Transdisciplinary Engineering for Complex Socio-technical Systems – Real-life Applications
J. Pokojski et al. (Eds.)

doi:10.3233/ATDE200097

Verification of Flutter Method for the Purposes of Building a Very Flexible Wing Generative Model

Kamil ZENOWICZ[1] and Wojciech SKARKA[2]
Silesian University of Technology, Faculty of Mechanical Engineering

Abstract. First step of aircraft design is calculation of initial parameters, based on assumptions determining flight parameters which designed aircraft should meet. During these calculations, it is possible to pre-detect structure instability called a flutter. These calculations are made based on the geometric parameters assumed in the first conceptual drawings of the flying vehicle. Assumed masses and speeds allow for preliminary analysis of forces acting on the structure. The next step is to determine the displacements and deformations occurring in the structure of the aircraft in different phases of flight and under different conditions. The article presents all the stages of wing analysis for a proposed stratospheric drone with a highly flexible wing structure. This analysis, after integration with CAD software, will allow for the preparation of a comprehensive generative model. The basic assumptions of the designed aircraft are: flight altitude, wings area, very extended or unlimited flight time, approximate flight speed, climbing time, hull parameters, rudder size and placement, wing profile and mass of the structure. These assumptions made it possible to carry out a preliminary analysis of loads, wing pressure distribution, lift force and total resistance force. The goal of the research is to develop a methodology of preliminary flutter analysis which can be easily integrated in the form of calculation backgound for generative model. This methodology has been developed to determine displacements, structure stability and critical vibration frequencies. CAD software after integration with constantly optimizing calculation software will allow the generation of optimal shape and structure rigidity for given initial assumptions.

Keywords. Flutter, elastic wing, drone, generative model, aircraft design.

Introduction

Designing modern aircraft requires confirmation of the strength and stability of all the elements of the designed structure. All newly designed aviation structures are analyzed in terms of possible flight parameters and loads occurring during flight. This analysis allows the determination of the strength limits of the structure. Based on such data, optimization is performed that streamlines the design and adapts the designed vehicle to the initial assumptions.

Large enterprises producing aircraft and other flying objest use tools developed for their own needs to assist in calculating the parameters of the designed aircraft. Smaller

[1] Corresponding Author, Mail: kamil.zenowicz@polsl.pl.
[2] Corresponding Author, Mail: wojciech.skarka@polsl.pl.

companies that develop and manufacture low-volume and single series aircrafts do not have software for this purpose.

The need is therefore to create software whose goal will be to support the design of highly flexible aircraft with light and ultra-light weight structure.

The article presents possible ways of aeroelastic analysis of the generative structure of an ultra-light stratospheric drone platform.

In order to facilitate the design of large load-bearing composite structures, with high flexibility and extremely low weight, it was decided to develop tools supporting the designer in the design of such structures. The tools are integrated directly in the CAD system. It have the form of generative model and integrate knowledge of composite structure design, composite strength, aeroelasticity of highly flexible structures, aerodynamics, composite shaping technology, flight mechanics and aircraftdesign. Generative models include solutions that integrate design automation methods, comprising integration of complex structures with many elements based primarily on experience in the automotive industry [1] [4], specific rules for the design of composite elements shaped in molds in analogy to experience in the field of shaping stamping dies [2] as well as modeling techniques and automation of the design of complex surfaces. They all constitute the basis in modeling in the automotive industry, aviation and plastic processing, in particular the design of wrrapeable and non-wrrapable surfaces [3]. Generative models and various aspects of this methodology were used to develop the experimental HALE UAV (High Altitude Long Endurance Unmanned Aircraft Vehicle) project called Twin Stratos.

1. Verification of aeroelastic phenomena

During the flight there is a occurrence of several dangerous aeroelastic phenomena. The most important are presented below:

1.1. Static type phenomena:

- Divergence - aerodynamic forces increase the angle of attack of a wing which further increases the force.
- Control reversal - where control activation produces an opposite aerodynamic moment that reduces, or in extreme cases, reverses the control effectiveness.
- Flutter - the uncontained vibration that can lead to the destruction of an aircraft.

