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An experimental investigation of laminar separation bubble formation on flexible membrane wing

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HIGHLIGHTS

- Unsteadiness included in laminar separation bubble lead to complicated unstable deformations.
- Different vibrational modes observe due to laminar separation bubble.
- Separation bubbles cause to time-dependent variations on membrane vibration.

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ABSTRACT

In this study, fluid–structure interaction over a flexible membrane wing with aspect ratio (AR) of 3 at low Reynolds numbers was investigated experimentally. Smoke wire flow visualization technique was performed for analyzing time-dependent behavior of flow over this flexible membrane wing. Furthermore, time dependent deformation of flexible membrane wing was measured. It was clearly seen that the value of membrane deformation increased with increasing angle of attack. Moreover, it was stated that the size of laminar separation bubble (LSB) changed with time due to the unsteady flow characteristics of membrane wing. The unsteady behavior over the flexible membrane wing caused different deformation modes to form at different angles of attack. For the flexible wings with higher aspect ratios, the LSB was more dominant in the membrane wings at low Re numbers, and caused the membrane vibration to increase based on the angle of attack which the LSB started to be overpowering.

1. Introduction

In recent years, scientific surveys related to aerodynamics have been concentrated upon low Reynolds number aerodynamics, transition and laminar separation bubble and effects this bubble on aerodynamic performance owing to the improvement in wind turbines, micro air vehicles (MAVs) and unmanned aerial vehicles (UAVs) [1–6]. That is why it is seen that there is an increasing concern in the study of membrane wings.

Because of the strong viscous effects, flows in low Reynolds number regard to MAVs result in laminar-transitional, separated flow hindering lift generation [7]. Both experimental and numerical results of studies in regard to low Reynolds number aerodynamics demonstrate that flow has a susceptibility to separate because of the lower inertia forces compared to the comparatively higher viscous forces. In other respects, owing to this phenomenon and adverse pressure gradients encountered on airfoils, LSB is presumably to be formed [2,3,8].

Genç [9] investigated on unsteady aerodynamics over the cambered membrane wing. Acquired experimental results exhibited that membrane wing's camber having excessive length induced the separated shear layer. Due to this circumstance, coefficient of lift increased. Besides, wings with excess length indicated small separated regions because shear layer was closer to the wing surface, although camber of the wing raised. As a deduction, it was stated that unsteadiness included vortex shedding and tip vortices, and the coalescence of vortex shedding and tip vortices occasioned complicated unsteady deformations of membrane wings.

Bleischwitz et al. [10] presented ground effect on aeromechanics of membrane wings and observed that ground-effect caused to higher lift production and a constant low drag at low to moderate angles of attack for both flat plates or membrane wings. Ke et al. [11] studied on aeroelasticity for flexible oscillating wing and noticed that adopting new kind driving way would not have flutter problems for the oscillating wing and it could generate propulsive force. Osterberg [12] deduced that membrane wings ensured

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Nomenclature

AR	Aspect ratio
c	Chord length
DIC	Digital image correlation
E	Young's modulus, MPa
f	Frequency
LSB	Laminar separation bubble
Re	Reynolds number
St	Strouhal number
t	Time, s
U	Freestream velocity
y/s	Location of smoke wire
Z	Flexible membrane displacement
Z_{std}	Standard deviation of flexible membrane displacement

Greek letters

α	angle of attack, °
ρ_m	density of rubber latex sheet, g/cm^3

remarkable improvements in maximum C_L when comparing to a rigid wing under pitching conditions. Zhang et al. [13] stated that membrane wing ensured higher lift curve declination, stall-region lift and lift-to-drag ratio when comparing to the rigid flat plate. Song et al. [14] stated that membrane wings had maximum lift coefficients, higher lift declination and led to delay stall. Hu et al. [15] examined flexible membrane wings aerodynamics experimentally utilizing particular flexibility of skin in flapping flight. According to obtained results, flapping motion ensured remarkable aerodynamic advantages at unsteady flapping flight regime. Greenhalgh et al. [16] noticed that increasing excess length led to decrease angle of attack at which separation occurred. Wrist et al. [17] made comparison between aerodynamic features for silicone rubber MAV wings with cambered and flat frames. It was deduced that cambering the frames of wings raised aerodynamic efficiency comparing the flat frames. Lian et al. [18] described the membrane aerodynamic and suitable rigid wings under flight condition of micro aerial vehicles. They realized that membrane wing both delayed stall and what is more adapted to the unsteady flight environments.

