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Parameter Optimization of a Bi-copter Type Unmanned Aerial Vehicle to Avoid Propeller-induced Vibrations During Hovering

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Abstract

The vibration parameters of a bi-copter-type unmanned aerial vehicle is optimized by considering operational vibration with payloads. The double electric ducted fan loads, which transmit excitations to the fuselage, are predicted and compared using optimization methods. While the minimum vibration amplitude for stress will be achieved at 7.69 Hz, it will be 9.80 Hz. for minimum deformation without sacrificing safety factor requirement. It ensures sensitive vertical acceleration. It is not seen significant differences on results from screening and genetic algorithm methods. Correlations between frequencies and structural responses are determined. It is observed that the stress and deformation amplitudes of the structure decreases at increasing frequencies up to the next natural frequency. While the highest amplitude is seen at the first frequency, it decreases in increasing modes. The airframe structural model's operational frequency must be 7.69 or 9.80 Hz to achieve sensitive vertical acceleration. Subsequently, it is aimed to develop an autonomous task by the implemented system controlled by various algorithm as a future work.

Keywords: Bi-copter, Tandem Rotor, Unmanned Aerial Vehicle, Genetic Algorithm, Optimization.

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1. INTRODUCTION

Bi-copters which mean two-rotor become a new idea as an unmanned aerial vehicle (UAV) and are inspired from helicopters. Helicopters have superior abilities compared to the fixed wing air vehicles. Especially the abilities to hover in the air and fly backwards make them mandatory for difficult tasks. They are useful as a portable surveillance tool. They will be able to carry load by performing small amount of design changes. Thanks to bi-copters, “tail rotor” and “ductless main rotor” requirements of helicopters are eliminated. Instead, electric ducted fans (EDF) are used as driver. Bi-copters have just two driver units. So energy consumption is the least among multi-rotor air vehicles. They require less space during landing/take-off. Bi-coppers also have six degrees of freedom to be able to be controlled by four input signals only. Although an additional drive system is generally used to provide stability besides the main drive system to ensure a stabilized flight on multi-copters such as quad-copter and tri-copters, no additional auxiliary system is necessary to obtain a stabilized flight on desired trajectories for bi-copters. Additional systems would bring extra electrical and mechanical loads to the aircraft. While the most-seen problem in propeller aircraft is stabilization during flight, bi-copters are far away from disturbing conditions. Balance can be obtained by control strategies. Direction can be adjusted by just changing of rotor angle.

Multi-rotor vehicles are useful in the air mapping, protection of agricultural land, crime detection by law enforcement officers [1]. More flight time is obtained by bi-copter with tilt mechanism [2]. Yoon and Lee [3] investigated the aerodynamic rotor shapes by considering flight control and kinematics. An optimization method provides suitable coefficients for controller. A control strategy to balance the bi-copter is achieved in 40% overshoot and the settling time 16 seconds [4]. Elias et al. [5] performed a wirelessly controlled bi-copter by hand gestures. It is seen that thrusts are provided by brushless motors, the direction is controlled by servo motors. Hand movements are transmitted to control signals through a special glove equipped with an Arduino© controller, accelerometer and flex sensors. By combining two bi-copters, direction control is obtained by just rotor angle.

Since UAV’s are constrained to have lower weight as little as possible for energy efficiency, optimizing the material properties is an important task for both its own or any attachment’s stabilization such as cameras during service life [6, 7]. The stiffness of the material affects vibration characteristics. Structural resonance can cause to impose malfunctioning and thereby degrading manoeuvrability.

