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Prediction of Static and Dynamic Derivatives of Damping Free-Flight Model Using Image Processing Method

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Abstract

To evaluate an aircraft's aerodynamic characteristics, measuring its aerodynamic coefficients is essential. The conventional method involves using a balance, where the model is mounted on a sting, introducing additional drag. To obtain dynamic stability derivatives, it requires additional experiments like the forced vibration method. To enable the model to fly with 6 Degrees of Freedom (6-DOF), the sting must be eliminated, leading to the development of the free-flight technique. This approach allows experiments in flight conditions, with obtained coefficients combining static and dynamic effects. Separating these coefficients into static and dynamic derivatives enables the acquisition of both types in a single experiment, demonstrating the efficiency of the method for obtaining aerodynamic coefficients. In this study, a damping free-flight model was designed to obtain both static and dynamic coefficients. A free-flight experiment was conducted in KULT (Konkuk University Ludwieg Tube). The Angle of Attack (AOA) for the model was determined using the Hough Algorithm, extracting information from images. The model's AOA can be derived from the slope of the straight line, and x and y velocities can be obtained from both endpoints. The aerodynamic coefficients obtained in the free-flight experiment represent a combination of static and dynamic coefficients. In this research, the multiple linear regression technique was employed to separate these coefficients into static and dynamic derivatives.

Keywords : *Image Processing Method, Free Flight, Damping Model, Aerodynamic Stability Derivatives, HB Standard Model*

Nomenclature

u – x-velocity
w – v-velocity
$\dot{u}$ – x-acceleration
$\dot{w}$ – v-acceleration
q – Pitch Rate
$\dot{q}$ – Pitch Angular Velocity
$\dot{\alpha}$ – AOA Rate
ρ – Density of Flow
V – Velocity of Flow
S_{ref} – Reference Area
L_{ref} – Reference Length
g – Gravitational Acceleration
θ – Pitch Angle
m – Mass of Model
C_D – Drag Coefficient
C_L – Lift Coefficient
C_m – Moment Coefficient
I_{yy} – Moment of Inertia
C_{mq} – C_m Derivative due to Pitch Rate
$C_{m\dot{\alpha}}$ – C_m Derivative due to AOA Rate
C_{Lq} – C_L Derivative due to Pitch Rate
$C_{L\dot{\alpha}}$ – C_L Derivative due to AOA Rate

1. Introduction

During flight, an aircraft is influenced by both state variables and time-history variables. Therefore, it is crucial to understand both the static and dynamic stability of an aircraft. Two parameters, called static derivatives and dynamic derivatives, represent static and dynamic stability. Traditionally, static derivatives can be measured using a balance mounted to a model fixed on a sting [1-2]. However, to

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obtain dynamic stability coefficients, additional experiments such as forced vibration methods [3-4] are necessary, as the balance method is not influenced by dynamic effects. The forced vibration method has limitations due to damping effects and the difficulty of separating the vibrations of the support structure and the model itself. Therefore, research on non-intrusive methods for measuring aerodynamic coefficients is needed to consider only the model's vibrations without time constraints.

One method for achieving this is the free-flight technique. In this method, the model flies in 6 Degrees of Freedom (6-DOF). The key point of this method is non-intrusive acceleration measurement, employing various sensors such as Inertia Measurement Unit (IMU) sensors and accelerometers. However, utilizing sensors in a supersonic wind tunnel poses challenges due to noise and response time, limiting the run time. To overcome these limitations, recent research has actively explored image-processing techniques for aerodynamic coefficient measurements [5-6].

In this study, the Hough algorithm, a type of image processing technique, was employed to recognize the model's straight line and endpoints, allowing for the determination of both the angle of attack (AOA) and accelerations. In free-flight experiments, aerodynamic coefficients are estimated in a combined form of static and dynamic derivatives. However, most free-flight experiments focus on static models, as isolating static and dynamic coefficients is challenging. If research can successfully separate static and dynamic coefficients from a free-flight model that experiences both static and dynamic influences, it would enable acquiring both types of coefficients in a single experiment. Therefore, a regression analysis was applied to separate static and dynamic coefficients obtained from free-fall experiments. The proposed method was validated through free-flight experiments with the HB-2 Standard model. The separated static coefficients were compared with calculated values (CFD, MissileDATCOM), and experimental values from balance tests, while dynamic coefficients were compared with theoretical formulations from previous studies [7-8].