1.2. Dynamic type phenomena:

- Self-excited vibration (flutter) - The airframe's self-excited vibrations occur at a certain flight speed, when at least one of natural vibrations frequency of the structure is combined with external stimulation vibrations frequency. The phenomenon itself is a complex dynamic system conditioned by aerodynamics, rigidity and mass characteristics of the airframe.
- Buffeting - Buffeting occurs when one of the forms of the airframe's own vibrations is stimulated by an external source. Most often, such a source may

be the impulse caused by the entering to the propeller streams or entering to the turbulence area with a regular oscillating character.

Due to the need to analyze each newly designed aircraft, the main subject of the analysis in this article will be determination of stability and aeroelastic analysis of an aircraft with a highly flexible load-bearing structure.

The main steps for checking the correctness of the designed structure are presented in the Figure 1.

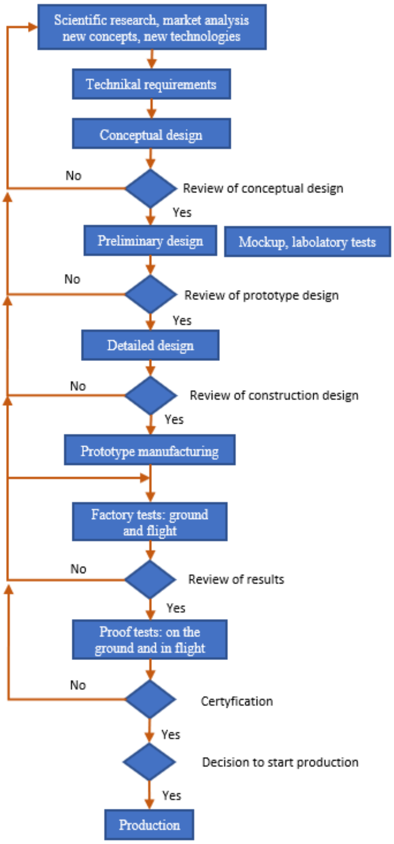

Figure 1. Algorythm of the presented aircraft designing process [4]

2. Preliminary analysis based on the center of gravity position of aircraft components

The basic analysis of the aircraft flutter occurence possibility is based on recommendations determined on the basis of testing existing aircraft of approximate design. Historical guidelines clearly determine the possibility of flutter depending on the location of the center of gravity of the elastic elements to the aerodynamic center of this component. This is the easiest method that allows to determine whether there is a possibility of this phenomenon in the proposed structure.

This method is called "stiffness tests" and to perform it, the stiffness of individual parts, the location of their centers of gravity and their resistance to forces are determined.

Due to the analysis of low-weight aircraft and high flexibility, this analysis is not accurate enough. This method determines whether there is a possibility of flutter occurrence in the designed object and whether it should be further analyzed or there is no possibility of this phenomenon in analised assembly [5], [6].

3. Analysis based on simplified mathematical model and aircraft shape parameters

This analysis is the next stage of aircraft testing. It involves testing a simplified mathematical model of the parts which are most vulnerable to flutter, i.e. parts that were considered risky during the analysis based on the location of the main gravity points of the structure.

This type of analysis is performed based on the basic parameters of the designed aircraft. Due to the need to simplify the analysis, the external shape is replaced there by simple two-dimensional gemometric figures. Then the parameters of the elements on the basis of which they were created are assigned to these figures.

Due to the availability of software, it was decided to use free access software for academic purposes to conduct the analysis in this step. The literature review of the available software has shown that the available means for performing the assumed aeroelastic analysis are the programs presented in table 1.

Table 1. Software with license aviable for students.