UAVs are unique vehicles due to their vertical take-off and landing capabilities. Although lightness is a criterion for its body designs, it may cause higher vibrations. This study focuses on vibrations due to rotation of motor-driven propellers. If any excitation frequency interferes with structures fundamental frequency, it causes resonance. To avoid resonance, the lowest fundamental frequency has to be higher than the maximum working excitation frequencies of the propellers. The fundamental frequency of the bi-copter depends on its dimensions, material (stiffness), boundary conditions mainly. Selecting lighter material and lower vibration without sacrificing safety requirement is main strategy. In this study, natural frequencies of the designed bi-copter are determined based on finite element (FE) simulations. Also an optimization is performed by following two methods so-called screening and genetic algorithm. Optimization gives the relations between frequencies and structural responses. An implementation of the bi-copter is carried out in accordance with the optimization results. It is tested for modal frequencies. The study is organized including a conceptual design of the vehicle which defines the parts based on their kinematics. Material and method section defines physical and mechanical properties of potential materials to be used for optimization. Also it includes the experimental modal test and FE simulations for structural analyses and optimization process.

2. CONCEPTUAL DESIGN

Bi-copters are mainly composed of one body and two thrust fans mechanically. The body also consists of a single board computer to run the flight firmware. Two servo motors provide the tilt angle of thrust motors. As a single board computer, a Raspberry Pi© computer is assembled to body with an electronic speed controller (ESC) and lithium polymer (Li-Po) batteries. A camera card is located on the bottom side of the body as seen in Figure 1. These are payloads for the vehicle. Its weight is 225.8 gr. totally.

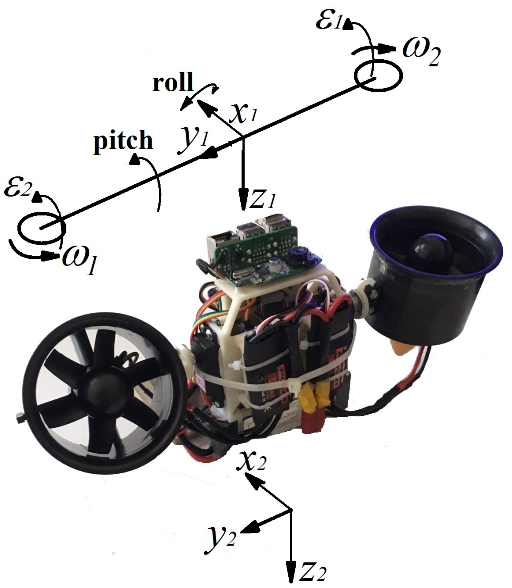


Figure 1. Kinematics of the design. ω: rotational speed, ε=pitching, z: vertical direction.

3. MATERIALS AND METHODS

Vibration analyses are performed on the UAV body experimentally. Results are compared with those from FE analyses. The subsequent sections describe how these FE results are validated by using experimental results from simulations.

Materials whose yield point is in between 25-280 MPa which correspond to polyethylene and aluminium alloys respectively are investigated due to its potential for being fuselage material. Mechanical properties are listed in Table 1.

Table 1. Material properties

	Aluminium alloy	Polyethylene
Density (kg/m^3)	2770	950
Young's Modulus (GPa)	71	1.1
Poisson Ratio	0.33	0.42
Bulk Modulus (GPa)	69	2.29
Shear Modulus (GPa)	26.7	0.38
Yield Strength (MPa)	280	25

3.1. Modal testing

Instead of surrogate model, the designed and implemented model is used for modal testing. Mass for each one of the components is measured accurately. The impulse hammer excitation test is performed on the body to determine modal frequencies. Free-free boundary connection is provided. It is elastically connected to the wall of experimental rig system as shown in Figure 2 in order to eliminate boundary effects.

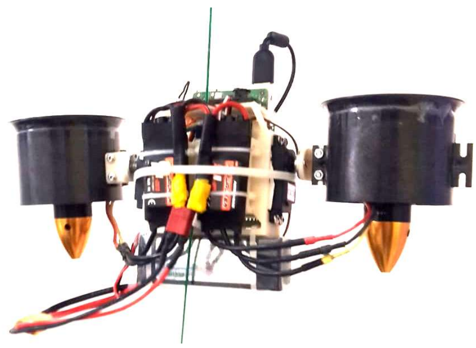


Figure 2. Experimental rig system with similar to boundary conditions during hovering.

