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DEVELOPMENT OF AN UAV WITH A VARIABLE-SPAN MORPHING WING

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Abstract: Morphing concepts for Unmanned Aerial Vehicles (UAVs) have been a significant topic in recent aerospace research field. The morphing wing is a bird-like wing and one concept of morphing is to change the wing configuration to accommodate multiple flight regimes. A variable-span morphing wing (VSMW) is designed to change its wing span for various flight conditions to reduce drag or increase maneuverability. The wing area and the aspect ratio of the VSMW increase as the wingspan increases. Total lift increases while the induced drag is reduced, whereas the wing root bending moment increases. Thus it requires a larger bending stiffness of the wing structure. The purpose of the present study is to investigate the aerodynamic characteristics and structural stability of a VSMW. Aerodynamic, structural, and aeroelastic analyses of a VSMW are performed by using AVL and MSC/NASTRAN, respectively. A semi-monocoque concept without front and rear spars is proposed to build a VSMW. Based on this concept a VSMW wing and its actuating mechanism are designed, fabricated, and tested. The developed VSMW is applied to an UAV and its flight test is performed to verify its performance and structural stability.

1 INTRODUCTION

Morphing concepts for aerial vehicles, particularly Unmanned Aerial Vehicles (UAVs), have been a significant topic in recent aerospace research. The “morphing wing” is a bird-like wing that has the ability to adapt to accommodate multiple flight regimes or to obtain better flight performance. A number of studies investigating morphing concepts have been performed over the past decade.

The morphing concept can be categorized into two classes: planform morphing and control morphing. The former changes the shape of an aircraft for various objectives and generally includes a variable span [1,2], variable sweep angle, variable dihedral angle, variable wing-area, and variable shape fuselage. With control morphing, an aircraft can gain control force for maneuverability by changing the wing twist [3], airfoil camber [4] and other elements of the wing instead of using a conventional control surface such as an aileron, flap, rudder, or elevator. Camber modification is carried out to earn the desired lift without discontinuity of control surfaces, and the torsion of the wing changes the twist angle of the wing to enhance lift and reduce drag. A wing that can perform continuous modifications during its operation does not have extreme turbulence around it. Hence, certain aerodynamic advantages, including delayed separation, decreased wakes, reduced drag, and increased lift, can be obtained [5].

A variable-span morphing wing, as shown in Figure 1, is designed to change its wing span for various flight conditions to reduce drag. As a result of increasing the wing span, the aspect ratio and wing area increase and the spanwise lift distribution decreases for the same lift. Thus, the drag of the morphing wing decreases and, consequently, the range of the aerial vehicle is increased. Unfortunately, the wing-root bending moment (WRBM) can be increased considerably due to the increase of the wing span. Therefore, not only the aerodynamic characteristics but also aeroelastic characteristics should be investigated in the design of the variable-span morphing wing.

The purpose of the present study is to investigate the aerodynamic characteristics and structural stability of a VSMW. Aerodynamic, structural, and aeroelastic analyses of a VSMW are performed by using AVL and MSC/NASTRAN, respectively. A semi-monocoque concept without front and rear spars is proposed to build a VSMW. Based on this concept a VSMW wing and its actuating mechanism are designed, fabricated, and tested. The developed VSMW is applied to an UAV and its flight test is performed to verify its performance and structural stability.