Software	Basic informations
Unsteady Vortex Lattice Method (UVLM)	Computation code NANSI (Nonlinear-Aerodynamics/ Nonlinear-Structure Interaction) which combines an Unsteady Vortex Lattice Method (UVLM) and a nonlinear beam theory. The UVLM is particularly useful in case of lowaspect- ratio wing or delta wing because the method is able to predict 3D effects. [7]
Program SHARP (simulation of High Aspect Ratio plane)	Proposed by Murua in SHARP program (Simulation of High Aspect Ratio Planes) using UVLM with a displacement based geometrically exact beam theory. [8]
Dreli ASWING	Some models are dedicated to high-aspect-ratio wing like Drela's program ASWING. This VFA conception tool combines a nonlinear isotropic beam formulation with an unsteady lifting line theory. [9]
UM / NAST. (University of Michigan / Nonlinear Aeroelastic Simulation Tool)	More recently, Shearer and Cesnik have developed a Matlab toolbox called UM/NAST. (University of Michigan/ Nonlinear Aeroelastic Simulation Toolbox) made up of a strain-based geometrically nonlinear beam formulation linked with a finite state two-dimensional incompressible flow aerodynamic theory proposed by Peters and al. [10]
Riberio in Matlab Aeroflex	Operating principle similar to UM / NAST. (University of Michigan / Nonlinear Aeroelastic Simulation Tool) [11]
NATASHA (Nonlinear Aeroelastic Trim and Atability of HALE Aircraft)	Because aeroelastic tailoring exploits the anisotropy of composite materials, a suited reduced order model must take this anisotropy into account. This capability resides in the Matlab toolbox proposed by Patil and Hodges called NATASHA (Nonlinear Aeroelastic Trim and Stability of HALE Aircraft) coupling an intrinsic beam formulation with Peters' theory. [12]

Details of comparison of available software for analysis of aerodynamical instabilities is presentaed in table 2.

Due to further analysis of available research environments, Unsteady Vortes Lattice Method and UM / NAST software were eliminated. The reason for the elimination of the software was the inability of modeling of aircraft specified for the design assumptions. This software focuses on the analysis of vibrations on the basis of moving elements, such as dragonfly wings.

After installing NATASHA, SHARP and Matlab Aeroflex software, difficulties were found in the operation of SHARP software, and due to that fact it was decided to opt out of this program. The NATASHA program has been eliminated because of low intuitiveness and ease of use.

Having analysed available software in this way, Matlab Aeroflex was selected for the next stage of analysis of the designed ship.

Table 2. Comparison of software for aerodynamical instabilitiesanalysis.

Program	Environment	Accuracy	Proposed confirmation of the result	Licence	Ease of use	Aerodynamic excitation flutter
Unsteady Vortex Lattice Method	Author’s	Very high	Wind tunel	Free for students	good	no
Program SHARP	Author’s	high	Numerical	Free for students	good	no
ASWING	Mat-Lab	high	Numerical	Free for students	sufficient	yes
UM / NAST.	Mat-Lab	high	Wind tunel	Free for students	sufficient	yes
Riberio in Matlab Aeroflex	Mat-Lab	Very high	Wind tunel, numerical	Free for students	good	yes
NATASHA	Mat-Lab	Very high	Wind tunel	Free for students	sufficient	yes

4. Analysis based on an detailed virtual 3D model

This type of analysis consists in generating a 3D model of the designed aircraft, and exactly all its parts together with the associated type of materials and methods of fastening between them. This method allows determining the possibility of flutter phenomena with very high accuracy. This type of analysis allows testing under different flight conditions of the designed aircraft, and hence for different forces acting on it.

The problem of this analysis is the need to use detailed model the whole structure so it is intended to use in the last phases of design. It results in extended time of the whole analysis and increase of hardware requirements necessary to perform the given coupled aerodynamical together with stress–strain analysis [6].

5. Analysis based on an accurate physical model of the designed aircraft

The last type of analysis is to determine the probability of flutter on the basis of a scalable model of the designed aircraft or part that is exposed to this phenomenon. The model is exposed to load conditions that were determined in previous analysis steps. Usually this type of test is performed in wind tunnels or on testing platforms adapted to test a specific part of the aircraft. This analysis can also be based on observation of an existing aircraft in which the part necessary for testing has been installed. At this stage of work, prototypes of aircrafts are usually built, which are then flown over the entire range of parameters for which they were tested numerically. It is important that at this stage of research the safety factors of the aircraft are not taken into account, and its parameters are checked experimentally in extreme conditions [8], [9]. Research is usually finalized with detailed flight testing of prototypes.