An accelerometer is used to capture the frequency responses of the body in the range of 0-200 Hz. Its weight is 0.5 grams. Measurements are done on a set of 100 excitation points along the complete structure. Up to 200 Hz, 10 mode shapes are clearly obtained.

3.2. Static Analysis

Stress distribution, deformation and safety factors are determined by means of structural analysis by applying flight loads on the model.

The model is supported by a frictionless support through the hole surface passing through its centre as it is hung in experiment. Each one of the EDF motors provides 1kgf trust loads per motor. Ansys© is used for simulations [8]. Figure 3 shows FE model and load and boundary conditions.

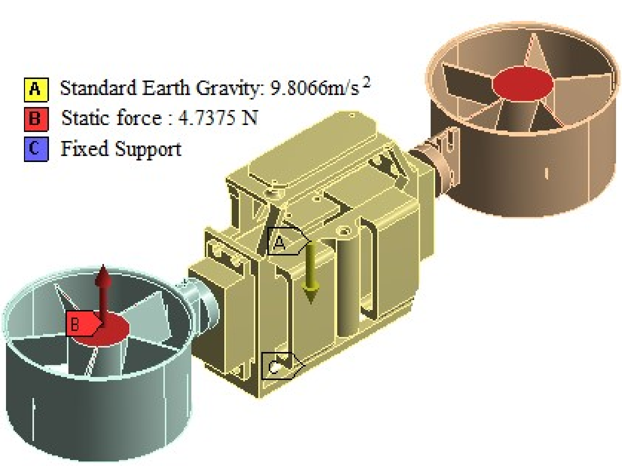


Figure 3. Load and boundary conditions

Also fatigue analysis is performed to determine the safety factor and working life in the cyclic load case. The Soderberg criterion mixed with Von Mises is used as mean stress correction theory. This is a useful criterion for materials which have ductile behaviour. Designs to be used in the aviation field must meet the requirement of fatigue strength. Stress-life (*S-N*) data from fatigue tests performed on polyethylene material are given in Table 2. The loading frequency is applied as 1 Hz. The mean stress caused by the applied periodic tension/compression load is zero (R=-1). K_f=0.87 is used in the analysis for fatigue strength reduction factor.

Table 2. *S-N* data

Cycle	Stress range (MPa)
6546	20.02369
5967	20.48856
5336	21.07367
4757	21.779
4027	22.47631
3145	23.65453
2617	24.70451
2088	25.64228
1458	27.63003
979	29.62579
577	31.84598
426	34.07418
274	36.53482
148	38.41035
98	39.69277

3.3. Forced Vibration Analysis

Forced vibration analysis gives how to be the stress and deformation responses of the structure in case of harmonic/random excitations. Prior to forced vibration analysis, a modal simulation is performed to determine the natural frequencies. The analysed frequency range is taken as 0-5000 Hz with 0.1 Hz increments in the simulations.

3.4. Optimization

The goal of the optimization is to find maximum force, without sacrificing safety factor=3 and a sensitive vertical acceleration with minimum vibration amplitude. The safety factor is calculated from both static and fatigue analyses. Stress and deformations responses are found for each frequencies from 0 to 5000 Hz with 0.1 Hz increment. Results from screening [8] and genetic algorithm (GA) [9, 10] methods are compared. Evaluated parameters are listed in Table 3. Ten thousand points are evaluated as designs of experiment.

Screening method is one of the easiest multi-objective optimization algorithms. Its approach is based on just sorting according to sampling table. It is preferred for preliminary designs.

