STABILITY & CONTROL CHARACTERIZATION OF FLIGHT VEHICLES FROM WINDTUNNEL TESTING

by:

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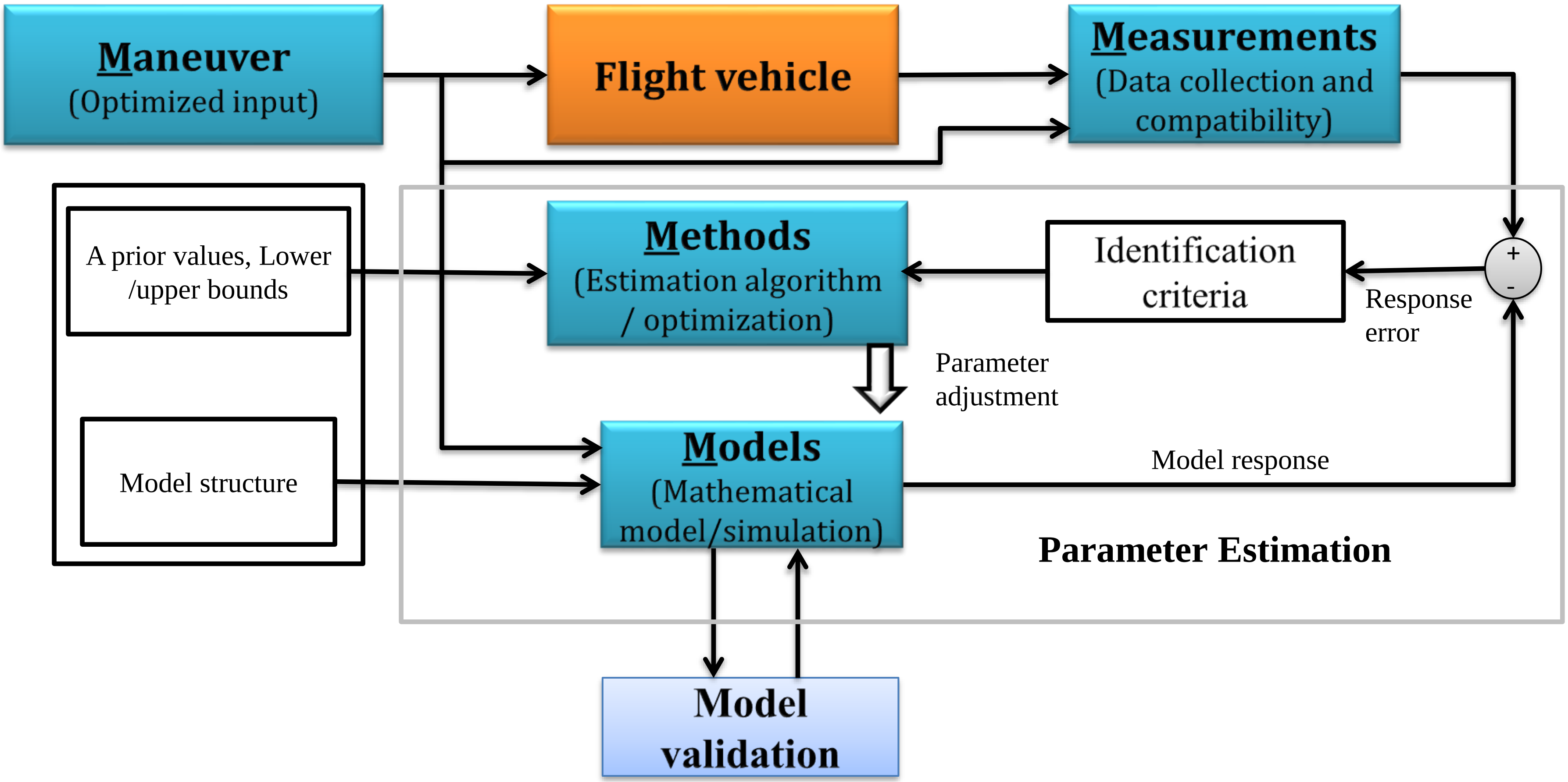
Road Map for Aerodynamic Characterization from flight data



Aerodynamic Characterization

Classical Estimation methods

1. Output Error Method (MLE)
2. Equation Error Method (LS)
3. Filter Error Method (EKF)

Neural based methods

1. Neural Gauss Newton method (NGN)

Flight Tests

1. Static tests
2. Dynamic tests

Wind tunnel Tests

Computational fluid dynamic methods

Analytical Estimates

Why wind tunnel testing ??

- Aircraft is considered as a rigid body to derive its equations of motion.
- Forces and moments acts about the c.g of the aircraft

$$\sum \delta \bar{F}_{ext} = \frac{d}{dt}\left(\sum \delta m \bar{V}\right) \Rightarrow \sum \bar{F}_{ext} = m\left(\frac{\partial}{\partial t}(\bar{V}) + \bar{\omega} \times \bar{V}\right)$$

$$\sum \bar{F}_{ext} = \bar{F}_{aerodynamic} + \bar{F}_{propulsion} + \bar{F}_{gravity}$$

$$\sum \delta \bar{\tau}_{ext} = \frac{d}{dt}\left(\sum \delta \bar{h}\right) \Rightarrow \bar{M}_{ext} = m\left(\frac{\partial}{\partial t}(\bar{H}) + \bar{\omega} \times \bar{H}\right)$$