2. The acquisition method for static and dynamic coefficients.

2.1. Image Processing Method (Hough Algorithm)

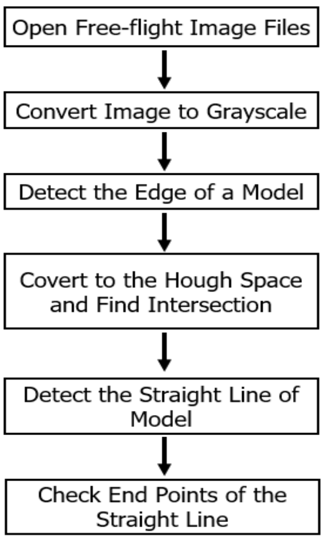

Fig 1. Schematic Diagram of Hough Algorithm

The Hough algorithm was utilized for the detection of the model's line. The principles of the Hough algorithm have been described in previous studies [9]. In this study, the algorithm was implemented through MATLAB bulit-in function 'Houghlines'. Fig. 1 shows the schematic diagram of the Hough algorithm, and Fig. 2 displays the recognition of the model's line through the Hough Algorithm. The pitch angle of the model can be obtained through the slope of the line. However, to measure the x and y velocity of the model, it is essential to select reference points. The Center of Gravity (C.G) point is chosen as the reference point, and it can be estimated using the endpoints of the line.

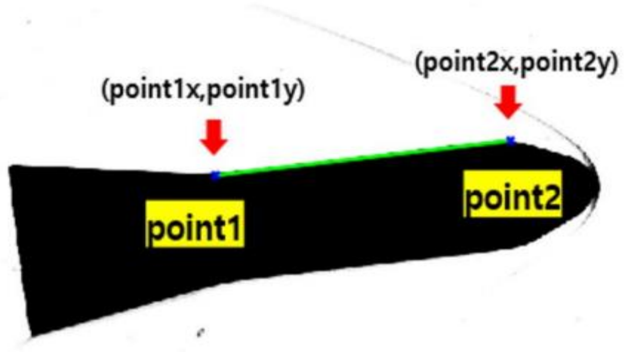

Fig 2. recognition of the model's line through the Hough Algorithm.

$$\begin{bmatrix} C_D \\ C_L \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}^{-1} \begin{bmatrix} m(\dot{u} + \dot{\alpha}w + g\sin\alpha) \\ m(\dot{w} + \dot{\alpha}u - g\cos\alpha) \end{bmatrix} / \frac{\gamma}{2} P_\infty M_\infty^2 S_{ref} \tag{1}$$

$$C_M = \frac{\ddot{\alpha} I_{yy}}{\frac{\gamma}{2} P_\infty M_\infty^2 S_{ref} L_{ref}} \tag{2}$$

Eq. 1 - Eq. 2 represent the 3-DOF equations in inertia coordinates. The variable α represents the pitch angle of the model which can be obtained using the slope of the recognized line. Its angular velocity ($\dot{\alpha}$) and angular acceleration ($\ddot{\alpha}$) can be acquired by differentiating α. The velocities along the x and y axes are represented as u and w. This value can be obtained tracking the Center of Gravity (C.G) point of the model, which can be estimated using the endpoints of the line. The x and y accelerations, $\dot{u}$ and $\dot{w}$, can also be obtained by differentiating u and w. The variable g represents the acceleration of gravity, and the standard acceleration of gravity ($9.8m/s^2$) can be used. Additionally, P_∞, M_∞, and γ represent the pressure, Mach number, and specific heat ratio of the free stream. In the free-flight experiment, the values at the nozzle exit can be used as these values. m, S_{ref}, L_{ref}, I_{yy} represent the mass, reference area, reference length, and moment of inertia of the model which is the specification of the model. Ultimately, the only unknowns in the equations are the aerodynamic coefficients. Recognizing the model's line and its endpoints allows for the estimation of these coefficients.

3. Experimental Details

3.1. Test Model (HB-2)

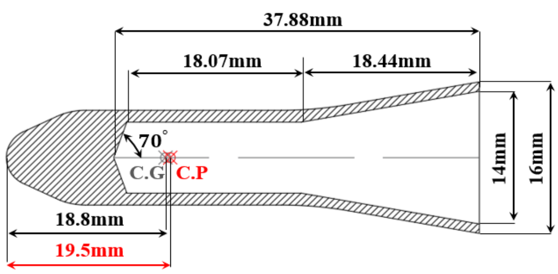

Fig 3. The HB-2 model with an empty space

To validate the measurement of aerodynamic coefficients using the Hough algorithm and multiple linear regression, the HB-2 model was chosen. The Center of Gravity (C.G) point must be positioned in front of the Center of Pressure (C.P) to design the damping model. Therefore, the model has empty space that helps position the C.G point in front of the C.P point, as illustrated in Fig. 3 Since the free-flight model is not reusable, it was manufactured using ABS-Like 3D printing. Table 1 shows the specifications of the model.