Table 3. Input/output parameters and lower/upper limits of input variables

	Initial value	Lower limit	Upper limit
Input parameters			
Tensile yield strength (MPa)	280	10	70
Harmonic force (N)	60	0	100
Static force (N)	60	0	100
Frequency for equivalent stress (Hz)	0	0	5000
Frequency for total deformation (Hz)	0	0	5000
Output parameters			
Deformation (m) (statical)	--	--	--
Equivalent stress (MPa) (statical)	--	--	--
Safety factor (statically)	--	--	--
Life minimum (fatique)	--	--	--
Safety factor minimum (fatique)	--	--	--
Equivalent stress (MPa) (harmonic)			
Deformation (m) (harmonic)			

GA sets an analogue between tabulated data and a set of solutions called population, represented by chromosomes. Yalçın et al [11] explained an application of this optimization method in detail. The GA parameters used in this study are given in Table 4.

Table 4. GA parameters used in the study

Parameters	Value
Estimated number of evaluation	2000
Number of initial samples	100
Number of samples per iteration	100
Maximum allowable Pareto percentage	70%
Convergence stability percentage	2%
Maximum number of iterations	20

The goal and applied constrains in the optimization are applied as follow to catch a sensitive vertical acceleration.

- Minimize the static deformation
- Minimize the harmonic deformation
- Minimize the static safety factor (SF) as long as SF ≥ 2
- Minimize the fatigue SF as long as SF ≥ 3
- Maximize the static force
- Maximize the harmonic force

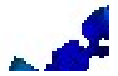
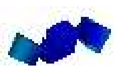
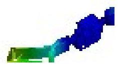
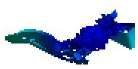
4. RESULTS AND DISCUSSIONS

Obtained data are given in this section. The experimental modal testing was conducted to verify the structural characteristics of the developed structural model of UAV.

4.1. Natural frequencies

A comparison on the frequency responses from experiment and analysis is given in Table 5. In the table "Exp." means the experimental results. Just first ten frequencies are listed. Vibration analysis simulates the steady state structural response of body to periodical loads. So, resonance can be kept away. Mode shapes are obtained from FE simulation. The maximum working frequency of the propellers is 2570 Hz in full throttle.

Table 5. A comparison of resonance frequencies on complete body.

Mode	Modal frequencies (Hz)		Mode shapes	Description
	FE	Exp.		
1	31.267	30.33		Rigid body pitch mode
2	37.845	38.22		Rigid body roll mode
3	55.088	56.74		1st axial mode
4	55.088	56.74		2nd axial mode
5	71.243	71.96		1st bending symmetric mode
6	82.219	84.69		1st bending antisymmetric mode
7	93.703	96.51		1st torsional symmetric mode
8	117.55	118.73		1st torsional antisymmetric mode
9	149.43	146.44		2nd bending symmetric mode
10	175.73	181.00		2nd bending antisymmetric mode

The difference between experimental and FE analysis is in the range of approximately 3%, which is also consistent with the value given in [12-14]. It is important to detect natural frequencies to avoid resonance. Thus, the driving frequency that will not stimulate the resonance can be determined. It is presented that the error between experimental results and simulations can become 7.99% for the whole models due to number of reasons such as the increased number of joints among components and the effect of the suspension rubber used to hang the bi-copter to the ceiling [7].

4.2. Optimum values

The optimized (best fitted) values are listed in Table 6, 7. For verification, analyses are repeated with optimized values. Tables include verified values. As seen in Table 6, minimum stress and deformation are obtained at frequencies 7.685

Hz and 9.80 Hz. respectively. While the structure has endurance up to 19.8 N harmonic force, it is limited to 4.74 N for static load case. Yield strength of the body material must be 12.91 MPa at least. Sawalakhe and Shaaikh [15] reported that 2.4525 N will be enough for acceleration of their 1000 gr. model. So it is concluded that 4.74 N will be enough for our case which is 225.8 gr.

