

## ABSTRAK

Keterbatasan data eksperimen mengenai karakteristik aerodinamika *chambered airfoil* pada kondisi *Reynolds number* rendah masih menjadi tantangan dalam pengembangan sistem pengujian aerodinamika berbasis laboratorium. Selain itu, pengaruh variasi *angle of attack* dan kecepatan aliran udara terhadap gaya *lift*, gaya *drag*, serta fenomena aerodinamika seperti *boundary layer*, *vortex wake*, *induced drag*, dan *flow separation* pada *airfoil* NACA 2412, NACA 4412, dan NACA 23012 masih perlu dikaji secara eksperimental menggunakan sistem akuisisi data yang terintegrasi dan mampu melakukan pengukuran secara real-time. Penelitian ini bertujuan menganalisis pengaruh variasi *angle of attack* ( $0^\circ$ ,  $5^\circ$ ,  $10^\circ$ , dan  $15^\circ$ ) dan kecepatan aliran udara (5 m/s, 6 m/s, 7 m/s, dan 8 m/s) terhadap karakteristik aerodinamika *chambered airfoil* NACA 2412, NACA 4412, dan NACA 23012 menggunakan *subsonic wind tunnel* berbasis *Internet of Things* (IoT). Sistem akuisisi data terdiri atas ESP32 sebagai mikrokontroler utama, AC Dimmer Module untuk pengaturan kecepatan blower, Servo MG995 untuk pengaturan sudut serang, *Loadcell*-HX711 untuk pengukuran gaya *drag*, Sensor ToF VL53L1X untuk pengukuran gaya *lift*, serta *platform* ThingsBoard untuk pengendalian dan pemantauan data secara *daring*. Hasil penelitian menunjukkan bahwa peningkatan *angle of attack* dan kecepatan aliran udara menyebabkan peningkatan gaya *lift* dan gaya *drag* pada seluruh *airfoil*. NACA 4412 menghasilkan performa aerodinamika terbaik dengan koefisien *lift* maksimum sebesar 3,931 dan rasio aerodinamika maksimum sebesar 69,027. Analisis *Reynolds number* berada pada rentang  $4,79 \times 10^4$  hingga  $7,66 \times 10^4$  dengan *Turbulence intensity* sebesar 1,11–4,61%. Hasil *Two-Way ANOVA* menunjukkan bahwa *angle of attack* merupakan faktor paling dominan yang memengaruhi karakteristik aerodinamika dengan nilai signifikansi  $P\text{-value} = 0,000$  dan  $R^2 > 99\%$ . Temuan ini menunjukkan bahwa sistem pengujian berbasis IoT mampu menghasilkan data aerodinamika yang valid untuk menganalisis performa *chambered airfoil* pada kondisi *Reynolds number* rendah.

**Kata Kunci :** *Chambered airfoil, Internet of Things, Wind tunnel, Reynolds number, Turbulence intensity, Lift, Drag, Two-Way ANOVA.*

## **ABSTRAC**

*The limited availability of experimental data on chambered airfoil aerodynamic characteristics under low Reynolds number conditions remains a challenge in the development of laboratory-based aerodynamic testing systems. In addition, the effects of angle of attack and airflow velocity variations on lift force, drag force, and aerodynamic phenomena such as boundary layer development, vortex wake formation, induced drag, and flow separation in NACA 2412, NACA 4412, and NACA 23012 airfoils require further investigation through integrated real-time experimental measurements. This study aimed to analyze the effects of angle of attack variations ( $0^\circ$ ,  $5^\circ$ ,  $10^\circ$ , and  $15^\circ$ ) and airflow velocities (5 m/s, 6 m/s, 7 m/s, and 8 m/s) on the aerodynamic characteristics of NACA 2412, NACA 4412, and NACA 23012 chambered airfoils using an Internet of Things (IoT) based subsonic wind tunnel. The data acquisition system consisted of an ESP32 microcontroller, an AC Dimmer Module for blower speed control, an MG995 servo motor for angle of attack adjustment, a Load cell-HX711 module for drag force measurement, a VL53L1X Time-of-Flight sensor for lift force measurement, and the ThingsBoard platform for real-time monitoring and control. The results showed that increasing the angle of attack and airflow velocity significantly increased both lift and drag forces for all tested airfoils. NACA 4412 exhibited the best aerodynamic performance, achieving a maximum lift coefficient of 3.931 and a maximum aerodynamic efficiency of 69.027. Reynolds number analysis yielded values ranging from  $4.79 \times 10^4$  to  $7.66 \times 10^4$ , while Turbulence intensity ranged from 1.11% to 4.61%. Two-Way ANOVA results indicated that the angle of attack was the most influential factor affecting aerodynamic characteristics, with a significance level of  $P\text{-value} = 0.000$  and coefficient of determination  $R^2 > 99\%$ . These findings demonstrate that the proposed IoT-based testing system is capable of providing valid aerodynamic data for evaluating chambered airfoil performance under low Reynolds number conditions.*

**Keywords :** *Chambered airfoil, Internet of Things, Wind tunnel, Reynolds number, Turbulence intensity, Lift, Drag, Two-Way ANOVA.*