$$\sum \bar{M}_{ext} = \bar{M}_{aerodynamic} + \bar{M}_{propulsion}$$

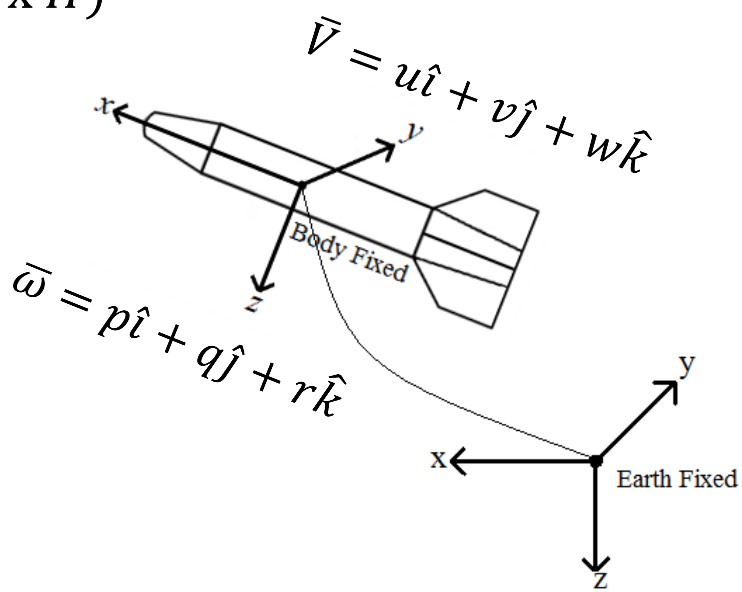
$$\bar{F}_{aero} = q_\infty s \bar{C}_{FA}$$

$$\bar{M}_{aero} = q_\infty s l \bar{C}_{MA}$$

where $q_\infty = \frac{1}{2}\rho v_\infty^2$ - dynamic pressure

s - reference planform area

l - characteristic length



SIX DOF Equations

$$\dot{u} = \frac{F_x}{m} - g * \sin\theta - \mathrm{q} * \mathrm{w} + \mathrm{r} * \mathrm{v}$$

$$\dot{v} = \frac{F_y}{m} + g * \cos\theta * \sin\emptyset - r * \mathrm{u} + \mathrm{p} * \mathrm{w}$$

$$\dot{w} = \frac{F_z}{m} + g * \cos\theta * \cos\emptyset - p * \mathrm{v} + \mathrm{q} * \mathrm{u}$$

$$\dot{p} = \left(\frac{1}{J_{xx}J_{zz} - J_{xz}^2}\right)\{J_{zz} * L + J_{xz} * N - q * r(J_{xz}^2 + J_{zz}^2 - J_{yy} * J_{zz}) + p * q * J_{xz} * (J_{xx} - J_{yy} + J_{zz})\}$$

$$\dot{q} = \left(\frac{1}{J_{yy}}\right)\{M - r * p * (J_{xx} - J_{zz}) - (p^2 - r^2) * J_{xz}\}$$

$$\dot{r} = \left(\frac{1}{J_{xx}J_{zz} - J_{xz}^2}\right)\{J_{xz} * L + J_{xx} * N - q * r * J_{xz} * (J_{xx} - J_{yy} + J_{zz}) + p * q * (J_{xz}^2 + J_{xx}^2 - J_{yy} * J_{xx})\}$$

$$\dot{\phi} = p + q\, tan\,\theta\, sin\,\phi + r\, tan\,\theta\, cos\,\phi$$

$$\dot{\theta} = q\, cos\,\phi - r\, sin\,\phi$$

$$\dot{\psi} = r\, cos\,\phi \sec\theta + q \sin\phi \sec\theta$$

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & \cos\varphi & \sin\varphi\\ 0 & -\sin\varphi & \cos\varphi\end{bmatrix}\begin{bmatrix}\cos\theta & 0 & -\sin\theta\\ 0 & 1 & 0\\ \sin\theta & 0 & \cos\theta\end{bmatrix}\begin{bmatrix}\cos\psi & \sin\psi & 0\\ -\sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}u\\ v\\ w\end{bmatrix}$$

SIMULATION → *Aerodynamic Model*

$$\begin{Bmatrix} C_{f_x} \\ C_{f_y} \\ C_{f_z} \end{Bmatrix} = \left(\frac{1}{q_\infty S}\right) x \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix}$$

$$\begin{Bmatrix} C_{m_x} \\ C_{m_y} \\ C_{m_z} \end{Bmatrix} = \left(\frac{1}{q_\infty S\bar{l}}\right) x \begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix}$$

$$\Rightarrow$$

$$\begin{bmatrix} C_L \\ C_D \\ C_y \end{bmatrix} = \begin{bmatrix} \sin(\alpha) & 0 & -\cos(\alpha) \\ -\cos(\alpha) & 0 & -\sin(\alpha) \\ 0 & \cos(\beta) & 0 \end{bmatrix} \begin{Bmatrix} C_{f_x} \\ C_{f_y} \\ C_{f_z} \end{Bmatrix}$$

$$C_L = C_{L_0} + C_{L_\alpha}\alpha + C_{L_q}q + C_{L_{\delta_e}}\delta_e$$

$$C_D = C_{D_0} + C_{D_\alpha}\alpha$$

$$C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}q + C_{m_{\delta_e}}\delta_e$$

$$C_Y = C_{Y_0} + C_{Y_\beta}\beta + C_{Y_r}r + C_{Y_{\delta_r}}\delta_r$$

$$C_n = C_{n_0} + C_{n_\beta}\beta + C_{n_r}r + C_{n_p}p + C_{n_{\delta_r}}\delta_r + C_{n_{\delta_a}}\delta_a$$

$$C_l = C_{l_0} + C_{l_\beta}\beta + C_{l_r}r + C_{l_p}p + C_{l_{\delta_r}}\delta_r + C_{l_{\delta_a}}\delta_a$$