Table 6. The values obtained from GA optimization method and verification of the results

	Optimized value	Verified value	Error (%)
Input parameters			
Tensile yield strength (MPa)	12.91		
Harmonic force (N)	19.80		
Static force (N)	4.74		
Frequency for equivalent stress (Hz)	7.69		
Frequency for total deformation (Hz)	9.80		
Output parameters			
Deformation (m) (statical)	0.00096	0.000958	-0.31
Equivalent stress (MPa) (statical)	2958392.36	2949810.37	-0.29
Safety factor (statically)	12.21	14.58	19.41
Life minimum (fatique)	9729901.80	10000000	-
Safety factor minimum (fatique)	4.95	3.88	-21.6
Equivalent stress (MPa) (harmonic)	10.55	10.55	-
Deformation (m) (harmonic)	34.25	34.25	-0.02

Table 7. The values obtained from screening optimization method and verification of the results

	Optimized value	Verified value	Error (%)
Input parameters			
Tensile yield strength (MPa)	13.0391		
Harmonic force (N)	19.998		
Static force (N)	4.7874		
Frequency for equivalent stress (Hz)	7.7669		
Frequency for total deformation (Hz)	9.898		
Output parameters	0		
Deformation (m) (statical)	0.00097	0.000968	-0.3131
Equivalent stress (MPa) (statical)	2987976	2979308	-0.2929
Safety factor (statically)	12.3321	14.7258	19.6041
Life minimum (fatique)	9827201	10100000	-
Safety factor minimum (fatique)	4.9995	3.9188	-21.816
Equivalent stress (MPa) (harmonic)	10.6555	10.6555	-
Deformation (m) (harmonic)	34.5925	34.5925	-0.0202

Figure 4-9 shows counter plots at the last load step when optimized variables are used in analyses.

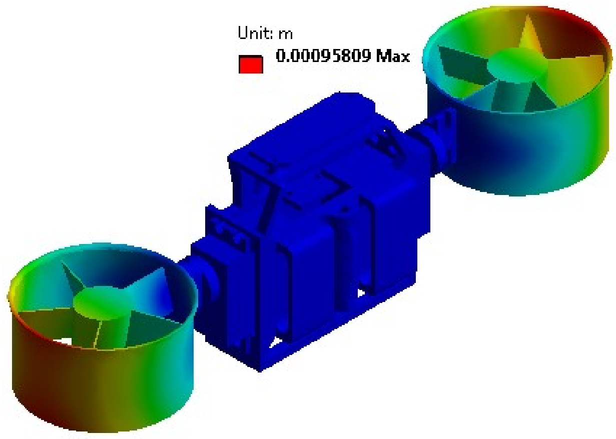


Figure 4. Deformation results

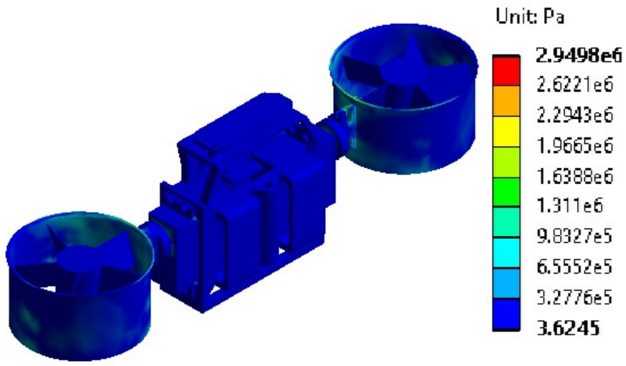


Figure 5. Stress results

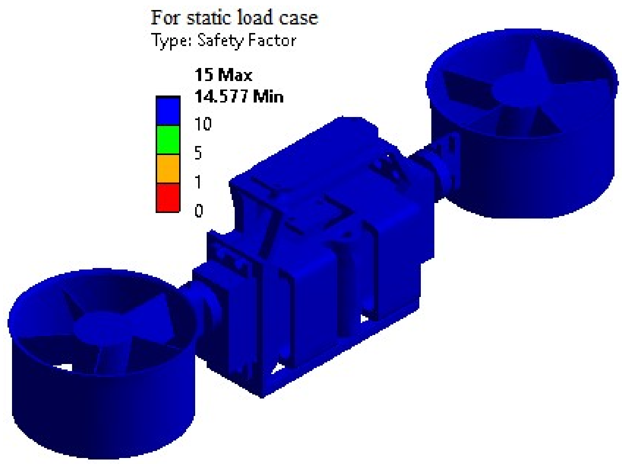


Figure 6. Safety factors (static)