Table 1. Specifications of HB-2 model

Property	Value
Height (m)	0.049
Reference Area (m^2)	0.00007853
Reference Length (m)	0.01
Mass (kg)	0.0015
Iyy ($kg \cdot m^2$)	2.314E-06

3.2. Test Facility (Konkuk University Ludwieg Tube)

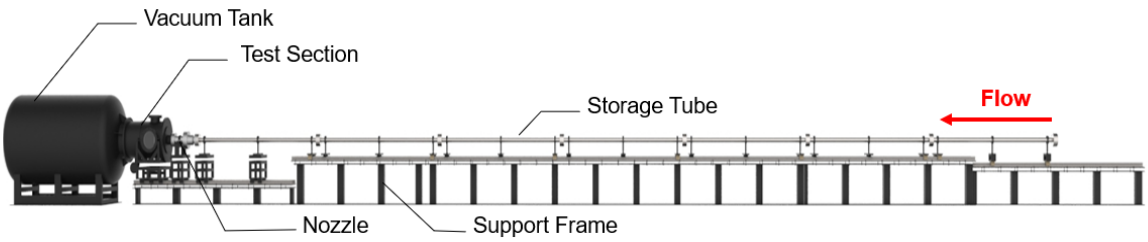

Fig 4. Rendering Image of KULT

Table 2 Properties of KULT

Property	Calculation	
	Analytic	CFD
$M_\infty(-)$	4.0	3.94
$p_\infty(kPa)$	15.9	16.0
$u_\infty(m/s)$	659	661
$\rho_\infty(kg/m^3)$	0.822	0.779
$T_\infty(K)$	71.4	67.6

The free-flight experiments were conducted using the Konkuk University Ludwieg Tube (KULT) [10]. It has a longer runtime (approximately 100ms) than other supersonic wind tunnels, making it suitable for free-flight experiments. Fig. 4 shows the configuration of KULT, and Table 2 provides the properties of KULT based on Computational Fluid Dynamics (CFD) calculations using ANSYS Fluent v16.1 [11]. To validate against previous studies, experiments were conducted at the same Mach number (Mach 4) and Reynolds number (6.0E+07) as in the prior research [12].

4. Results

4.1. Free-Flight Results

Fig. 5 - Fig. 7 shows the aerodynamic coefficients of the free-flight HB-2 model, which were acquired through the Hough Algorithm. It can be observed that the graph exhibits a counterclockwise hysteresis loop pattern, which appears when the state of the model changes. The counterclockwise indicates that the model is consuming dynamic energy and displaying dynamic stability.

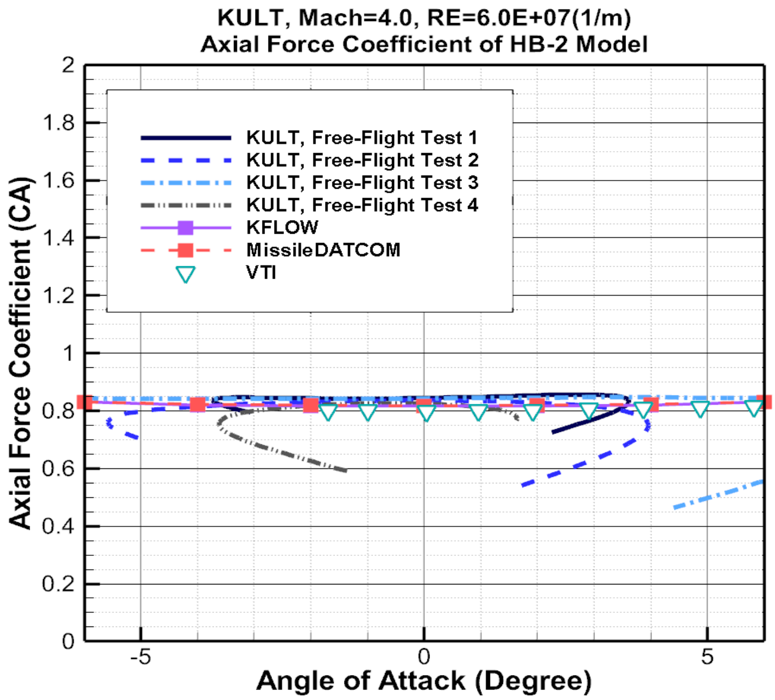

Fig 6. Axial Force Coefficient of HB-2 model (Static + Dynamic Derivatives)