6. Analysis of designed UAV process

The aircraft design process is iterative. After the first market analysis preliminary technical, economic and environmental impact assessments are then carried out. This stage usually ends with the formulation of technical and economic requirements [10], [13].

The next stage inculdes the conceptual design, also called the feasibility study, which defines the basic parameters of the new concept. There are also drawings showing its appearance and arrangement of the device. Mass distribution, aerodynamic properties, stability, performance and loads are further analyzed. The structure is designed and tested. Finally, costs are analyzed. All these analyzes are carried out in the absence of very necessary accurate information, so they should be carried out by the most experienced designers.

This process is repeated many times. Usually, in each subsequent iteration, designers learn more and more about the new aircraft and bring its properties closer to the assumed ones.

Then we proceed to the implementation of the initial design, which aims to verify the assumptions adopted at the conceptual design stage and determine the solutions used.

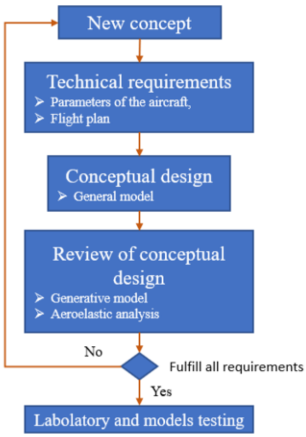

Figure 2. Algorythm of the presented aircraft analysis process. Generative model.

In order to clearly define the way or ways that were used during work on the solution of the presented problem, it was necessary to understand the work pattern when designing similar aircraft. This scheme is presented in the pictrue (see Figure 1). During work on a specific issue, the focus was on the first three steps with a feedback (see Figure 2). The problem, however, is the combination of the results of the analysis carried out with the preliminary data to the project. At the stage of such an early analysis, it is not possible to combine data with results and introduce automatic change of assumptions.

One of the methods to deal with this problem is to automate the design process by applying Generative Modeling. It involves building associative CAD models in the CAD system environment. Model features are controlled through identified relationships and design knowledge.

The construction of generative models consists in enriching the usual geometric CAD model with design and design knowledge introduced into the system using various forms of its representation, such as:

- Parameters - defined by numerical or descriptive values,
- Formulas - the most common mathematical dependencies,
- Rules and reactions - used e.g. for the automatic selection of standardized parameter values or parameters that the constructor reads from charts or tables in traditional design,
- Check - by which the model user may be notified in the event of failure to comply with certain conditions or exceeding certain design restrictions,
- Design tables and their configurations - enabling you to control the activity of sets of multiple parameters,

- Knowledge templates - which are a form of knowledge management and sharing.
- To perform more complex design calculations, you can use the internal capabilities of the CAD system as well as external software such as Excel or MATLAB / Simulink.

The "Riberio in Matlab Aeroflex" is selected for preliminaryaeroelastic analysis. This software allows for very quick structure analysis and helps determine its critical points. This software is written in the MATLAB environment which enables very large modifications of model assumptions and test conditions [11], [15].

7. Twin stratos, High Altitude, Long Endurance Unmanned Aerial Vehicle (HALE UAV)

Figure 3. Designed HALE UAV.

For the purpose of analyzing a specific aircraft (see Figure 3), an analysis of its parameters was performed. All variables necessary for calculations were pre-determined, such as the lenght of the wings, area of the wing, wing profile, average wing chord, etc. This was the determination of the parameters necessary to perform the first step in the design algorithm of this ship (see Figure 2).

At this stage, a preliminary sketch of the aircraft was created along with the assumed rear tail system. It was assumed that the aircraft would be a double-hull structure with a constant chord wing between the fuselages. Due to the flight mission plan and tasks to be performed by a given aircraft, the flight altitude, speeds and payload were assumed.