Aerodynamic Model → WIND TUNNEL TESTING @ NWTF

- To extract the longitudinal, lateral – directional aerodynamic stability and control derivatives

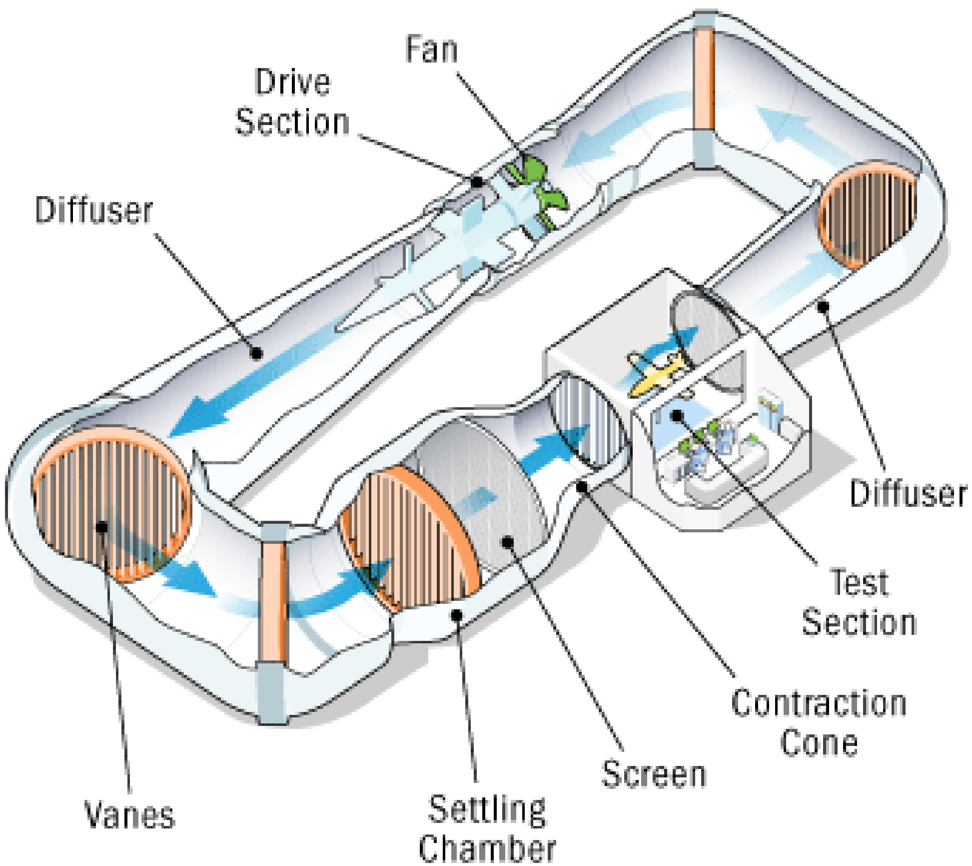
- Static tests were performed
  - α sweep : -5^0 to 50^0
  - β sweep : -10^0 to 10^0

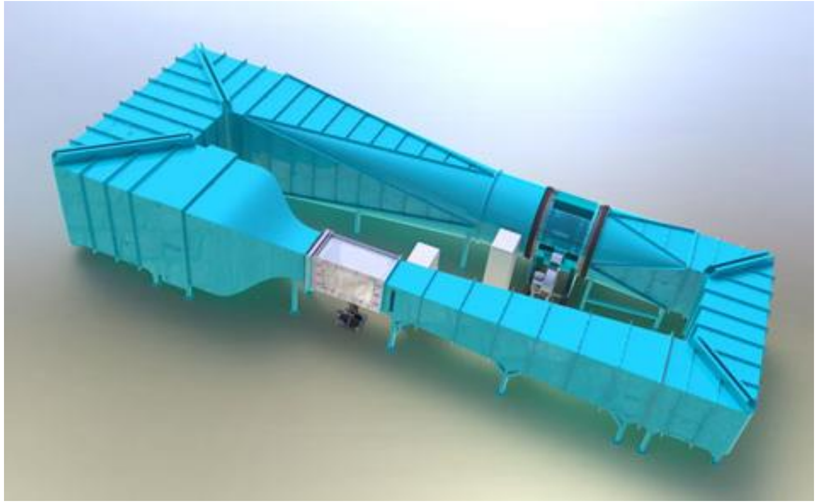
- Six component Load balance is used to measure the forces and moments of the model.

- Reynolds number : 3.45×10^5

- Velocity : 8 m/s.