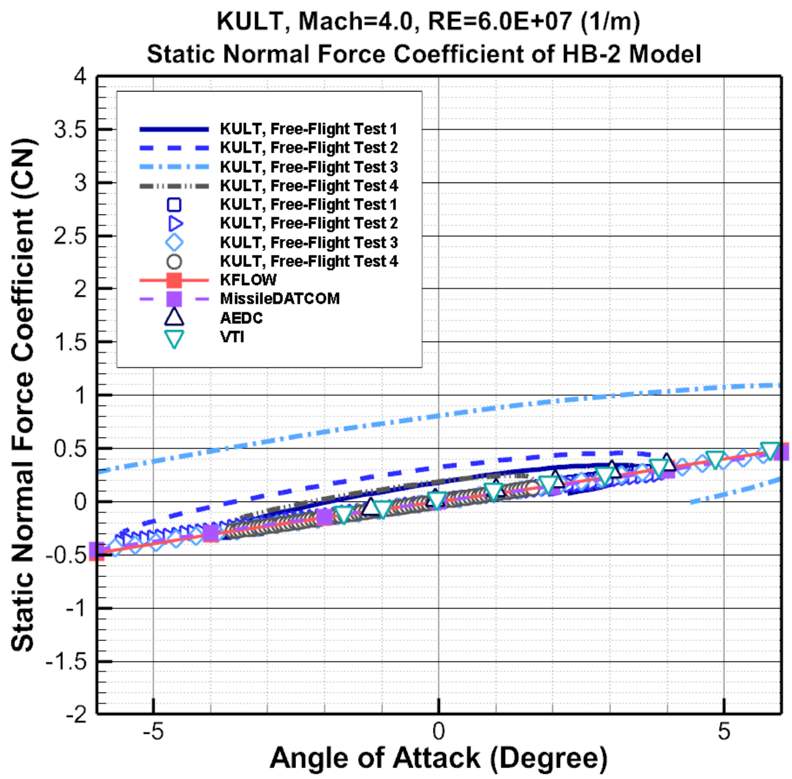

Fig 5. Normal Force Coefficient of HB-2 model (Static + Dynamic Derivatives)

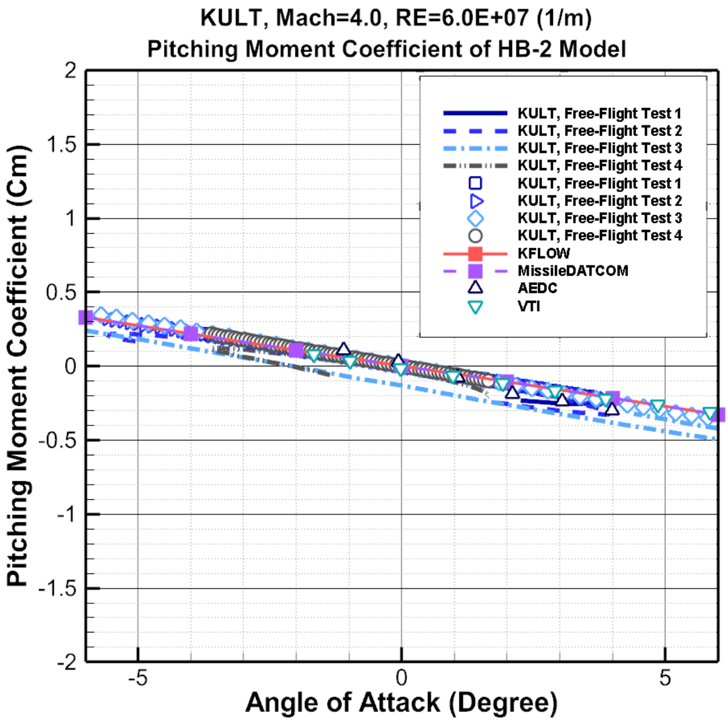

Fig 7. Pitching Moment Coefficient of HB-2 model (Static + Dynamic Derivatives)