After determining the range of parameters included in the analysis. Next stage requires the use of preliminary calculations of loads, lift and resistance as well as structural adjustment.

The wing profile with its center of gravity is shown in Figure 4. Due to the possibility of unfavorable effects of the flutter in these elements, it is necessary to carry out a more detailed analysis of the given elements.

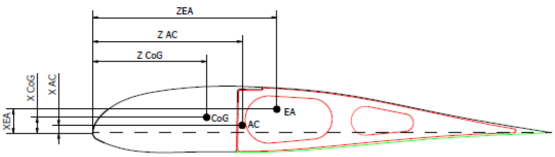

Figure 4. Position of elastic axis, center of gravity and aerodynamic center in the wing crosssection [12].

To increase the accuracy of the analysis and confirm or eliminate this hypothesis, the wings were analyzed using the Aeroflex environment [14].

Initial assemblies were included into the previously prepared environment and then all parameters were optimized for the intended flight altitude and mission objective [16]. Due to the difficulty of modeling the double-hull system in a given environment, the system was simplified and only the parts of the aircraft that showed the possibility of the flutter phenomenon were tested.

Both hulls, tail and part of the wing connecting the hulls were omitted. It has been fitted with a profile and chord to the results of the analysis and optimization of the outer wing [17].

The pictures below show the maximum displacements obtained for an example which has the flutter has been prepared (see Figure 5), and the designed and optimized aircraft. For an accurate presentation of the optimization process, the figure below shows the wings for which the average chord of the wing was changed (see Figure 6).

The change in the average wing chord, and more precisely the extension of this parameter, allowed to reduce the vibrations until this phenomenon is completely stopped. An analysis was carried out for ten different lengths of average wing chord. Figure 6 shows results of displacement of the designed wing tip for 10 values of length of the average wing chord.

In this way it was determined that for the designed aircraft the flutter phenomenon occurs for an average chord lenght from 1 meter to 1.2 meter. Other parameters remained unchanged. Due to this study, it was determined that the designed UAV does not show flutter tendencies after fulfilling the assumption that the average chord of the outer wing with respect to the hull axis should be higher than 1.3 meters. In designed UAV length of average chord is equal 1.45 meters.

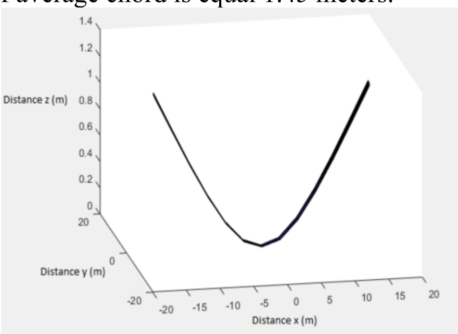

Figure 5. Example with flutter.

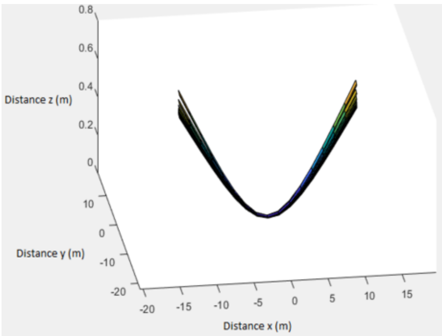

Figure 6. Optimization process desplacements.

The most important results of the analysis are presented in the figures. The results of the wing in which the flutter phenomenon occurs (see Figure 7) were compared with the results of the wing of the designed aircraft (see Figure 8), for which the optimization of the average chord of the wing was carried out.

Comparing the obtained results, it can be clearly stated that the flutter phenomenon should not occur in the designed structure after numerical optimization.

Due to another software limitation, we cannot simulate a linear speed change. This would require specifying a very large number of speeds for which the object would be examined, and so the initial test speed would always be zero.