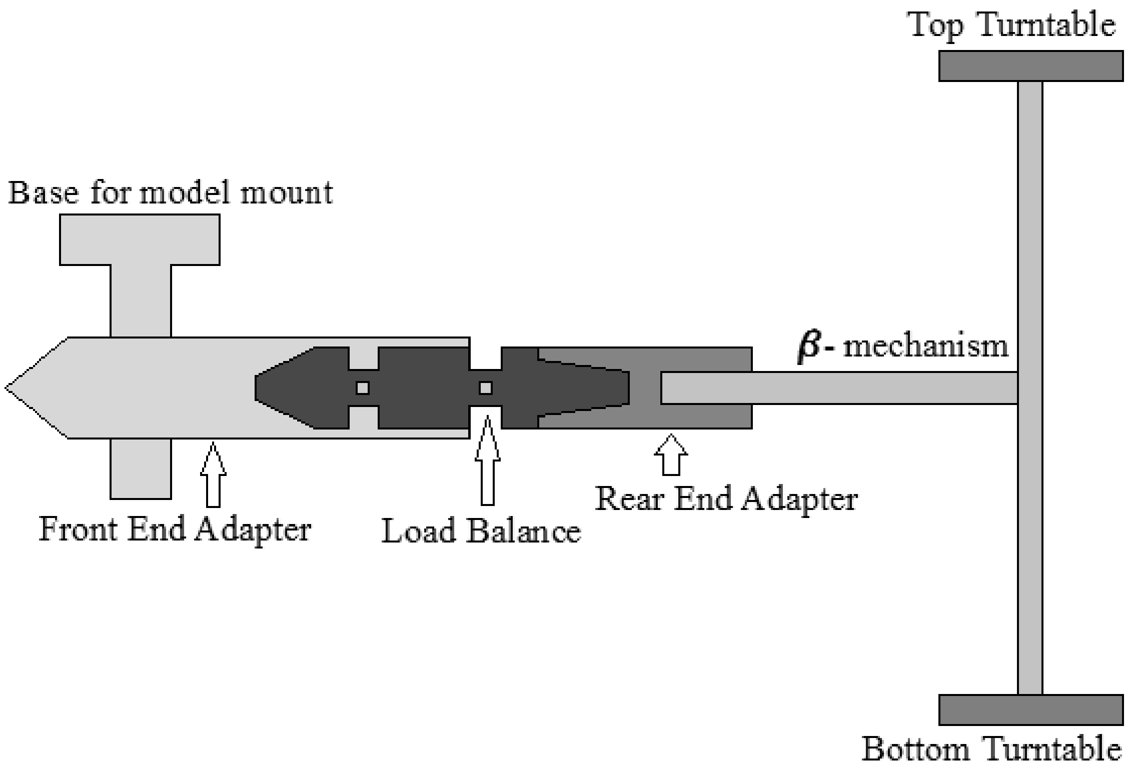
Aerodynamic Model → WIND TUNNEL TESTING @ NWTF





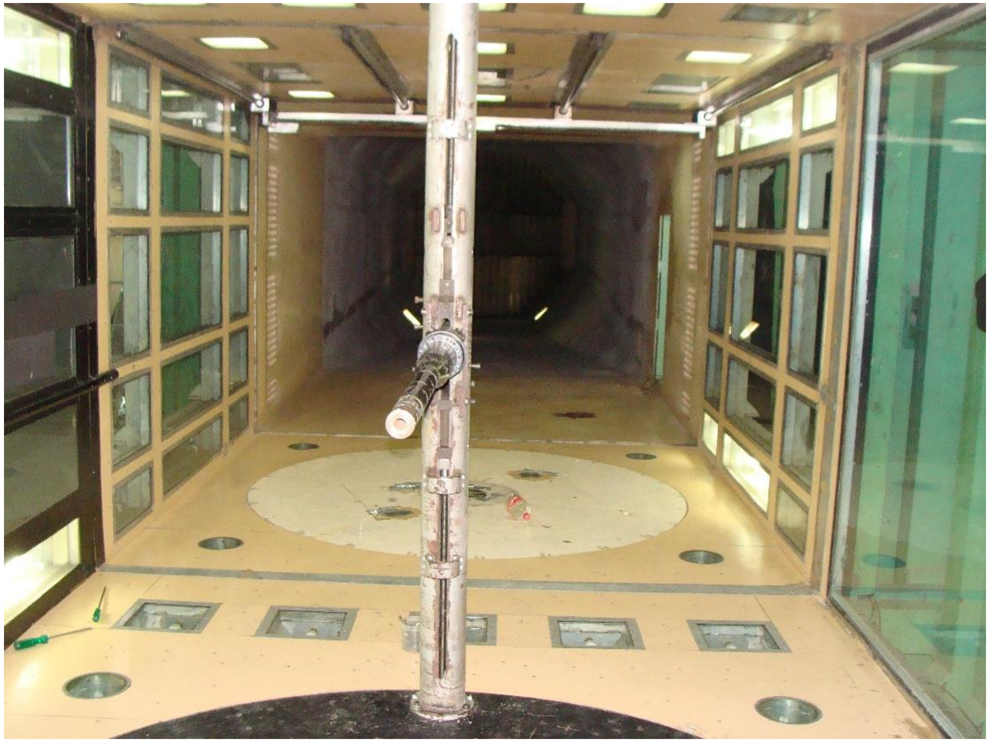
 Model Mounting

- Model is mounted inside the test section of the wind tunnel with the help of β – mechanism.
- β – mechanism which in turn fixed to turn table, enables the model to have variable angle of attack(α), side slip angle(β).

