Investigation on Forced Vibration Behavior of WIG Craft Main Wing Structure Excited by Propulsion System

Changduk Kong, Jaehuy Yoon, Hyunbum Park
Department of Aerospace Engineering, Chosun Universtiy
375 Seosuk-dong, Dong-gu, Kwangju, Rep. of Korea
Cdgong@chosun.ac.kr

Keywords: WIG craft, Propulsion system, Forced vibrations

Abstract

Previously study on structural design of the main wing of the twenty-seat class WIG (Wing in Ground Effect) craft. In the final design, three spars construction was selected for safety in the critical flight load, and the Carbon-Epoxy material was selected for lightness and structural stability. In this study, the forced vibration analysis was performed on the composite main wing structure of the twenty-seat class WIG craft with two-stroke pusher type reciprocating engine. The vibration analysis based on the finite element method was performed using a commercial FEM code, MSC/NASTRAN. Excitations for the frequency response analysis were assumed as the H-mode (horizontal mode), the V-mode (vertical mode) and the X-mode (twisted mode) which are typical main vibration modes of engine. And excitations for the transient response analysis were assumed as the L-mode (longitudinal mode) with the oscillating propeller thrust which occurs in operation. According to the result of forced vibration analysis, structural design was modified to reduce the vibrations.

1. Introduction

Recently, various kinds of high speed maritime transportation systems using WIG(Wing In Ground Effect) have been developed in the world.[1] The WIG flight craft has a specific behavior that its wing can enhance the lift by Wing-In-Ground-Effect between the wing and the surface if it may fly near by land or sea water surface. So the wing of WIG craft structure is relatively larger than the conventional aircraft wing to obtain the WIG effect. The WIG crafts have been mostly developed by Russia. Also several research works have been performed in Rep. of Korea.

Structural design and analysis of the main wing for a small scale WIG craft was previously performed by C. Kong. et al.[2] The skin-spar structure with a urethane foam sandwich was adopted for improvement of lightness and structural stability, and the carbon/epoxy composite was selected as the major structure materials because of high strength and stiffness. Structural design loads were estimated through critical flight load case study.

In this study, the forced vibration analysis was performed on the composite main wing structure of the twenty-seat class WIG craft with two-stroke pusher type reciprocating engine. The vibration analysis based on the finite element method was performed using a commercial FEM code, MSC/NASTRAN. Excitations for the frequency response analysis were assumed as the x-mode(longitudinal mode), the y-mode(lateral mode), the z-mode(vertical mode) and three twisted modes which are typical main vibration modes of engine. The engine was assumed as a rigid body which can generate the thrust of 1000hp(horse power) at maximum rpm of 7000. The unit harmonic load was applied at each mode to excite the engine. And excitations for the transient response analysis were assumed as the x-mode with the oscillating propeller thrust which occurs in operation. When an aircraft is maneuvered in the air, propeller cyclic loading can be presented as the sine pulse load due to the gyroscopic effect and the side slip motion. Thus, the sine pulse thrust may excited the wing with the direction of the center of propeller hub having propeller rotational frequency, and 2% propeller thrust rate of change was applied to the excitation thrust for considering the flight conditions. According to the analysis results, structural design was modified to avoid resonance possibilities and reduce vibration.

2. Structural Design

2.1 Design Requirement

The maximum speed of the study WIG Vehicle is 170km/h and the total weight is estimated as 8.5 ton with 2 ton payload including passengers. Table 1 shows the specification of the small scale WIG vehicle as a target in this study, and Fig. 1 shows the 3-D CATIA model of the whole aerodynamic configuration.

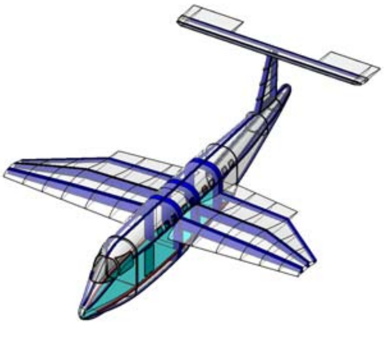

Fig. 1, 3-D CATIA Model of Whole WIG Craft

Table 1, Specification of A Small Scale WIG Craft

Design requirement	
Crusing speed	150km/h
Maximum speed	170km/h
Gross weight	8.5ton
Engine thrust	1000Hp×2
Aerodynamic configuration	
Length	23.5m
Height	7.75m
Wing area	$108m^2$
Wing span	20.4m
Target weight of wing	383kg

2.2 Structural Design and Analysis

The preliminary structural design was performed by the netting rule and the rule of mixture. Through stress analysis results for structural safety by Tsai-Wu failure criterion and structural stability by buckling analysis, it was found that the upper skin between the front spar and the rear spar was unstable. In order to improve the unstable skin structure, several design modifications were performed. The final structural configuration was fixed through several repeated design modifications and analyses. In the final design, the middle spar and the foam sandwich skin structure and webs were added. And three spar construction was adopted for the main wing and through design modification the structural safety and stability of the final design feature was confirmed. Table 2 shows structural analysis result of the modified main wing and Figure 2 shows the structural design modification procedure of the main wing applied to this study.