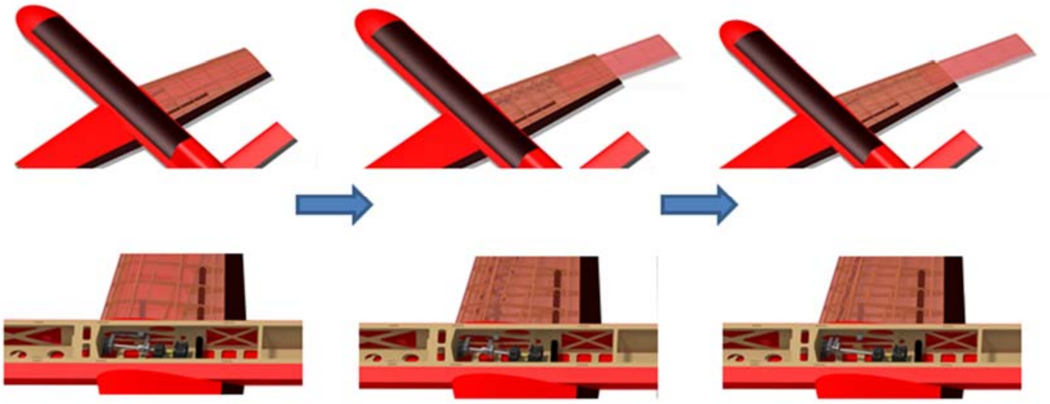


Figure 1: Concept of a Variable-Span Morphing Wing (VSMW)

2 ANALYTICAL METHODS

Aerodynamic Coefficients

The wing area and aspect ratio of a conventional wing are fixed. To increase the lift, the lift coefficient should be increased. This is accomplished via an increase in the angle of attack. Alternatively, a variable-span morphing wing can change its lift coefficient, wing area, and aspect ratio by changing its wingspan. Hence, we should compare the lifts of the conventional wing and the morphing wing instead of the lift coefficient, C_L, which requires a new definition for the aerodynamic coefficient. The definitions of the aerodynamic coefficients used in the present study are as follows:

$$C_L\bar{S} = \frac{L}{qS_C}, \; C_M\bar{S} = \frac{M}{qS_C}, \; C_D\bar{S} = \frac{D}{qS_C} \tag{1}$$

where, $\bar{S}\left(= S/S_C\right)$, S_C, and $q\left(= \rho V^2/2\right)$ are the area ratio, the area of the conventional wing, and a dynamic pressure, respectively.

Aeroelastic Equations

The aeroelastic equations for the wing structure can be written as

$$[M]\{\ddot{x}\} + [K]\{x\} = \{f\} \tag{2}$$

where, $[M]$, $[K]$, $\{f\}$, and $\{x\}$ are the mass matrix, stiffness matrix, aerodynamic force vector, and structural displacement vector, respectively.

For the static problem, such as divergence or aerodynamic deformation, Equation (2) can be written as

$$[K]\{x\} = \{f\} \tag{3}$$

In Equation (3), the aerodynamic force vector can be written as

$$\{f\} = \{f(x)\} + \{f_0\} \tag{4}$$

where, the first term, $\{f(x)\}$, is due to the wing deflections, and the last term, $\{f_0\}$ is due to the airfoil shape or the angle of attack.

Using the modal approach, Equation (3) can be transformed to the generalized coordinates of Equation (2) as

$$[GK]\{\eta\} = [\phi]^T\{f(x)\} + [\phi]^T\{f_0\} \tag{5}$$

where, $[GK]$, $\{\eta\}$, and $[\phi]$ are the generalized stiffness matrix, displacement vector, and the modal matrix, respectively. These quantities are defined as

$$\{x\} = [\phi]\{\eta\} \tag{6}$$

$$[GK] = [\phi]^T[K][\phi] = \left[\omega_i^2\right] \tag{7}$$

where $[GK]$ and $[\phi]$ can be obtained from the free vibration analysis of Equation (2).

The generalized aerodynamic influence coefficient (AIC) $\left[\bar{Q}\right]$ is introduced as follows:

$$[\phi]^T\{f(x)\} = q[\phi]^T[Q][\phi]\{\eta\} = q\left[\bar{Q}\right]\{\eta\} \tag{8}$$

Finally, the generalized static aeroelastic equations can be written as

$$[GK]\{\eta\} = q[\overline{Q}]\{\eta\} + [\phi]^T\{f_0\} \tag{9}$$

For a given dynamic pressure, Equation (9) can be solved iteratively to obtain the modal displacement $\{\eta\}$. Also, Equation (9) can be solved directly if $([GK] - q[\overline{Q}])$ is not singular and the wing displacement can be easily obtained from Equation (6).