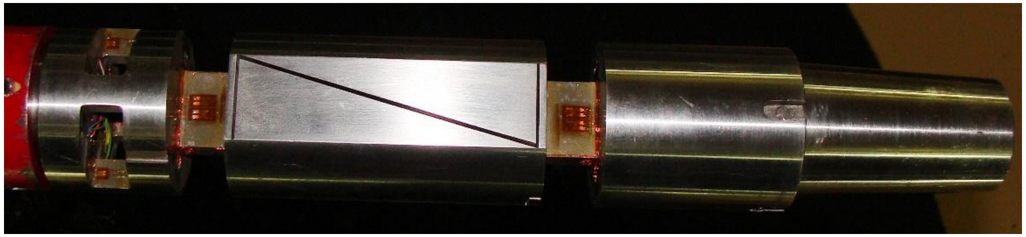


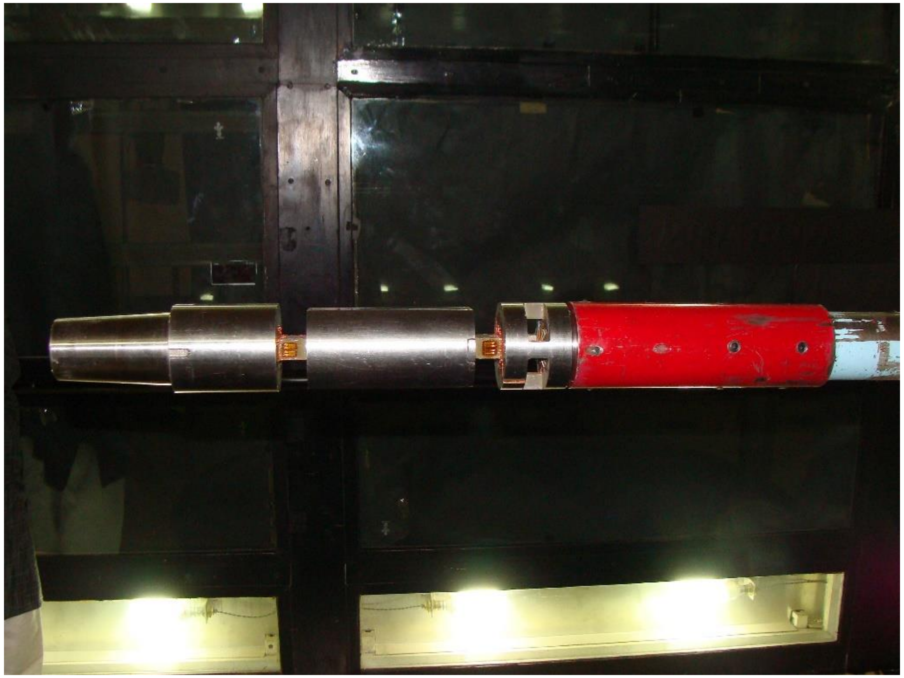
Aerodynamic Model → WIND TUNNEL TESTING → **β mechanism**

