	Full-scaled Model	Model E
Mode 1	5,8	5,8
Mode 2	28,9	22
Mode 3	36,4	87
Mode 4	101,5	165,3
Mode 5	145,2	300,6
Mode 6	176,9	328,1

By examining Table 8, it is observed that full-model's frequency values can be obtained, especially for Mode 1, as a result of filling with different materials up to 36 mm length of the plate.

Looking at the results in Table 7 and Table 8, it is seen that the natural frequencies of the plate can be captured by filling material with a density higher than the plate density, and adjacent to each other from the free end of the plate. In this case, in order to support the analyzes with experimental data, it was decided to produce the 1/3 scaled model with a wall thickness in the size of the 3-D printer's nozzle tip.

EXPERIMENTAL

Modal analysis of the full-scale model

After a series of numerical analysis, the experimental analysis was performed on the rectangular plate with dimensions of 423x30x6 mm and made of polycarbonate. The plate is fixed with a fixture, leaving 50 mm of fixing margin (Figure 7.a). The plate is marked with equal of 10 parts to determine the scaling point. The experimental setup is given in Figure 7.b. The plate was driven with a hammer and analysis data were saved with accelerometers placed on the marked sections. Comparison of the numerical results and experimental results are given in Table 9. The results were found as comparable.

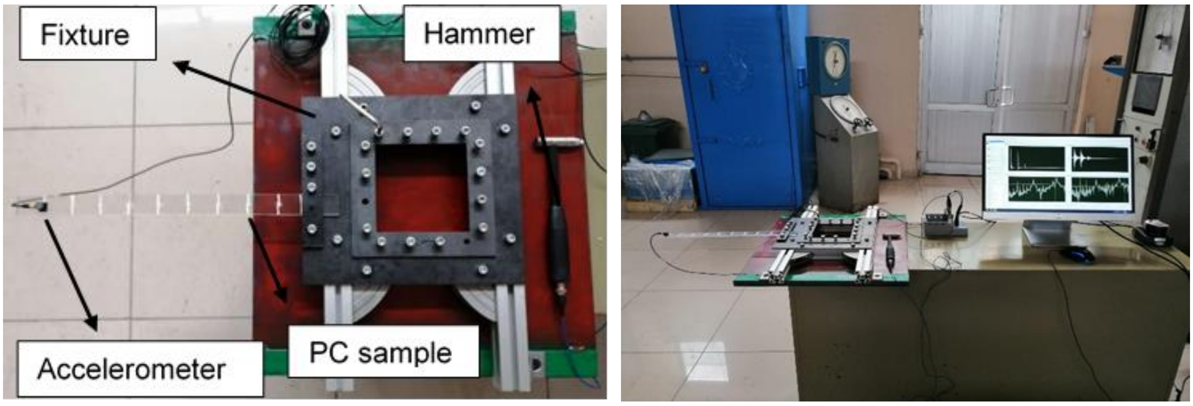

Figure 7. a) Positioning of the PC part of interest, b) general view of the experimental setup

Table 9. Comparison of numerical and experimental results

Mode Shape	Numerical (Hz)	Experimental (Hz)
1.Bending mode (Mode 1)	7,201	6,25
1.Lateral bending mode (Mode 2)	35,734	37,25
2.Bending mode (Mode 3)	45,081	38,25
3.Bending mode (Mode 4)	126,114	144,25
2.Lateral bending mode (Mode 6)	218,797	218
4.Bending mode (Mode 7)	246,885	223,25
5.Bending mode (Mode 8)	407,644	445,5
3.Lateral bending mode (Mode 10)	591,863	594,75

Modal analysis of the 1/3 scaled models

The 1/3 scaled PLA plate in 141x10x2 mm dimensions, and with a wall thickness of 0.4 mm, was completely emptied and produced in a 3-D printer. However, while the inner section of the produced model was planned to be rectangular in the designs, it was formed in an elliptical structure in practice and is too weak and fragile to bear any load on the plate. These cases showed that it was possible to test in a hollow model. For this reason, it was decided to produce the plate as 100% full (no gap, porosity) to obtain experimental data.

It was learnt from the numerical analysis studies that the 100% filled model cannot reach the desired natural frequency value. Even if the plate has different filing ratios, a material with a higher density must be added to the plate. It is known that the 100% filled model will not achieve the desired natural frequency in the produced plate. For this reason, it is planned to perform experiments by adding mass with higher density materials to the outer surface of the plate.

The 100% filled, 1/3 scaled plate was produced in the 3-D printer is shown in Figure 8. Modal analysis experiments of the reduced scale, and 100% filled model were performed. A comparison of numerical analyzes and experimental analyzes is given in Table 10.

