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UNSTEADY AERODYNAMIC CHARACTERISTICS OF THE OSCILLATING AIRFOIL USING MSBS

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Abstract

This paper presents magnetic suspension and balance system (MSBS) based wind tunnel system for studying unsteady aerodynamic characteristics of the oscillating airfoil in low Reynolds number flow fields. Since MSBS can levitate and control the experimental model using magnetic forces, no mechanical apparatuses are required; thereby the unsteady aerodynamic characteristics without the support interferences can be identified. In this study, we measured the aerodynamic forces while the NACA 0015 finite wing model was oscillated under the condition of weak unsteadiness at pre-stall region using MSBS. The results showed that the lift coefficients had an increasing hysteresis characteristics as oscillating frequency increases.

1 Introduction

Unsteady aerodynamics in low Reynolds number flow fields, which lead to laminar separation and reattachment on airfoils, bring on complicated time-dependent characteristics such as dynamic stall, flutter and divergence as shown in Fig. 1 [1]. These are undesirable for small-scale aerial system such as micro aerial vehicles (MAVs). To avoid these undesirable effects and to provide appropriate design parameters, several experimental studies have been performed using wind tunnel such as measurement of the aerodynamic coefficient variation or visualization of the flow field under unsteady flow field [2,3]. However, the systematic studies on unsteady aerodynamics, especially for the finite wing in low Reynolds number flow fields which corresponds to MAVs, have been rarely reported until now.

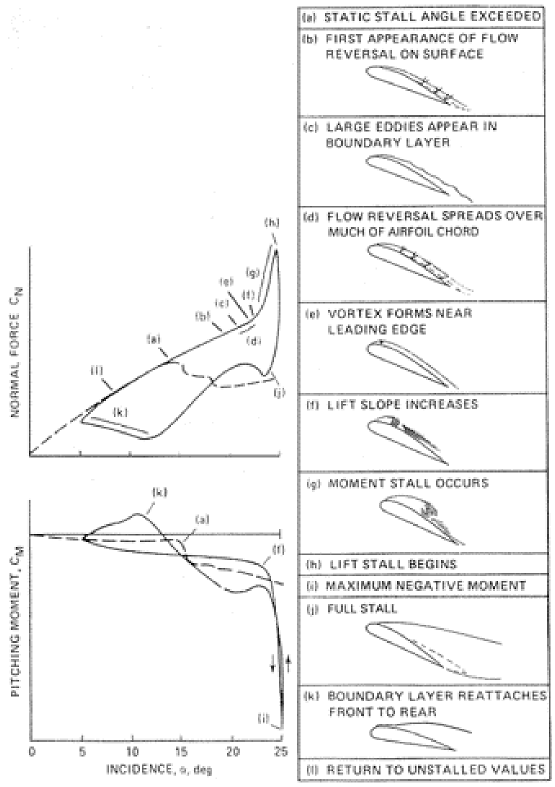


Fig. 1. Schematic of dynamic stall [1]

Moreover, in conventional wind tunnel testing, mechanical apparatuses to support and control the experimental model interfere with a precise measurement. For MAVs, this mechanical support interference has a considerable effect due to their tiny sizes and low flight speeds. In order to eliminate the interferences, applying magnetic suspension and balance system (MSBS) to wind tunnel test can be an effective solution. Since the MSBS can levitate and control the experimental model using magnetic forces, the mechanical supports are not required. The accurate aerodynamic forces can be measured using the additionally applied electric current to control the experimental model when the aerodynamic forces act.