Aerodynamic Model → WIND TUNNEL TESTING → **Turning Vanes**

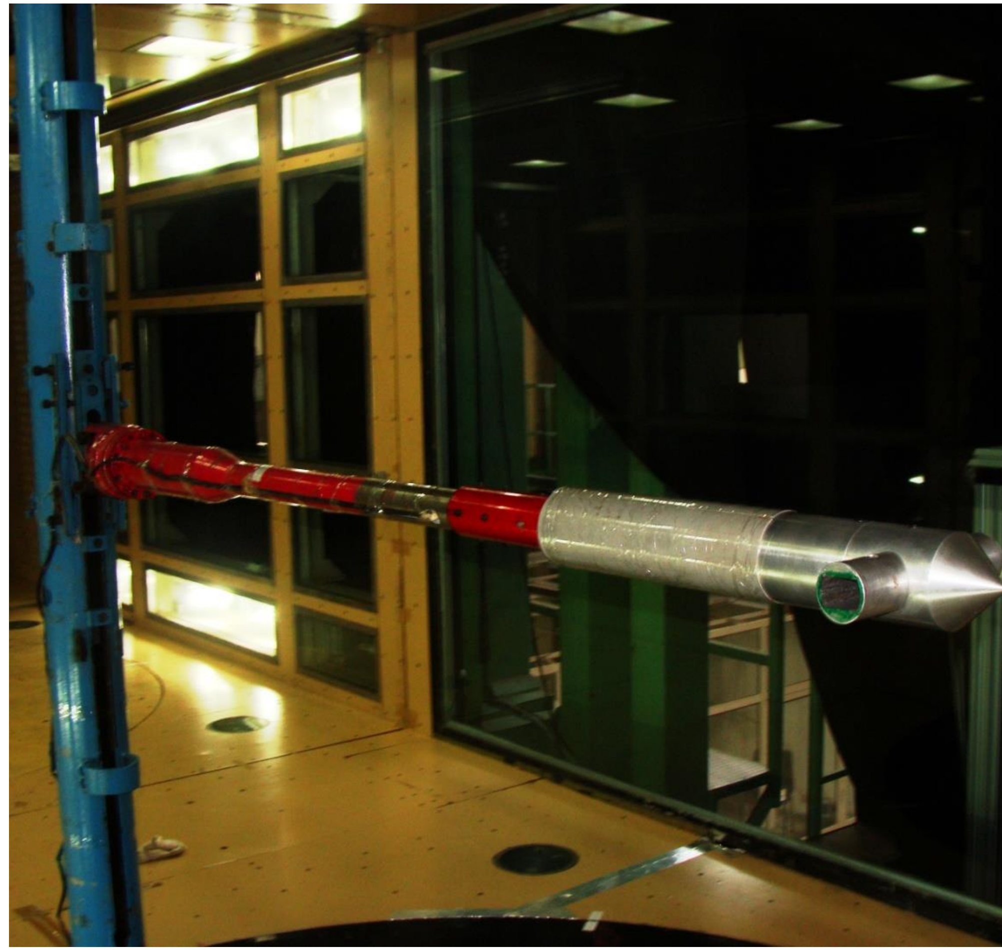


Aerodynamic Model → WIND TUNNEL TESTING → **Six Component Load Balance**

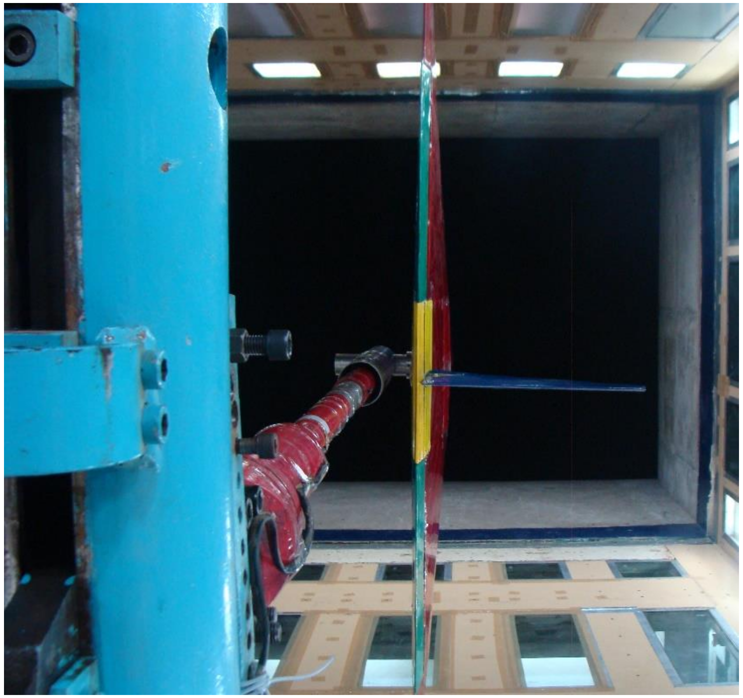


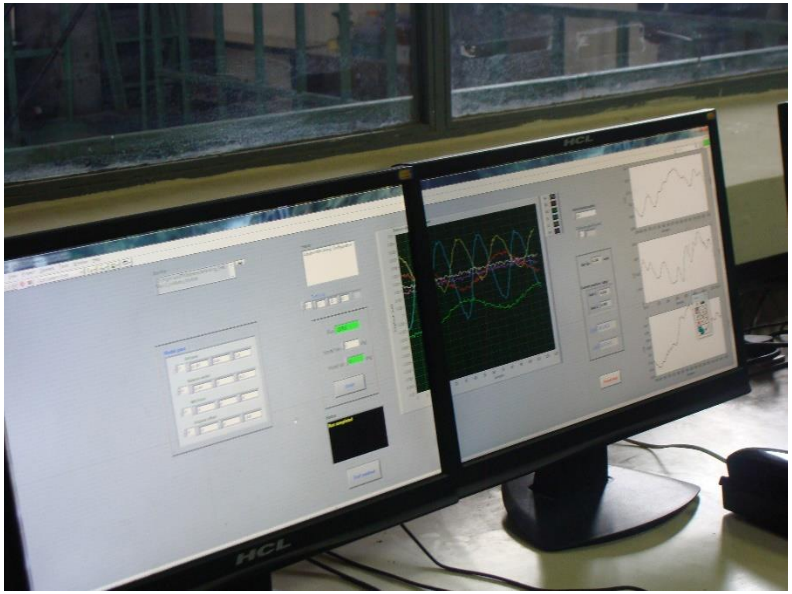


Aerodynamic Model → WIND TUNNEL TESTING → **Model Mounting**



Aerodynamic Model → WIND TUNNEL TESTING → **Model Mounting**





Aerodynamic Model → WIND TUNNEL TESTING → **Load Balance Calibration**

- Data from load balance is obtained about balance center in the form of normalized voltage signals

- Step1: Convert the obtained normalized voltage signals to kg and kg-m.

$$\text{Let} \quad [\boldsymbol{A}] = \begin{Bmatrix} A_f \\ N_1 \\ N_2 \\ S_1 \\ S_2 \\ Rm \end{Bmatrix} \text{ and } [\boldsymbol{a}] = \begin{Bmatrix} a_f \\ n_1 \\ n_2 \\ s_1 \\ s_2 \\ rm \end{Bmatrix}$$

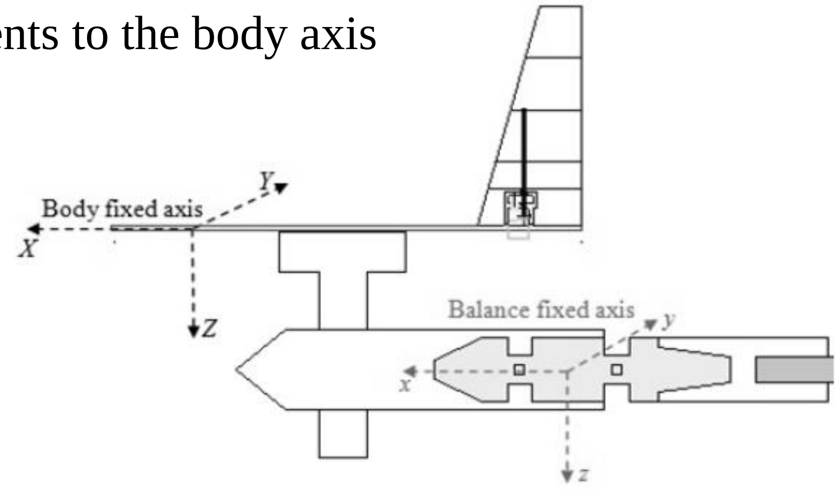
$$[\boldsymbol{A}]_{6\,\mathrm{x}1} = [\boldsymbol{CM}]_{6\,\mathrm{x}\,6} \,\mathrm{x}\, [\boldsymbol{a} - \boldsymbol{NW}]_{6\,\mathrm{x}\,1}$$