The optimized design of the wing allowed the selection of parameters in such a way that even a very large change in the force acting on the wing did not introduce them into self-excited vibrations. As it can be seen in the Figure 8. Wing tip displacement stabilized automatically, even though its initial state was air pressure at 0 [km / h] and at one moment it was increased to 100 [km / h]. Because of this change in speed, we can observe a large wing tip displacement stroke that occurs during the first five seconds of the test. Then the structure stabilizes itself at a 0.5 meter displacement of wing tip.

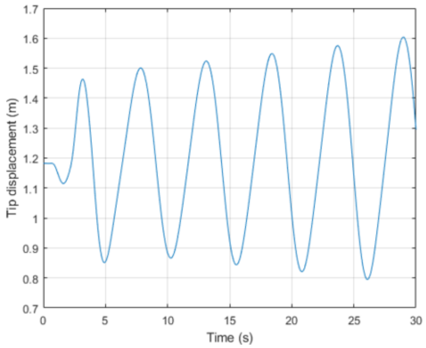

Figure 7. Example of flutter wing tip vibrations altitude.

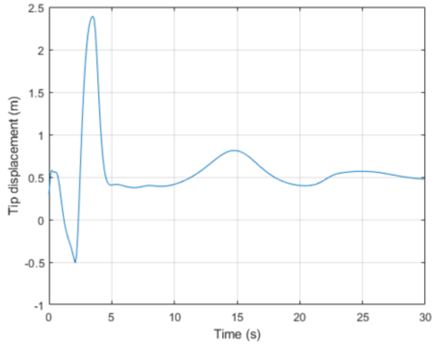

Figure 8. Designed plane wing tip vibrations altitude.

The tested structure shows the ability to very well damp vibrations very well.

The analysis allowed for significant changes to be made to the design of the planned aircraft. The next stage of work related to the described project requires to make a scaled model of the aircraft and check the results of calculations in an experimental way.

8. Discussion and conclusions

Unmanned aerial vehicles of this type can perform many days of missions that would be very difficult and expensive to perform by a human. The technology being developed will allow the study of very high layers of the atmosphere and the development of accurate maps of air currents at high flight altitudes.

The analysis presented in the article allows errors to be excluded at a very early stage of aircraft design. The method is accurate enough to be able to make changes to improve the design.

Creating the presented method of analysis required the use of mechanical engineering based on the laws on which preliminary calculations, IT techniques and mathematical programs were performed, which simplified the analysis process and material engineering on the basis of which the initial properties of the structure were determined.

The problem of the presented analysis is the inability to model the exact properties of structure rigidity. All parameters are approximate and very accurate results cannot be obtained. In addition, it is not possible to design the initial velocity of the aircraft, which is modeling the air impact on the analyzed parts.

At the concept stage, the external shape including the UAV supporting structure was determined. All assumptions were used to perform initial calculations and necessary analysis.

For highly flexible structures, there is a need to verify aeroelastic phenomena at an early design stage. This allows you to reduce the defectiveness of the conceptual design.

Due to the need to integrate the presented analysis into the generative model, in this article have been presented methods easily to combine with model variables. The mass analysis carried out enables integration into the generative model.

The article presents methods of analyzing aeroelastic phenomena available for students. Becouse of the possibility of using the analysis results in the generative model, the Riberio in Matlab Aeroflex program was selected.

Due to the lack of a real model of the examined object, it is not known if the results are correct and require confirmation in a more advanced environment. The analysis confirmed the supposition that flutter phenomena may occur in the examined elements.

Acknowledgement

We wanted to express gratitude for SkyTech eLab company for providing documentation of the Twin Stratos UAV project for research purposes.
Co-financed by the European Union through the European Social Fund (grant POWR.03.05.00-00-Z305).

9. References

[1] A. Jałowiecki, W. Skarka, Generative Modeling in Ultra-Efficient Vehicle Design, *Advances in Transdyscyplinary Engineering*, Vol. 4, 2016, pp. 999-1008.

[2] A. Jałowiecki and W. Skarka, Generative Modelling Technique Application for Unfold Surface Designs, *Advances in Transdyscyplinary Engineering*, vol. 7, 2018, pp. 674-683.