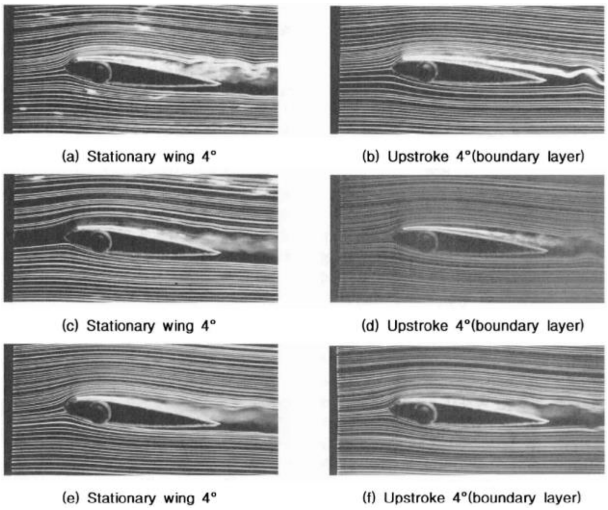


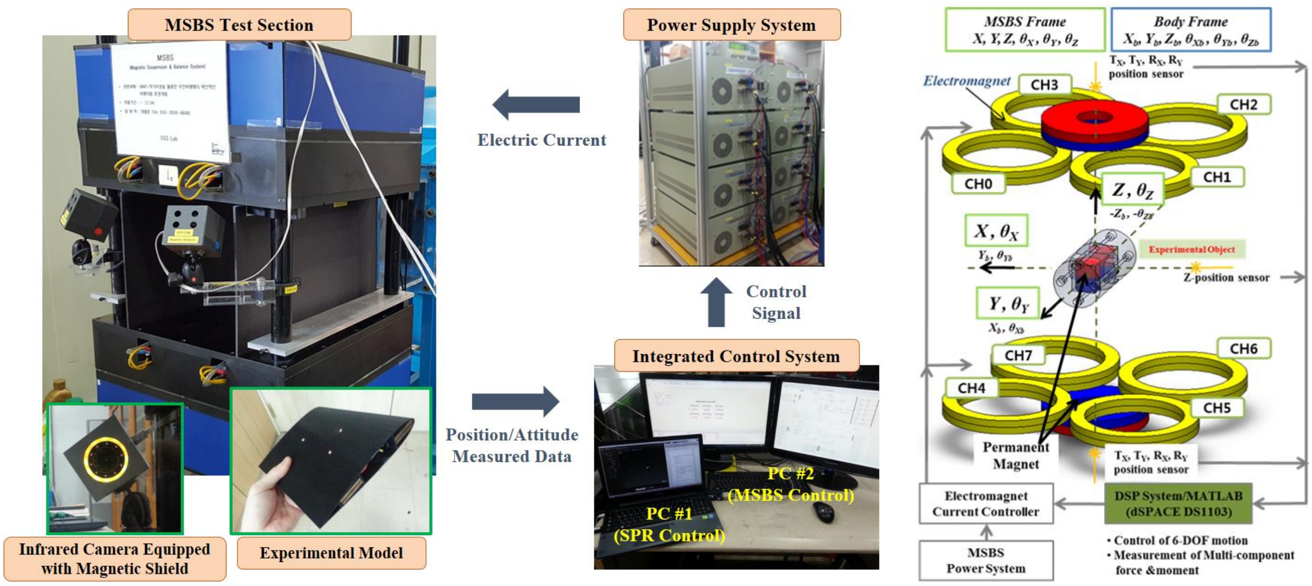
Fig. 2. Smoke-wire visualizations of boundary layer of stationary (a,c,e) and oscillating airfoil (b,d,f) at different Reynolds numbers [3]

From this aspect, we have developed and employed the MSBS to study unsteady aerodynamics. The developed MSBS-based wind tunnel system has the capability to measure accurate aerodynamic forces using electric current and high-precision positioning data of the model using vision-based positioning method. In this study, a finite wing model was magnetically levitated and oscillated under the condition of weak unsteadiness at pre-stall region in low Reynolds number. This MSBS-based wind tunnel system can be utilized to identify unsteady aerodynamic characteristics in low Reynolds number region.

2 Experimental Model and Methodologies

2.1 Magnetic Suspension and Balance System

The MSBS is a device that can levitate the experimental model using the principle of magnetic levitation. Since the MSBS is able to levitate the experimental model by controlling the magnetic field using its embedded electromagnets, the mechanical apparatuses for supporting and controlling the model are not required. Therefore, in comparison with conventional wind tunnel test, it is possible to measure more precise aerodynamic forces by excluding the mechanical support interference effect when applying MSBS to wind tunnel test.



(a) (b)

Fig. 3. Configurations of the KAIST 30cm magnetic suspension and balance system (MSBS)

From this aspect, several MSBS have been developed and utilized to wind tunnel test to study aerodynamic characteristics of the model itself without support interference effect, mainly focused on static cases until now, by measuring the aerodynamic coefficients or visualizing the flow pattern [4-7]. In addition, relatively easy re-positioning of the experimental model and simple dynamic testing procedure are other advantages of MSBS-based wind tunnel test [8].

Taking notice of the advantages stated above, KAIST has developed its own MSBS to study unsteady aerodynamic characteristics of the oscillating airfoil. Fig. 3 shows the overall configuration of 30cm MSBS developed by Smart Systems and Structures Laboratory at KAIST [9,10]. This MSBS is composed of two large permanent magnets, eight electromagnets with power supplies, stereo pattern recognition (SPR) position measurement system and control system with a digital signal processor board.