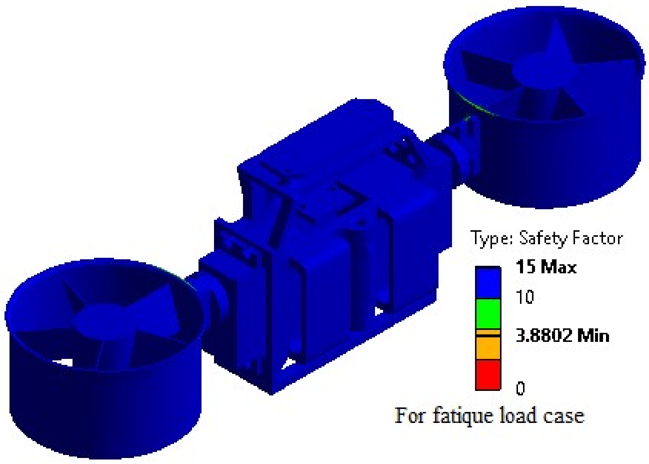


Figure 7. Safety factors (fatigue)

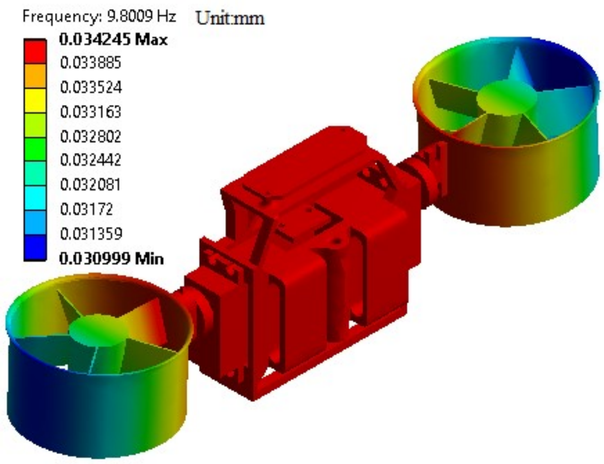


Figure 8. Displacement response at a frequency (9.8009 Hz.)

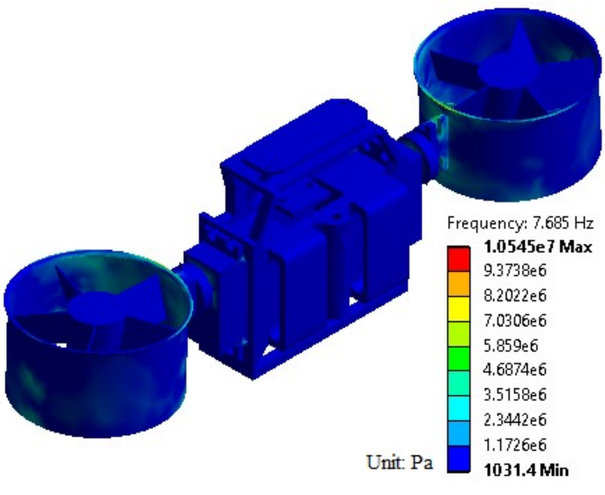


Figure 9. Stress response at a frequency (7.685 Hz.)

When the values determined by means of optimization were applied on the bi-copter, the responses shown in Figure 4-9 would be obtained. The maximum deformation value is 0.9mm, this value is much less than that of Das et. al [16] where the maximum deformation amplitude is 27.29 mm. The safety factor is 14.77, well above 3 which is the goal. Where the stress is at its maximum, its value is 2.9 MPa, and the value is well below the yield strength. So, the validation of the optimum values is done.