Divergence is a static aeroelastic instability, and the divergence equations can be obtained from Equation (9). Ignoring the last term in the right-hand side of Equation (9), the divergence equations can be written as

$$\lambda_D\{\eta\} = [GK]^{-1}[\overline{Q}]\{\eta\} \tag{10}$$

where,

$$\lambda_D = \frac{1}{q_D} \tag{11}$$

The $\lambda_{Di}\,(i = 1 \sim n)$ can be obtained by solving the eigenvalue problem of Equation (11). Taking the largest positive value of the real eigenvalues, divergence speed V_D can be calculated by

$$V_D = \sqrt{\frac{2}{\rho\lambda_D}}$$

3 AERODYNAMIC CHARACTERISTICS

Aerodynamic Coefficients

Figure 2 shows the angle of attack required to produce the desired lift. As shown in Figure 2, the lift coefficient is linearly proportional to the angle of attack. Hence, to obtain the same lift, the conventional wing requires a larger AOA (angle of attack) than variable-span morphing wing.

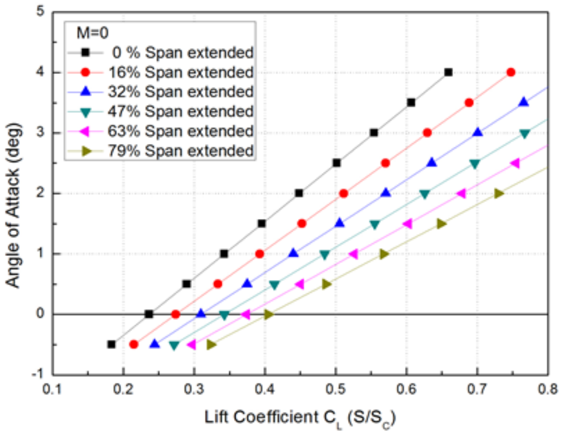


Figure 2: Desired lift vs. angle of attack

Figure 3 shows the required AOA vs. increase of span to obtain the lift coefficient of 0.4. As the span increases the required AOA decreases. Figure 4 shows the lift coefficient vs. drag coefficient. Total drag includes profile drag and induced drag. As the wing span increases the induced drag decreases but profile drag increases. As shown in Figure 4, the high aspect ratio (AR) wing has larger lift-to-drag ratio when lift coefficient is larger than about 0.35. Hence, it can be concluded that a high AR wing (span-extended) has better aerodynamic performance.

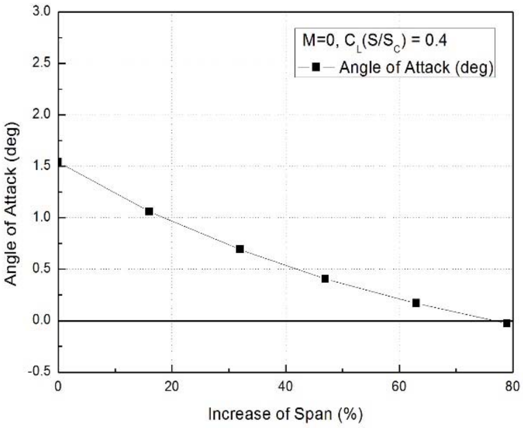


Figure 3: Increase of span vs. required AOA.

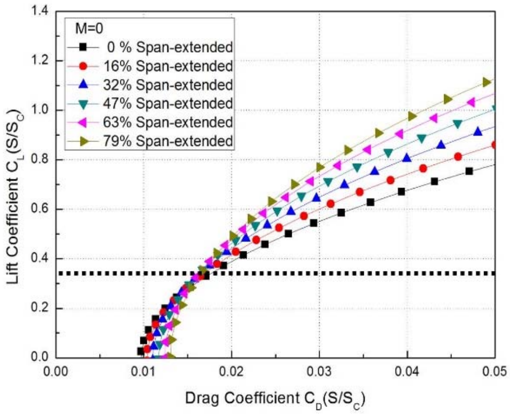


Figure 4: Drag coefficient vs. lift coefficient.