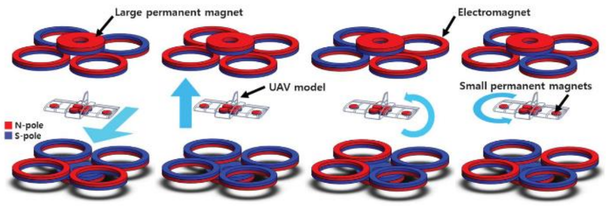


Fig. 4. Position and Attitude Control Method of the KAIST MSBS [9]

As shown in Fig. 3 (a), eight electromagnets generate the appropriate magnetic forces to control the experimental model by adjusting the magnitude and direction of the electric current. The pole arrangements of electromagnets to control the model are illustrated in Fig. 4. The MSBS control system generates the control signals for electromagnets based on proportional-differential (PD) control method using real-time position measurement data of the model. To acquire the high precision positioning data of the model for wide range in real-time without making mechanical contact, a stereo pattern recognition (SPR) system, which is a vision-based positioning system using images from synchronized stereo cameras, was applied. Two infrared cameras were mounted at both sides of the MSBS test section to take optical images for SPR system, as shown in Fig. 5.

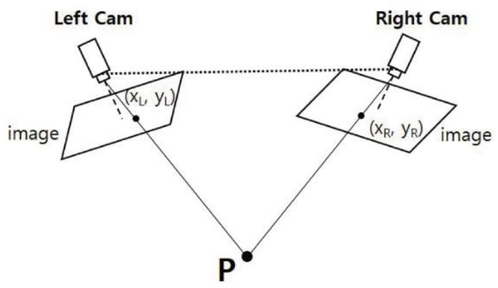


Fig. 5. Stereo Camera Images for Position Measurement in SPR System [11]

The MSBS has the test section size of 30cm x 30cm, and the model can be independently controlled for all the six degrees of freedom (DOFs), rapidly and accurately. From the performance evaluation, the finite wing model, which will be explained in section 2.2, could be controlled within 60mm for translational DOFs and 40deg for rotational DOFs. The mean error for step input response test in X, Y, Z, RX, RY, RZ directions were 0.043mm, 0.048mm, 0.088mm, 0.104deg, 0.040deg and 0.023deg, respectively, when the step input of 3mm for translational DOFs (X,Y,Z) and 3deg for rotational DOFs (RX, RY, RZ) were applied. The coordinate system for step input response test is shown in Fig. 6. Moreover, the MSBS has the capability to measure accurate aerodynamic forces, even for low Reynolds number region, using the additional current applied for controlling the model when aerodynamic forces act, and it was verified by conducting static wind tunnel test in Reynolds number of 3.2 and 6.4 x 10^4 [10].

In this study, we applied the developed MSBS to study unsteady aerodynamics in low Reynolds number flow fields, since this system was expected to provide enough controllable range for the model oscillation and to have capability of accurate aerodynamic force measurement. The detailed procedure for the experiment will be explained in section 3.

2.2 Experimental Model

Fig. 6 shows the magnetically levitated experimental model inside of the MSBS test section, which was developed to study unsteady aerodynamic characteristics of the oscillating airfoil. This model has finite wing shape with chord length of 160mm and aspect ratio (AR) of 1.2. The cross section shape of the model is NACA 0015 airfoil. High-resolution 3D printing using poly lactic acid (PLA) material was used to fabricate the model. After fabrication, the wet sanding procedure using ultra fine grit level sandpapers was conducted to make the surface smooth.

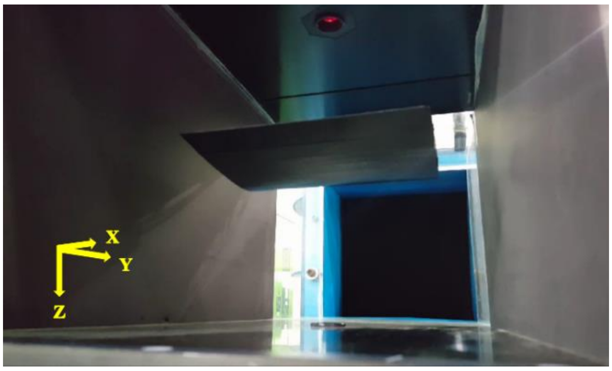


Fig. 6. Magnetic Levitation of the Finite Wing Model

Since the position and attitude of the model was controlled using magnetic forces generated by electromagnets of MSBS, this model was designed to embed 12 small permanent magnets. Electrical circuit comprised of three infrared LEDs with small lithium-polymer battery was also embedded in order to provide optical images for SPR system to compute real-time position of the model. Of note is all of these components were embedded inside of the model for not making protrudent part which might cause the interference effect, thereby the model could be utilized to MSBS-based wind tunnel test.