4.2. Separation Results

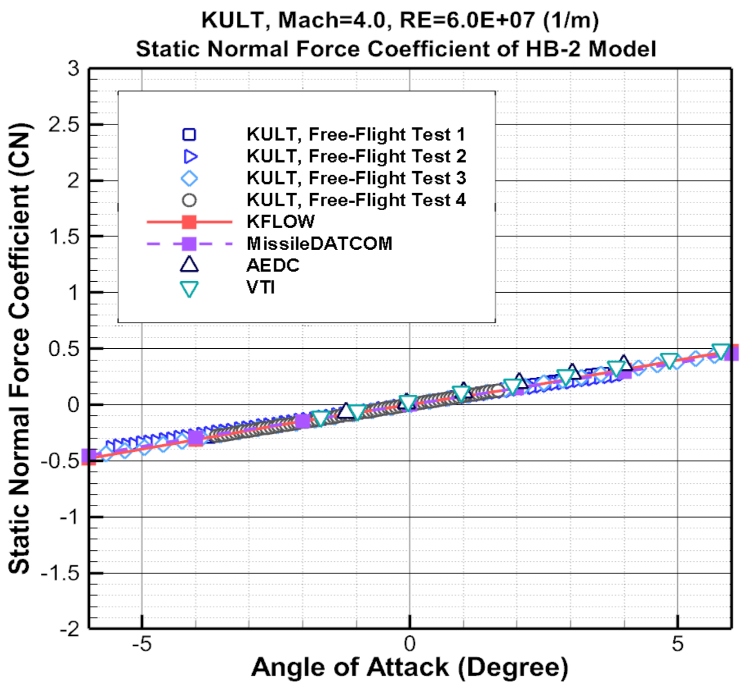

Fig 8. Normal Force Coefficient of HB-2 model (Static Derivatives)

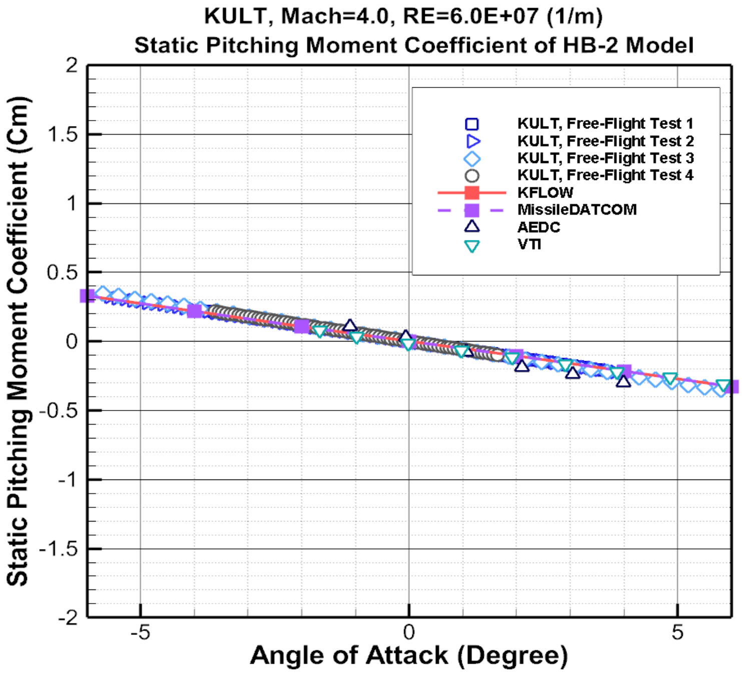

Fig 9. Pitching Moment Coefficient of HB-2 model (Static Derivatives)

Utilizing Scikit-Learn, which is a form of multiple linear regression. It is possible to separate aerodynamic coefficients into static and dynamic coefficients. Fig. 5 – Fig. 6 shows the static aerodynamic coefficients of the HB-2 model after separation. In comparison with previous studies (VTI, AEDC) and MissileDATCOM, CFD results, it can be confirmed that the separation of static and dynamic coefficients has been achieved

Conclusion

In this study, the Hough algorithm was applied to estimate the aerodynamic coefficients of the free-flight model. Additionally, research was conducted to separate the aerodynamic coefficients obtained from free-flight experiments into static and dynamic components using multiple linear regression. To validate the algorithm, the Damping HB-2 model was utilized, and free-flight experiments were conducted in the Konkuk University Ludwieg Tube (KULT) under the same flow conditions as in previous studies.

Acquired normal force coefficients and pitching moment coefficients were separated into static derivatives and dynamic derivatives using multiple linear regression. The separated static derivatives were validated by comparing them with calculated values (CFD, MissileDATCOM) and experimental values from previous studies (VTI, AEDC). The results showed that the aerodynamic coefficients obtained through free-flight experiments align in a single plane. As a result, the utilization of the multiple linear regression method confirmed its ability to separate these coefficients into static and dynamic components.

Typically, acquiring both static and dynamic derivatives involves conducting individual experiments for each angle of attack (AOA). By employing the Hough and multiple linear algorithms, the efficient acquisition of both derivatives for various angles of attack can be achieved with a single experiment. Furthermore, this approach helps overcome errors such as support structure and sensor noise.

Acknowledgments

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