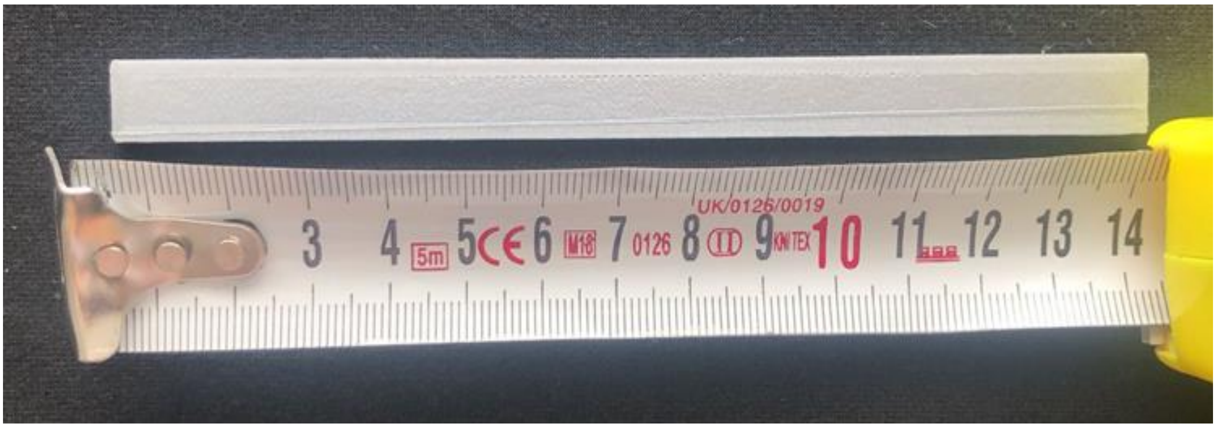

Figure 8. The 100% filled plate produced with 3-D printer

Table 10. Comparison of numerical and experimental results for 1/3 scaled-model

Mode	Numerical (Hz)	Experimental (Hz)	Difference (%)
Mode 1	17,40	16,8	3,6
Mode 2	86,7	64	35,5
Mode 3	109,2	95	14,9

As it can be noted from Table 10, there was a 3% difference for mode 1 between the experimental results and the numerical results. The increase in the difference in Mode 2 and Mode 3 seen in the experimental study of the full-scale model was also seen in the 1/3 scaled-down model.
The first three frequencies of the full-scale model were obtained as 5.8 Hz, 28.9 Hz, and 36.4 Hz, respectively. To reduce the frequencies obtained in the 1/3 scaled model to the frequency values of the full-scale model, mass addition was carried out on the plate. Models with 1/3 scale and mass-added parts for experimental modal analysis are given in Figure 9. Masses of 10x10x10 mm^3 (7.90 g) and 10x10x15 mm^3 (11.8 g) blocks were prepared from of Armox Advance material and attached to the plate.

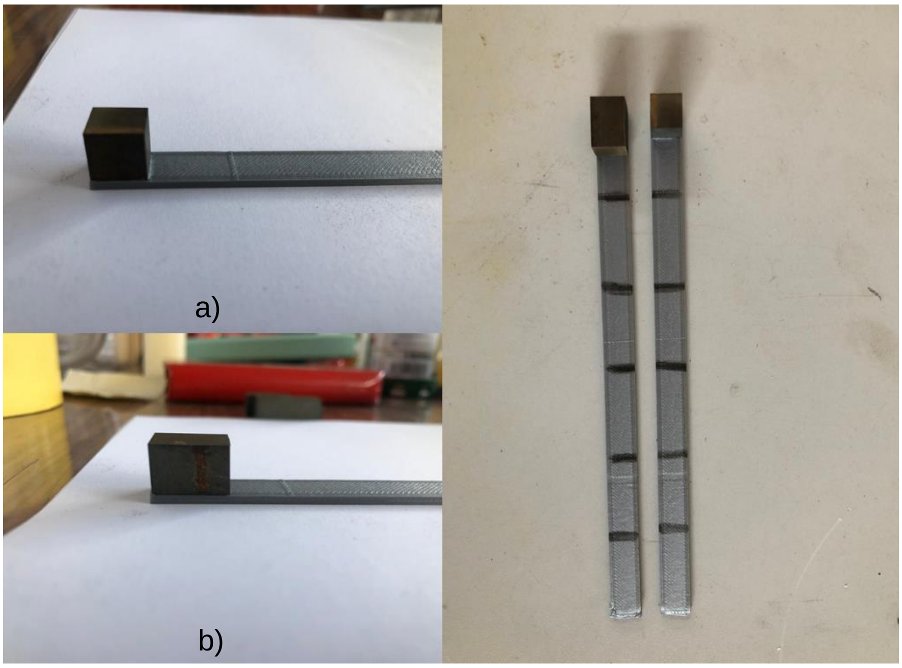

Figure 9. Models with 1/3 scale and mass added a) 10x10x10 mm^3 b) 10x10x15 mm^3

Modal analysis experiments of the models shown in Figure 9 were carried out. The two models were compared with the modal analysis results of the full-scale model. Obtained results are tabulated Table 11.

Table 11. Comparison of 1/3 scaled-model numerical and experimental results

Mode	**Full-scaled model**	**Mass Added Model (10x10x10 mm^3)**	**Difference (%)**	**Mass Added Model (10x10x15 mm^3)**	**Difference (%)**
1	5,8	7,8	25,5	6,6	12,5
2	28,9	54,2	46,7	52,4	44,8
3	36,4	167,8	78,3	159,2	77,1

According to the data in Table 11, the best result was found by adding a mass of 10x10x15 mm^3 with a difference of 12.5% for Mode 1. Due to the fact that the plate is very light and flexible, bending occurred with the addition of mass and accelerometer during the experiment. This situation caused us to find higher frequency values than the expected experimental results.