3 Experimental Study on Unsteady Aerodynamic Characteristics of Oscillating Airfoil Using MSBS

3.1 Experimental Procedure

In order to study unsteady aerodynamic characteristics, we installed our 30cm MSBS at the KAIST low-speed wind tunnel facility as shown in Fig. 7. This AD-OWT300 model open circuit type wind tunnel was developed by Sewon Engineering co., and has the same test section size as MSBS. It has moderate turbulence intensity (less than 0.8%) and velocity variation (within 1.0% at 1-5m/s and 0.8% at 5-30m/s) to perform wind tunnel test [12]. The test section wall made of non-reflecting plastic material, which could minimize the optical noise from other light sources except the model for SPR position detection, was installed for wind tunnel test.

Fig. 7. KAIST MSBS Installed at Wind Tunnel [10]

Fig. 8 is a block diagram representation of the experimental procedure for identifying the unsteady aerodynamic characteristics using MSBS. First of all, the static wind tunnel test was conducted to align the model parallel to the freestream. The aerodynamic forces acting on the model perpendicular to the freestream should be zero since it has symmetric airfoil shape, and this feature was used to find the zero angle of attack (AOA). After alignment of the model, the sinusoidal input command was given for oscillating in pitching direction.

Since the model was controlled by using magnetic forces, more electric current for electromagnets was needed when external force acts. Therefore, the aerodynamic forces acting on the model could be calculated by measuring the additional electric current needed when the forces act. In this context, the model was oscillated in pitching direction with the same frequency and amplitude for two different freestream condition; with (wind on condition) and without (wind off condition) aerodynamic forces. While the model was oscillating, we measured the electric current using ammeter and the AOA data using SPR system, thereby the aerodynamic forces for certain AOA could be calculated. Here, to calculate the aerodynamic forces from the measured current, dynamic calibration result was used. The dynamic calibration is the calibration procedure to find the relationship between the magnetic forces and the applied electric current by applying dynamic motion [13]. Finally, using the ensemble averaged aerodynamic forces, the aerodynamic coefficient was calculated for each experimental cases, which will be explained in section 3.2.

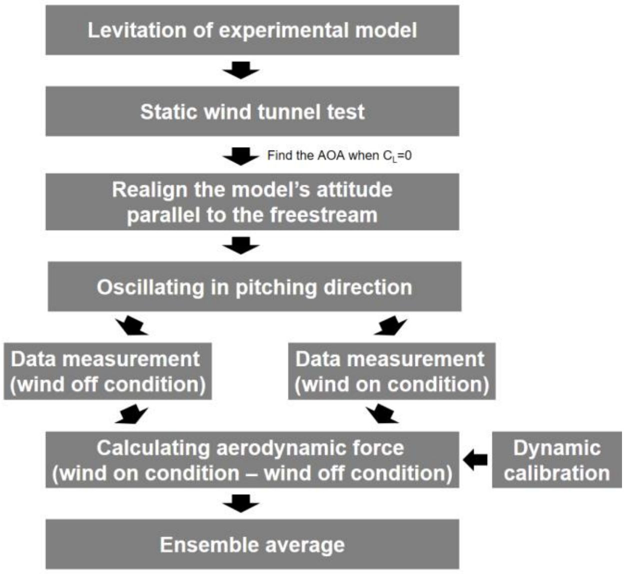


Fig. 8. Experimental Procedure

3.2 Experimental Result

In this study, we chose the oscillating amplitude of 6 deg and the reduced frequencies (k) of 0.01 to 0.06 at intervals of 0.01, which corresponded to weak unsteadiness at pre-stall region. Here, the reduced frequency, often denoted k, is defined as πfc/U where f, c and U indicate the oscillation frequency, chord length of the model and freestream speed, respectively.