Wing Load Distributions

Figure 5 shows the lift distribution along the span of the wing for a Mach number of 0.0 and a lift coefficient of 0.4. For this flight condition, the angles of attack of the morphing wing are 1.54, 0.43, -0.25, and -0.75 degree for 0%, 26%, 52%, and 78% span-extended cases, respectively. The area under the lift distribution is equal to the total lift produced by the morphing wing. To obtain the same lift, the lift per unit span decreases as the wingspan increases. Figure 6 shows the bending moment distributions. The bending moment of the morphing wing increases considerably as its wingspan increases. As the wingspan increases, the contribution of the moving wing on the bending moment significantly increases although the spanwise lift decreases. Thus, the bending moment along the wingspan of the morphing wing is much larger than that of the conventional wing.

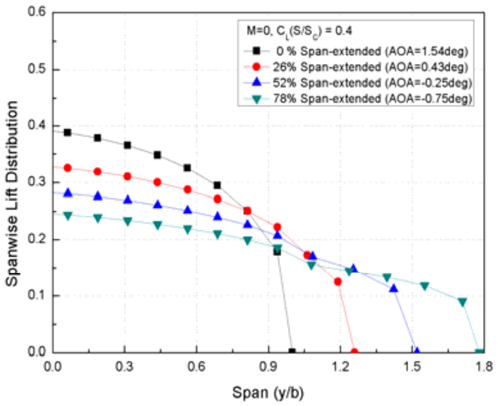


Figure 5: Spanwise lift distribution.

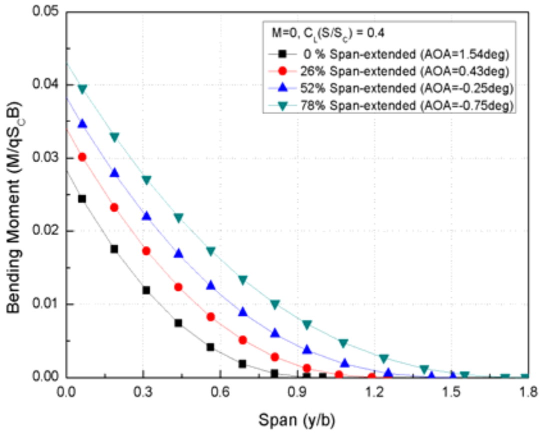
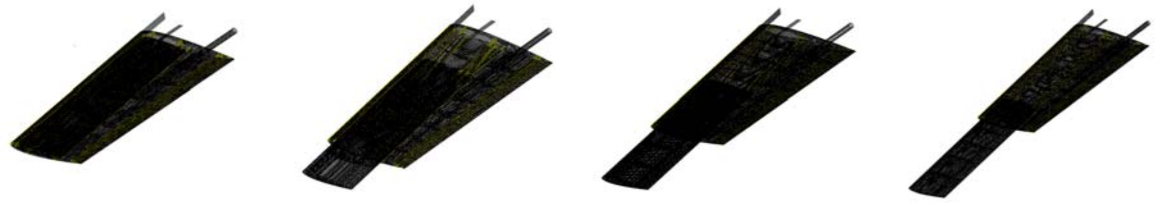


Figure 6: Spanwise bending moment distribution.

4 STRUCTURAL AND AEROELASTIC CHARACTERISTICS

Static Characteristics

The present VSMW has a semi-monocoque structure without any spar. All loads including bending, shear, and torsion are supported by stringers and skin. MSC/NASTRAN is used for FE modeling. Materials used for the wing are assumed to be isotropic. Figure 7 shows the finite element model of the VSMW wing for various span-lengths. Figure 8 shows the stress distribution of the VSMW. A load factor is assumed to be 3.0 for a static test. Von-mises stresses of 0%, 26%, and 52% span-extensions is less than yield stress. When span-expension is 78% Von-mises stress is close to the yield stress of skin at the root. Figure 9 shows the static test of a VSMW when the load factor is 3.0. Same as FE analysis, the skin fracture is observed at the leading edge root.