[3] W. Skarka and T. Neumann, New Methods of Designing Stamping Dies Assemblies by Using Generative Models, *Advances in Transdyscyplinary Engineering* Vol. 5, 2017, pp. 456-463.

[4] W. Skarka and D. Kadzielawa, Automation of Designing Car Safety Belts, *Advances in Transdyscyplinary Engineering,* Vol. 5, 2017, pp. 1041-1048.

[5] B. Kirsch, O. Montagnier, E. Benard, T. M. Faure, Computation of very flexible high-aspect-ratio composite wing flutter speed using optimised open source solver, *53rd 3AF International Conference on Applied Aerodynamics,* 2018, https://hal.archives-ouvertes.fr/hal-01780180/document.

[6] Z. Wamg, P. C. Chen and D. D. Liu, Nonlinear-Aerodynamics/Nonlinear-Structure Interaction Methodology for a High-Altitude Long-Endurance Wing*, Journal of Aircraft,* Vol. 47, 2010, pp. 556-566.

[7] M. Drela, ASWING 5.97 User Guide 2012, Accessed 01.11.2019. [Online]. Aviable: www.web.mit.edu/drela/Public/web/aswing/aswing_doc.txt

[8] W. Su, J. Zhang, C. E. S. Cesnik, Correlations between um/nast nonlinear aeroelastic simulations and experiments of a cantilever slender win, *Chinese Journal of Aeronautics*, Vol. 27, 2013, www.researchgate.net/publication/268420631_Correlations_between_UMNAST_Nonlinear_Aeroelastic_Simulations_and_Experiments_of_a_Cantilever_Slender_Wing, Accessed 01.11.2019.

[9] F. L. C. Ribeiro, P. Pagilione, R. G. Annes da Silva and M. Santiego de Sousa, Aeroflex: a toolbox for studying the flight dynamics of highly flexible airplanes, *VII Congresso Nacional de Engenharia Mecânica*, São Luís - Maranhão - Brasil 31 de julho a 03 de agosto.

[10] Z Sotoudeh and D. H. Hodges, Valitation Studies for Aeroelastic Trim and Stability Analysis of Hihly Flexible Aircraft, *Journal of Aircraft*, Vol. 47, 2010, pp. 1240-1247.

[11] T. E. Fritz and L. N. Long, Object-Oriented Unsteady Vortex Lattice Method for Flapping, *Journal of Aircraft*, Vol. 41, 2004, pp. 1275-1290.

[12] K. Eskandary, M. Dardel, M. H. Pashaei and A. M. Kani, Effects of Aeroelastic Nonlinearity on Flutter and Limit Cycle Oscillations of High-Aspect-Ratio Wings, *Applied Mechanics and Materials*, Vols. 110-116, 2012, pp. 4297-4306.

[13] W. Chajec and A. Dziubiński, Modal approach in the fluid-structure interaction applied to aerodynamic flutter analysis, *Polish Congress of Mechanics & Computer Methods in Mechanics*, 2015. DOI: 10.13140/RG.2.2.26005.12000

[14] A. Alsahlani and T. Rahulan, Composite Structural Analysis of a High Altitude, Solar Powered Unmanned Aerial Vehicle, *International Journal of Mechanical Engineering and Robotics Research*, Vol. 6, 2017, pp. 71-76.

[15] B. N. Goud, G. S. Sathyanarayana and S. S. Babu, Dynamic Aero elastic (Flutter) Instability Characteristics of an Aircraft Wing, *International Journal of Engineering and Innovative Technology*, Vol 4, 2015, pp.114-120.

[16] L. Liu, T. Kim and K. L. Lai, Efficient Analysis of HALE Aircraft Structure for Static Aeroelastic Behavior, *Journal of Aerospace Engineering*, 2016, Vol 30, 04016075.

[17] Rajesh, M. Kumar, G. Prasad, Flutter Analysis on an HALE UAV- Morphing Wing, *International Journal of Software & Hardware Research in Engineering*, Vol. 3, 2015, pp. 58-65.