Table 2, Structural analysis results of the finally modified main wing

Analysis result		
Max. Stress [Mpa]	Ten.	114
	Com.	120
Max. Disp. [mm]		93.4
First buckling load factor		2.78
Designed wing weight		351.4

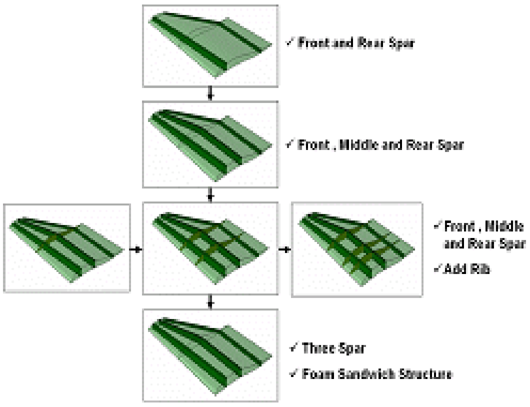

Fig. 2, Flow of design modification

3. Forced Vibration Analysis

3.1 Excitations

Excitations for the frequency response analysis were assumed as the x-mode (longitudinal mode), the y-mode (lateral mode), z-mode (vertical mode) and the three twisted modes which are typical main vibration modes induced by the engine. The engine was assumed as a rigid which can generate the thrust of 1000hp(horse power) at maximum rpm of 7000 and the unit harmonic load was applied at each mode to excite the engine.

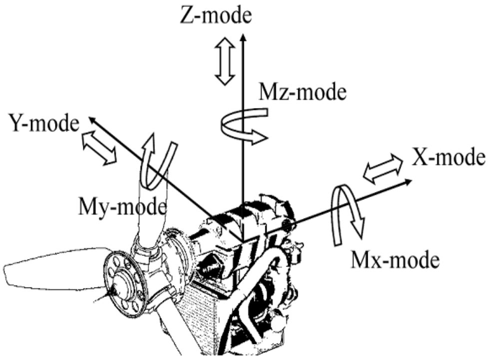

Fig. 3, Definition of vibration modes

Excitations for the transient response analysis were assumed as the x-mode (longitudinal mode) with the oscillating propeller thrust which occurs in operation. When an aircraft is maneuvered in the air, propeller cyclic load can be presented as the sine pulse load due to the gyroscopic effect and the side slip motion. Thus, the sine pulse thrust may excited the wing with the direction of the center of propeller hub having propeller rotational frequency, and the 2% propeller thrust rate of change was applied to the excitation thrust for considering the flight conditions. Figure 4 shows the propeller thrust of the engine at each flight speed with the following relationship.

$$T = \frac{\eta_p \cdot HP \cdot 550}{V} \qquad (1)$$

Where T = excitation thrust, H.P = engine horse power, η_p = propeller efficiency coefficient, V = velocity.

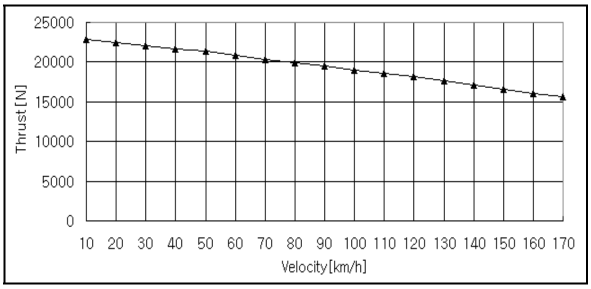

Fig. 4, Thrust estimation of the twenty-seat class WIG craft

3.2 Normal Mode Analysis

The normal mode analysis must be firstly performed for the forced vibration analysis. In this study normal mode analysis was performed until 300th modes for the accuracy of the next vibration analysis of which frequency and transient FEM analysis. As the result, it indicates that natural frequency was 15Hz at the first vibration mode and 278Hz at the last vibration mode. Figure 5 shows natural frequency at each mode number between 1st and 25th mode numbers.