Rojratsirikul et al. [19] investigated experimentally flow-induced vibrations of rectangular membrane wings with aspect ratio (AR) of 2. They conducted flow field and time-accurate measurements of membrane deformations. Deformations showed different vibration mode shapes as a function of the Re number and angle of attack. The membrane oscillations were observed in a chordwise two mode at higher angles of attack. Since the combination of tip and leading edge vortices caused a mixture of chordwise and spanwise vibrational modes. Moreover, they deduced that vortex shedding frequency of rigid wings emerged remarkably slight influence of aspect ratio even when it was as nominal as unity. Furthermore, Rojratsirikul et al. [20] studied about the effects of pre-strain and excess length of membrane in terms of unsteady fluid–structure interactions. They observed that airfoil with excess length ensured the largest strain and camber. Additionally, for the excess length airfoils, prelude of the wing vibration was detained to a higher angle of attack. In addition to this, with increasing angle of attack, both St number and mode number were disposed to diminish.

The purpose of this study is to survey flow over flexible membrane wings and the formation of separation bubbles occurring in the flow and effects of bubbles on the wing deformation. In this regard, aspect ratio of 3 (AR $=$ 3) flexible membrane wing was utilized and formation of separation bubble in the region of wing center at which tip vortices had no effect were investigated at different low Reynolds numbers and miscellaneous angles of attack.

2. Measurement procedure

The study was conducted in the wind tunnel in Erciyes University. The test section of wind tunnel is geometrically square. The size of tunnel is 500 mm by 500 mm consisting of optically transparent walls. Free-stream turbulence intensities of tunnel are 0.3% for maximum speed of 40 m/s and 0.7% for lowest speed of 5 m/s, respectively, [3,21,22] which are appropriate to perform experiments at low Reynolds numbers in order to determine separation and reattachment point, LSB and stall in accordance with Mayle, [23]. All the flexible membrane wings used in this study were designed in conjunction with 0.2 mm black latex rubber sheet which had Young's modulus (E) of 2.2 MPa, and density (ρ_{m}) of 1 g/cm^3 [20]. There was no pre-stress or excess length on latex rubber sheet. To this end, flexible material was glued to the airfoil-formed frame which was made of rigid stainless steel. As illustrated in Fig. 1, this rigid frame was manufactured for having a cross-section of airfoil shape.

2.1. Flow visualization experiments

In order to visualize flow, smoke wire technique was opted, since it was simple and reliable to conduct. A smoke-wire which was strained between the upper and lower tunnel walls was used for heating the machine oil and fluid for marking the streamlines to visualize flow in the tunnel. Adequate quantity of voltage was applied to smoke-wire that was coated with oil. The oil evaporated forming smoke lines in the tunnel. The smoke lines were fulfilled by this technique indicated the flow over the related airfoil and the flow phenomena such as laminar separation bubble or stall were made easily visible. Canon EOS-D1100 camera was used for capturing related images during experiments. The picture frequency of Canon EOS-D1100 camera was chosen as 30 frames per second. Reflection of images in tunnel's wall test section that was manufactured by plexiglass was the main problem. That is why camera and lighting arrangements were conducted thoughtfully to gain dark medium. As shown in Fig. 1, the location of smoke wire was designated as y/s, and the flow visualization experiments were conducted for two locations ($y/s = 0.4$ and $y/s = 0.1$) to indicate the effects of LSB and tip vortices. However, with increasing the Reynolds number, it gets difficult to capture a convenient image of streamlines and the image becomes blurred, because the filaments are quickly dissipated in the flow.

2.2. Evaluation of deformation

Deformations and displacements of flexible membrane wing were measured by means of Digital Image Correlation (DIC) system as illustrated in Fig. 2. In accordance with this purpose, deformation measurements of the AR $=$ 3 membrane wing were conducted by way of utilizing DANTEC Dynamics three-dimensional high-speed image correlation system (Q-450: the number of pixels was 1280 × 800) and DANTEC Al-11-BMB_9 × 9 was chosen as calibration target. Furthermore, frame rate was 1 kHz. Throughout the deformation measurements, 1000 frames were captured for each experimental case. This system captures successive images afterwards calculates the displacement over AR $=$ 3 flexible membrane wing by following the deformation of spots (Fig. 3) fulfilled to the surface of the AR $=$ 3 flexible membrane wing using a cross-correlation method. The minimum and maximum uncertainties of deformation measurement were ±0.030 mm at