(a) 0% Span-extension (b) 26% span-extension (c) 52% span-extension (d) 78% span-extension

Figure 7: FE model of VSMW.

Figure 8: Static test of VSMW.

Aeroelastic Characteristics

Figure 9 shows the natural frequencies vs. increase of span. As a wing span varies the natural frequencies of the second bending and torsion modes varies considerably. Table 1 shows the results of the aeroelastic analysis of the VSMW. As the wing span increases both divergence and flutter speeds decreases considerably and the divergence speeds are less than the flutter speed for all span-extended cases. Therefore, it is important to investigate the divergence characteristics of a fully-extended VSMW.

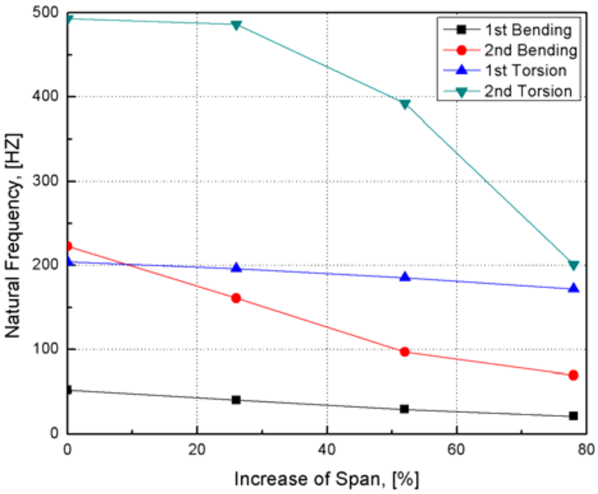


Figure 9: Natural frequencies vs. increase of span.

Span extension (%)	Divergence speed ratio	Flutter speed ratio
0	1	1.01
26	0.86	1.00
52	0.72	1.01
78	0.58	0.76

Table 1: Aeroelastic results of VSMW

5 BUILD AND FLIGT TEST OF VSMW

Based on the aerodynamic, structural, and aeroelastic analyses the UAV with VSMWs is designed and built. Figure 10 shows the schematic of a VSMW with its mechanism. A morphing mechanism to extend the outboard wing is designed and built using an electric motor and scissor-type mechanical linkages. Figure 11 shows the present UAV with VSMWs. Its specifications are presented in Table 2. The morphing UAV is propelled by electric motor and propeller, and LIPO batteries. In take-off and landing the VSMWs are fully-extended to obtain much lift and decrease its air speed.

Length (mm)	2,000
Wing Span (mm)	1,700 (conventional) 2,820 (fully extended)
Weight (kg)	8.7
Wing Load (kg/m^2)	17.1 12.0

Table 2: Specifications of present UAV with VSMW

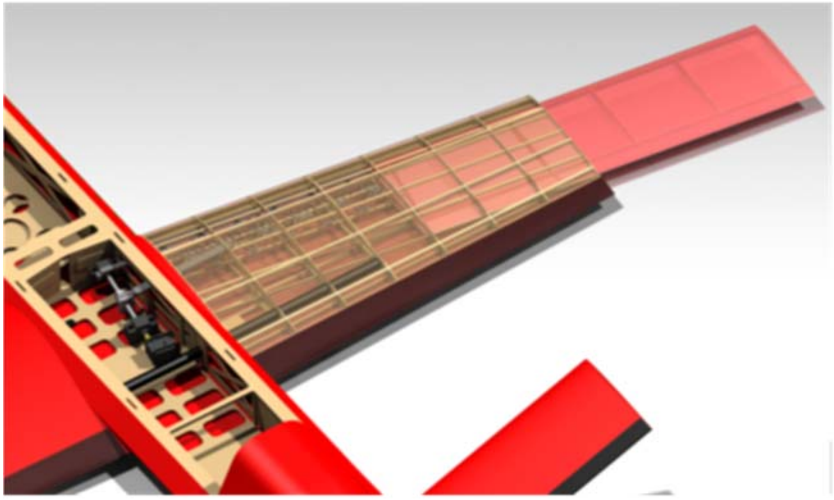


Figure 10: Schematic of VSMW and morphing mechanism.