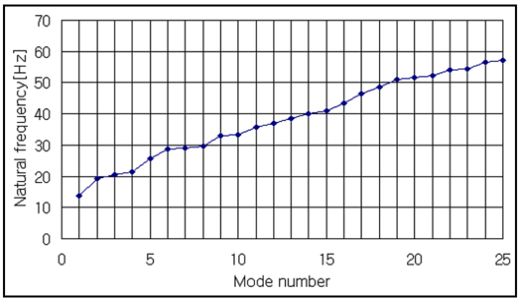

Fig. 5, Natural frequency at each mode number between 1st and 25th mode number

3.3 Frequency Response Analysis

The frequency response analysis was performed to find out resonance possibilities of the main wing. Between 0Hz and 300Hz frequencies was excited with unit harmonic load in order to consider propeller blades. The result shows that the highest vibration level was presented in x-mode and there may be a resonance possibility around 180Hz at the wing root measuring point. And three twisted vibration modes at each axis generated very lower vibration levels than the other vibration modes. 180Hz frequency occurs at 40km/h flight velocity. Figure 6 shows frequency response spectrum at each translation vibration mode.

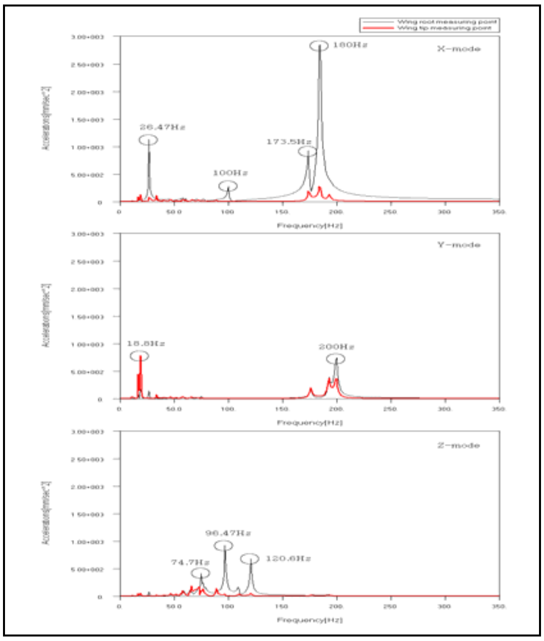

Fig. 6, Frequency response spectrum at each translation vibration mode

3.4 Transient Response Analysis

From the frequency response analysis results, excitation thrust of 10729N force and rotational frequency of 180Hz for 50cyclic loading were applied to consider 40km/h flight speed condition. The result indicate the acceleration level of 18547mm/sec^2 at the wing root measuring point and the displacement level of 0.03mm at the wing root measuring point. Figure 7~8 show transient acceleration and displacement response spectrums at 40km/h velocity in the z-direction.

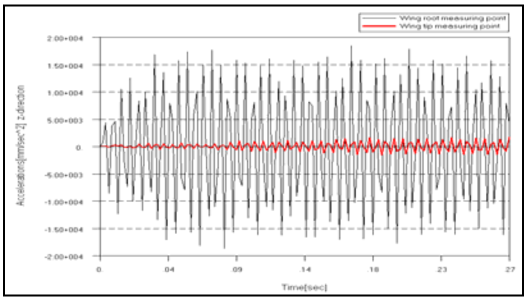

Fig. 7, Transient acceleration response for 50cyclic loading in 40km/h

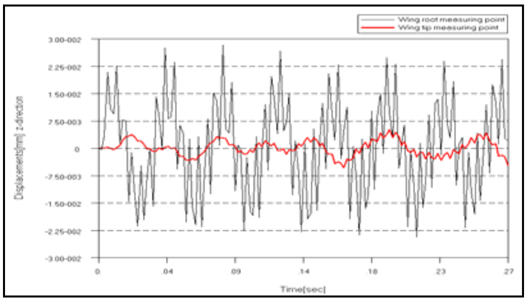

Fig. 8, Transient displacement response for 50cyclic loading in 40km/h

Conclusion

This study investigated on forced vibration behavior of the main wing for a small scale WIG craft. According to analysis results, it was found there were resonance possibilities around 180Hz in the x-mode. When the WIG craft is operated at 40km/h speed, it was calculated that the acceleration levels were 18547mm/sec^2 and the displacement levels were 0.03mm at the wing root measuring point by the propeller thrust excitation. However, because these acceleration levels are low and resonance possibilities can be avoided by controlling the operation conditions. It was confirmed that the designed wing has structural safety from vibrations.

References

1) Nikolai Kornev, Konstantin Matveev, “Complex Numerical Modeling of Dynamics and Crashes of Wing-In-Ground Vehicles”, AIAA2003-600.
2) C. Kong. et al., “Structural Design on Wing of a Small Scale WIG Vehicle with Carbon/Epoxy and Foam Sandwich Composite Structure”, 16th ICCM, 2007.