RESULTS AND DISCUSSION

When the analysis of the 423x30x6 mm full-scale plate were performed using polycarbonate and 3-D printer filament materials, it was observed that the natural frequencies obtained in the full-scale form of the plate decreased when PLA material was used. This situation has been interpreted as the fact that the structure can be produced by 3-D printers, resulting in a decrease in natural frequencies to a certain extent.

It is aimed that the natural frequency values obtained from the full-scale model used in the study are equal to the frequency values of the scaled-down models. As a result of the reduction of the 423x30x6 mm plate in different scales, it was observed that the natural frequencies increased inversely with the scale. This result is also confirmed for 1/10, 1/5, and 1/3 scaled models.

Different models have been designed to reduce the frequency increase resulting from the scaling of the plate. In terms of the feasibility of the production and testing phase, it was deemed more appropriate to work on 1/3 scaled models. In the 1/3 scaled models, the filling of the structure was changed by making different excretion in the fully filled model (100% full). When the results of the analysis were examined, it was observed that the model (60% filling ratio) filled up to half of the 1/3 scaled plate without adding any different material gave the best results compared to the other models. However, the desired frequency value could not be reached in this case.

Since the desired frequency drop could not be obtained by discharging the material from the down-scaled plate, it was considered to add different densities of material to the top/inside of the plate, and studies were carried out in this direction. Steel plates were added to the plate in a transverse or longitudinal manner. Steel plates are attached to different parts of the plate, with different lengths and different sizes. When the results were examined, it was seen that the steel plates should be placed adjacent to each other and filling should start from the wingtip in order to obtain the values closest to the natural frequency of the plate. In models with transverse or longitudinal steel plates added, the closest value to the natural frequency of the full-scale model was obtained by filling up to 36 mm length. At the same time, it has been seen that it is possible to decrease the frequencies below the desired values in case of adding material starting from the plate end to the half-length of the plate.

After the numerical analysis, firstly the full-scale plate and then the 1/3 scale plates were experimentally studied. First, the experimental setup was set up for the full-scale plate made of polycarbonate, and the analysis data were carried out and compared with the numerical results.

In the experimental analysis of the plate, which was reduced to 1/3 of the original dimensions, the models to be produced in the 3-D printer were determined first. For this, models with steel plates to be added, in which we obtained the closest results to the desired in numerical analysis, were selected. The plate, in which a steel plate will be placed, was produced in a 3-D printer with a wall thickness of 0.4 mm, completely empty. However, the produced plate was not suitable for experimental work as it was too fragile. For this reason, it is planned to produce the plate to be 100% full and to place materials of different densities on the plate.

It has also been experimentally seen that the natural frequencies of the full-scale model can be approached when masses added to the plate. However, factors such as the weight of the accelerometer and the density of the scaled-down model must also be taken into account. The added masses and the mass of the accelerometer is close to the mass of the plate itself causes the plate to tilt, which affects the accuracy of the experimental results.

CONCLUSION

In this study, the modal analysis of the geometric scaling and scaled-down models of the rectangular plate while preserving the dynamic properties of the full-scale model were investigated using MSC.Nastran and Matlab softwares, and the results are compared. At the same time, the experimental analysis of the full-scale plate was conducted and compared with the numerical analysis. The difference, as a result of the comparison, was obtained as 17% and this difference is acceptable.

In the current study, it was aimed to obtain the natural frequency values obtained in the full-scale model with the scaled-down models. The full-scale model was scaled down in 1/5, 1/10, and 1/3 ratios, and analysis were obtained. However, since the natural frequency of the plate is inversely proportional to the scaling factor, the natural frequency value increases as the scale decreases. For this reason, the reduced plates were completely emptied and the analyzes were repeated by filling the wing from the tip of the wing. Although there was a decrease in frequency values, the desired value could not be reached. The Armox Advance material, whose density is higher than the plate density, is placed inside the plate. Structural steel parts was placed transversely and longitudinally and their performances were analyzed. Although the steel plates decrease the frequency, it has been observed that the desired value is reached when modeled adjacent to each other. Although the desired result can be obtained numerically, it has been seen that it is not appropriate to produce the plate by emptying the inside of the experimental analysis. For this reason, it has been deemed appropriate to produce plates to be 100% full and to add Armox Advance material on them. In the experimental results, there was a 3% difference for the first mode. This showed that the frequencies of the full-scale model could be captured. However, it should be kept in mind that more than one accelerometer must be used and the plate is tilted by adding mass to it.

In this study, the factors that determine the natural frequency of the structure were determined by considering the models designed in different configurations. The factors determined in the later stages of the project can be transferred into a software. By writing an optimization algorithm to obtain the easily and quickly and adding it to the interface of the program to be used, the approach proposed can yield faster results.

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