- Step2: Calculate the forces and moments about the balance center.

$$[\boldsymbol{f}/\boldsymbol{m}]_{b.c} = \begin{Bmatrix} A_x \\ S_f \\ N_f \\ R_m \\ P_m \\ Y_m \end{Bmatrix} = \begin{Bmatrix} A_f \\ S_1 + S_2 \\ N_1 + N_2 \\ Rm \\ (N_1 - N_2) * 0.065 \\ (S_1 - S_2) * 0.065 \end{Bmatrix} \mathrm{x}\, g$$

- Step3: Transform the forces and moments to the body axis

$$[\boldsymbol{F}/\boldsymbol{M}]_{b.c} = \begin{Bmatrix} f_x \\ f_y \\ f_z \\ m_x \\ m_y \\ m_z \end{Bmatrix} = \begin{Bmatrix} -A_x \\ S_f \\ -N_f \\ R_m \\ P_m \\ Y_m \end{Bmatrix}$$



- Step4: Transform the forces and moments to the C.G of the flight vehicle.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix}_{c.g} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & -z & y & 1 & 0 & 0 \\ z & 0 & -x & 0 & 1 & 0 \\ -y & x & 0 & 0 & 0 & 1 \end{bmatrix} \text{x} \begin{Bmatrix} f_x \\ f_y \\ f_z \\ m_x \\ m_y \\ m_z \end{Bmatrix}$$

$$\begin{Bmatrix} C_{f_x} \\ C_{f_y} \\ C_{f_z} \end{Bmatrix} = \left(\frac{1}{q_\infty S}\right) x \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix}$$

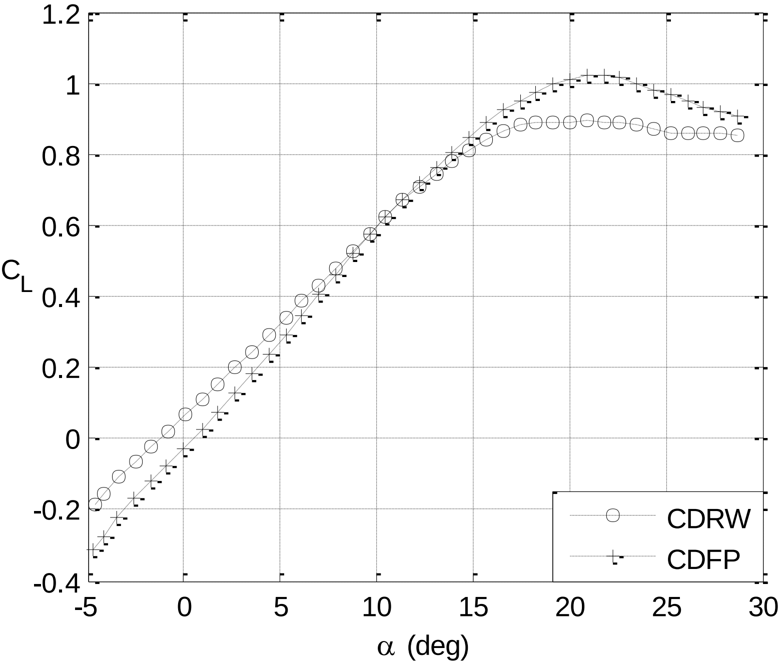
$$\begin{Bmatrix} C_{m_x} \\ C_{m_y} \\ C_{m_z} \end{Bmatrix} = \left(\frac{1}{q_\infty S\bar{l}}\right) x \begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix} \begin{matrix} \mathbf{L} \\ \mathbf{M} \\ \mathbf{N} \end{matrix}$$

$$\begin{bmatrix} C_L \\ C_D \\ C_y \end{bmatrix} = \begin{bmatrix} \sin(\alpha) & 0 & -\cos(\alpha) \\ -\cos(\alpha) & 0 & -\sin(\alpha) \\ 0 & \cos(\beta) & 0 \end{bmatrix} \begin{Bmatrix} C_{f_x} \\ C_{f_y} \\ C_{f_z} \end{Bmatrix}$$

Aerodynamic Model → WIND TUNNEL TESTING →**CDFP & CDRW**

Photographs of **cropped delta flat plate** (left) and **cropped delta reflex wing** (right) configurations mounted inside the test section of wind tunnel