Fig. 9 shows the levitation of the model in AOA of +6 deg and -6 deg, while oscillated in the sinusoidal motion. Two different freestream speeds of 4.0 and 6.0m/s was chosen which corresponded to Reynolds number of 4.4 and 6.5 x 10^4 respectively, and the center of oscillation was 0.4c. Aerodynamic forces were measured while the model was sinusoidally oscillated in pitching direction, following the same procedure as explained in section 3.1.

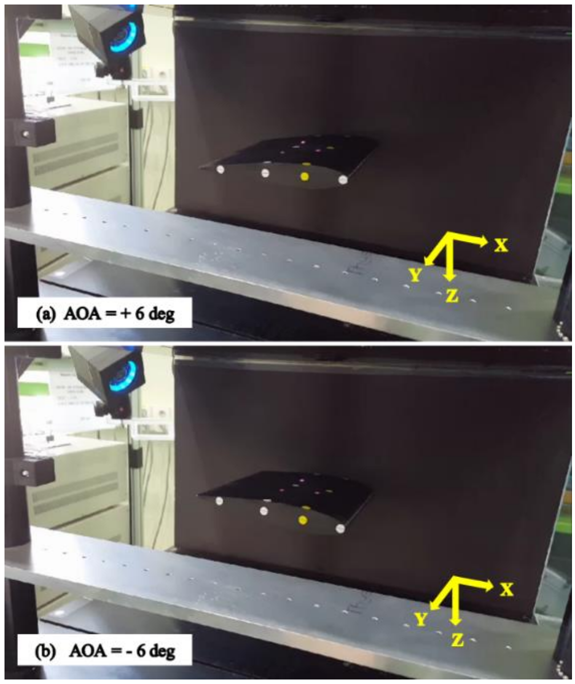


Fig. 9. Levitation of the Finite Wing Model in (a) AOA = +6 deg, and (b) AOA = -6 deg

Figs. 10 and 11 show the lift coefficient measurement result at reduced frequency of 0.06 in Reynolds number of 4.4 and 6.5 x 104, respectively. For the static case, slight lift augmentation in small AOA was observed, which is supposed to be induced by leading edge bubble [14]. For oscillating cases up to k=0.06, the hysteresis loop was observed, which is believed to be induced by the weak aerodynamic force delay. As shown in Figs. 10 and 11, the hysteresis loops have twisted doughnut shape, with counter-clockwise rotation in the middle and clockwise rotation in both ends, and tend to be grown with an increase in reduced frequency.

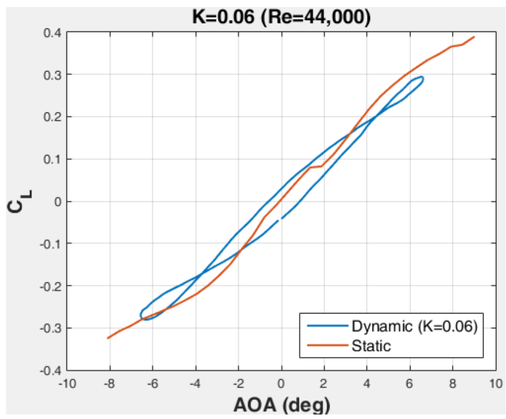


Fig. 10. Measurement of lift coefficient at Re=44,000, k=0.06

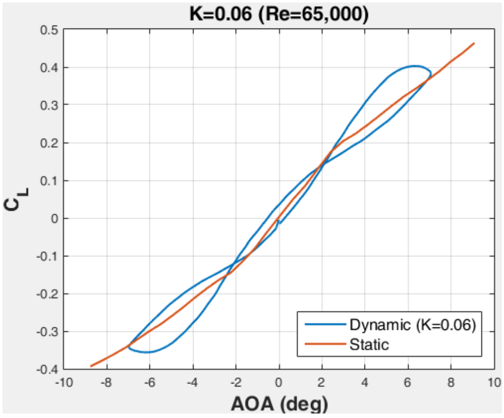


Fig. 11. Measurement of lift coefficient at Re=65,000, k=0.06

The aerodynamic force delay with complicated flow pattern arisen from the oscillation of the model and the 3D effect might be the reason for these complex hysteresis characteristics. To investigate the flow pattern, thereby identifying the unsteady aerodynamic characteristics, further studies are under consideration, including the visualization of the flow pattern around the oscillating airfoil model using particle image velocimetry (PIV) technique.