Figure 11: UAV with VSMWs

The flight test is performed to verify the feasibility of an UAV with VSMW. It was manually and stably controlled to keep it air speed and attitude during extending its outer wing. Figure 12 shows the flight test results of the UAV. Although the flight test is not autonomous its flight is considerably stable. When the wing is fully extended its air speed is and the power used by the motor lower than those of retreated. No structural damages is observed during flight test as its structural stability is ensured by the analysis.

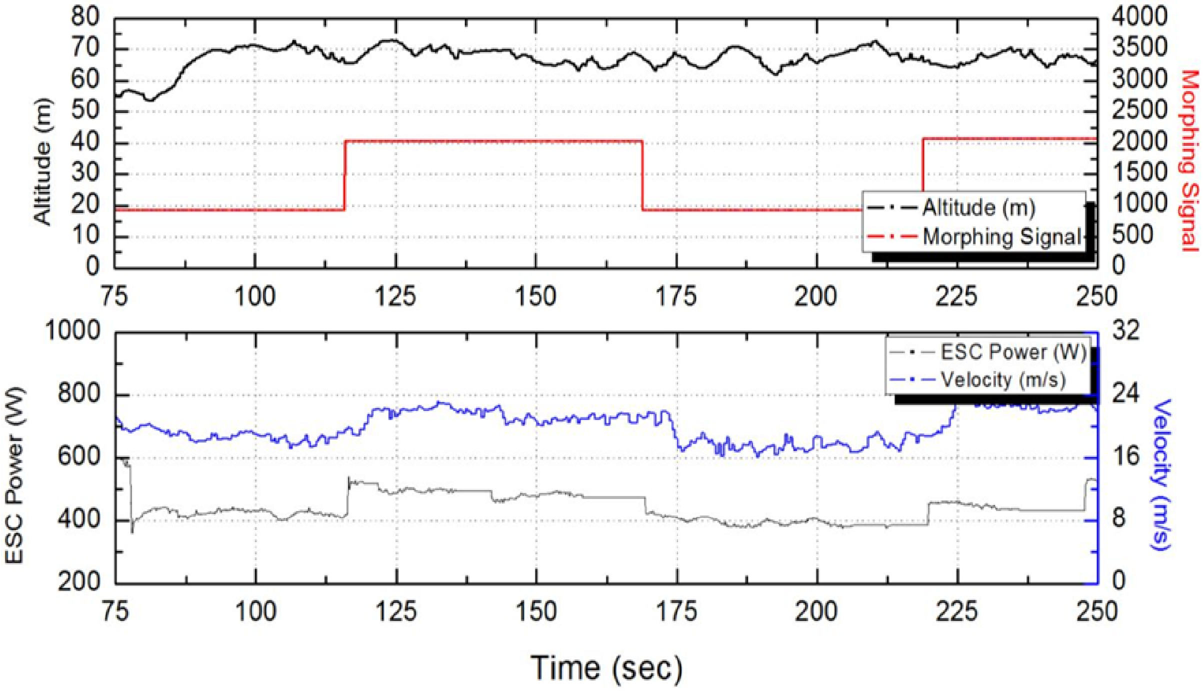


Figure 12: Flight test results of UAV with VSMWs

6 CONCLUSIONS

In the present study the aerodynamic characteristics are investigated by using AVL. The advantages and disadvantages of the VSMW are presented. A semi-monocoque structure design concept without spar is proposed for the VSMW. Structural and aeroelastic stabilities of the present VSMW are investigated and its static test is performed. Based on the present concept a VSMW wing and its actuating mechanism are designed, fabricated, and tested. The developed VSMW is applied to an UAV and its flight test is performed to verify its performance and structural stability and investigate the feasibility of the development of the VSMW.

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