4.3. Relation between Parameters

The relations among all variables especially between excitation force and frequency response are obtained in the optimization procedure using Kriging method [10] as response surface investigation. Results are given in Figure 10.

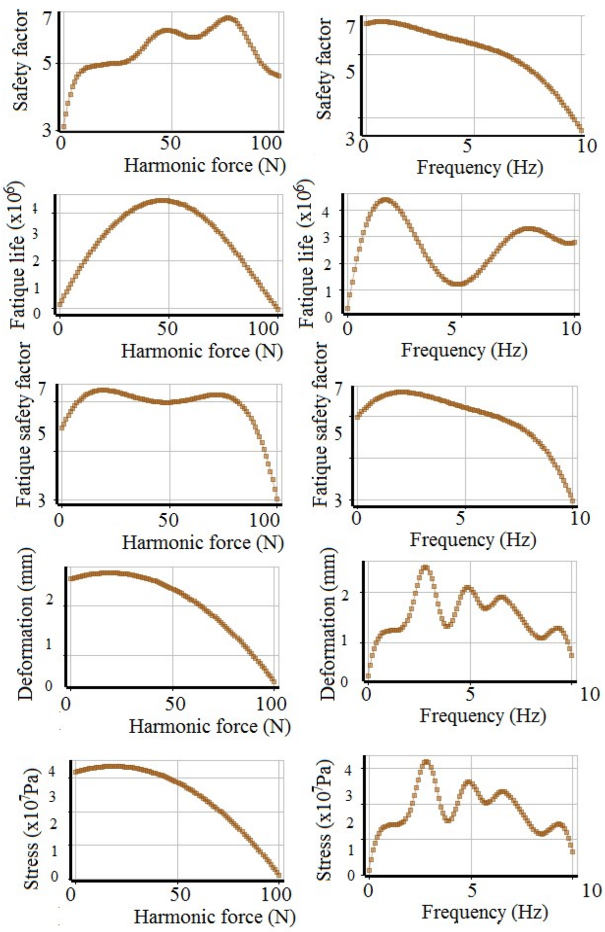


Figure 10. Relations between parameters

The influence of the force and frequency is seen from the curves. It is seen that the safety factor tends to decrease in static and fatigue states with increasing force, as expected. However, with the increase of harmonic force, it is seen that the safety factor increases. The reason for this can be explained as excessive vibration in the structure and the resonance leading to increase the stress amplitude. For the same reason, it is understood that at increasing frequencies, the safety factor decreases.

5. CONCLUSIONS

In this paper, an optimization process is performed considering operational frequencies to achieve a sensitive hovering of a bi-copter type unmanned aerial vehicle to avoid propeller-induced vibrations. Structural endurance and stability of UAV is the main concern. Optimal force and frequency values are determined. So the following inferences are concluded.

- The minimum lift force 4.74 N provides the softest movement in hovering. So any attachment like camera will take images in both hovering and lifting cases with the maximum energy efficiency due to minimum propeller rotation requirement
- Any material whose yield point is bigger than 12 MPa will be enough for flight endurance.
- The structural analysis is done for calculating stresses, displacements, and safety factors. The displacements observed are negligible and within the limit. The maximum stresses produced are 2.9 MPa which are within range.
- The comparison of the FE results and experimental modal results shows that the modal characteristics are in close agreement within the of 3% error for the first then elastic global modes.
- The maximum working frequency of the propellers is 2570 Hz in full throttle which is far away from the first then fundamental frequencies.

Within the scope of this study, just optimum parameters are determined and verified. For subsequent studies, it is aimed to apply different control techniques on flight stability and equilibrium.

Research and Publication Ethics

This paper has been prepared within the scope of international research and publication ethics.

Ethics Committee Approval

This paper does not require any ethics committee permission or special permission.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of the paper.

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