4 Concluding Remarks

This paper presents the MSBS-based wind tunnel system for studying the unsteady aerodynamic characteristics of an oscillating airfoil. Since the model is magnetically levitated and oscillated, the aerodynamic forces can be precisely measured by excluding the mechanical support interference effect, which gives great advantage compared with conventional wind tunnel test. Taking notice of these advantages, the MSBS was developed that features the enough controllable range for model oscillation and the capability of accurate aerodynamic force measurement.

In this study, the aerodynamic forces were measured using the additional electric current needed while the NACA 0015 finite wing shape model was sinusoidally oscillated in pitching direction in low Reynolds number flow fields. The oscillating amplitude of 6 deg and the reduced frequencies of up to 0.06 were chosen in this study, which corresponded to weak unsteadiness at pre-stall region. To acquire high-precision positioning data of the model, the SPR system, which is a vision-based positioning system using synchronized stereo cameras, was used.

The result showed that the lift coefficient of the oscillating airfoil had twisted doughnut shape hysteresis loops with counter-clockwise rotation in the middle and clockwise rotation in both ends. The hysteresis characteristics tends to be grown with an increase in reduced frequency. The aerodynamic force delay with complicated flow pattern arise from the model oscillation and the 3D effect might be the reason for these complex hysteresis characteristics. Visualization of the flow pattern around the oscillating airfoil with in-depth parametric studies are under consideration for future studies to understand the unsteady aerodynamic characteristics.

Acknowledgements

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References

[1] L. W. Carr, “Progress in analysis and prediction of dynamic stall”, *Journal of Aircraft*, Vol. 25, No. 1, pp 6-17, 1988.

[2] D. H. Kim, C. W. Chang, H. B. Kim and C. S. Jeon, “Drag coefficient variations of an oscillating NACA 0012 airfoil”, *Journal of the Korean Society for Aeronautical and Space Sciences*, Vol. 36, No. 2, pp 137-145, 2008.

[3] D. H. Kim, J. W. Chang and H. B. Kim, “Near-wake measurements of an oscillating NACA 0012 airfoil”, *Journal of the Korean Society for Aeronautical and Space Sciences*, Vol. 34, No. 12, pp 1-8, 2006.

[4] M. Vlajinac and E. E. Covert, “Sting-free measurements of sphere drag in laminar flow”, *Journal of Fluid Mechanics*, Vol. 54, No. 3, pp 385-392, 1972.

[5] D. A. Dress, “Drag measurements on a modified prolate spheroid using a magnetic suspension and balance system”, *Journal of Aircraft*, Vol. 27, No. 6, pp 523-528, 1990.

[6] H. Higuchi, P. van Langen, H. Sawada and C. E. Tinney, “Axial flow over a blunt circular cylinder with and without shear layer reattachment”, *Journal of Fluids and Structures*, Vol. 22, No. 6-7, pp 949-959, 2006.

[7] H. Higuchi, H. Sawada and H. Kato, “Sting-free measurements on a magnetically supported right circular cylinder aligned with the free stream”, *Journal of Fluid Mechanics*, Vol. 596, pp 49-72, 2008.

[8] J. Eskins, “An investigation into force/moment calibration techniques applicable to a magnetic suspension and balance system”, *NASA Contractor Report*, 1988.

[9] D. K. Lee and J. H. Han, “Safety-guaranteed flight test environment for micro air vehicles”, *AIAA Journal*, Vol. 54, No. 3, pp 1018-1029, 2016.

[10] Y. H. Sung, D. K. Lee, J. S. Han, H. Y. Kim and J. H. Han, “MSBS-SPR integrated system allowing wider controllable range for effective wind tunnel test”, *International Journal of Aeronautical and Space Sciences*, Vol. 18, No. 3, pp 414-424, 2017.

[11] J. M. Yun, H. Y. Kim, J. H. Han, H. I. Kim and H. J. Kwon, “Performance evaluation method of homogeneous stereo camera system for full-field structural deformation estimation”, *International Journal of Aeronautical and Space Sciences*, Vol. 16, No. 3, pp 380-393, 2015.

[12] Sewon Engineering Co., http://www.sewon-eng.co.kr/html/product_view.html

[13] D. K. Lee, J. S. Lee, J. H. Han and Y. Kawamura, “Dynamic calibration of magnetic suspension and balance system for sting-free measurement in wind tunnel tests”, *Journal of Mechanical Science and Technology*, Vol. 27, No. 7, pp 1963-1970, 2013.

[14] E. V. Laitone, “Wind tunnel tests of wings at Reynolds numbers below 70,000”, *Experiments in Fluids*, Vol. 23, No. 5, pp 405-409, 1997.

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