Aerodynamic Model → WIND TUNNEL TESTING → **Generated Aerodynamic Database**



$$C_{L_0} \approx 0 \ at \ \alpha \approx 0°$$

$$C_{L_\alpha} = 3.273 \ /rad$$

$$C_{L_{max}} = 1.022$$

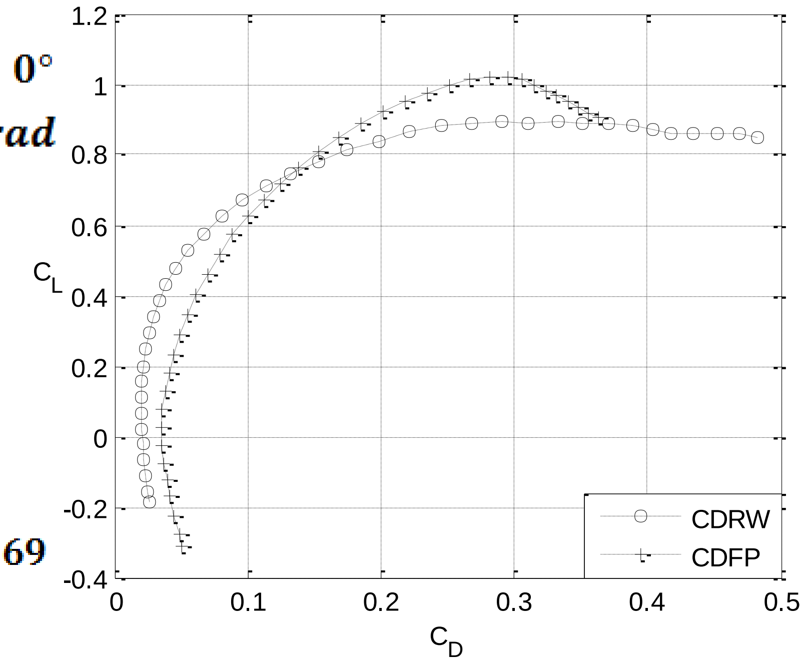
$$\alpha_{stall} \approx 20.89^0$$

$$C_{D_0} = 0.035$$

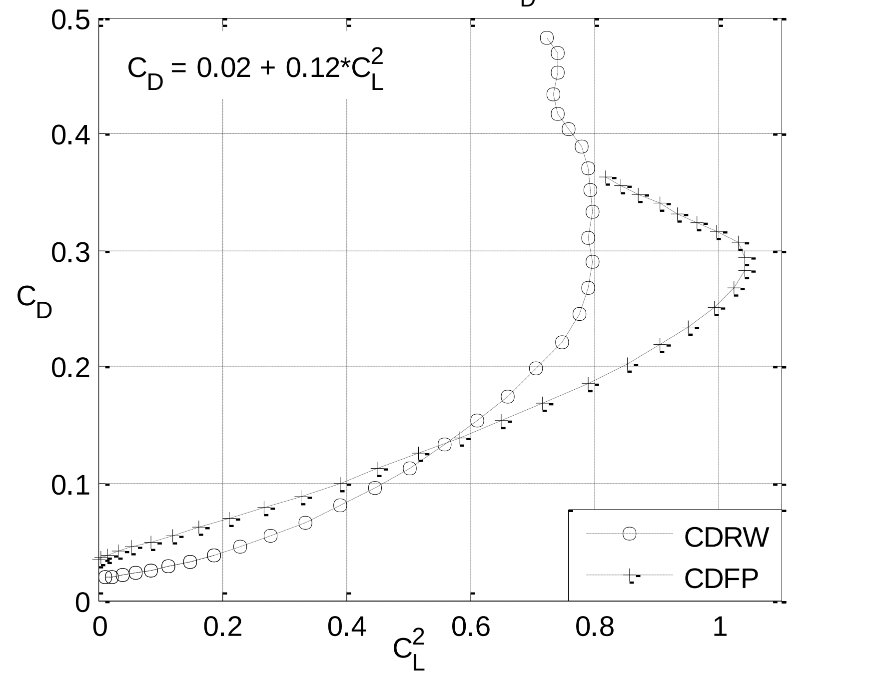
$$k = 0.16$$

$$\Downarrow$$

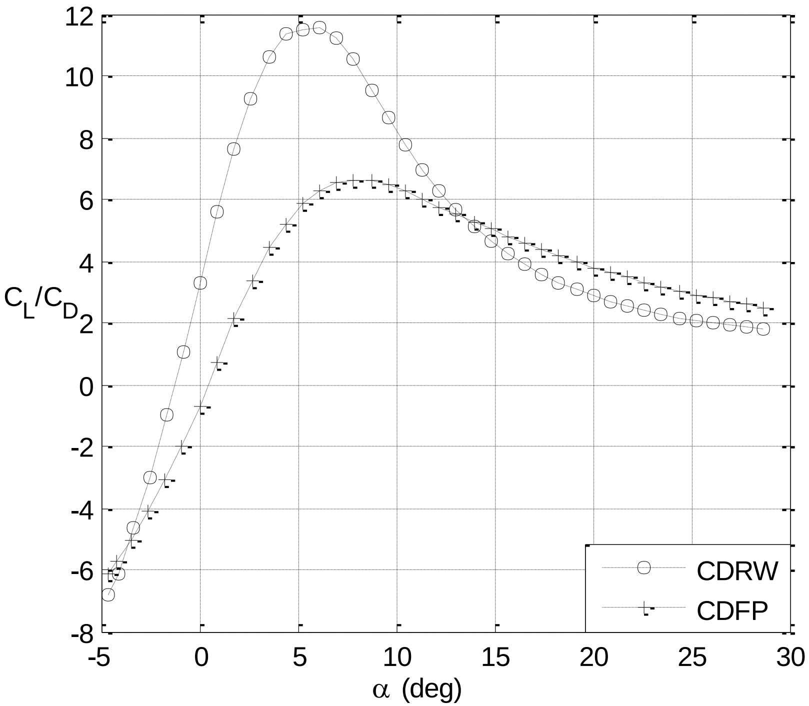
$$e = {}^{1}/_{(\pi k AR)} = 0.69$$

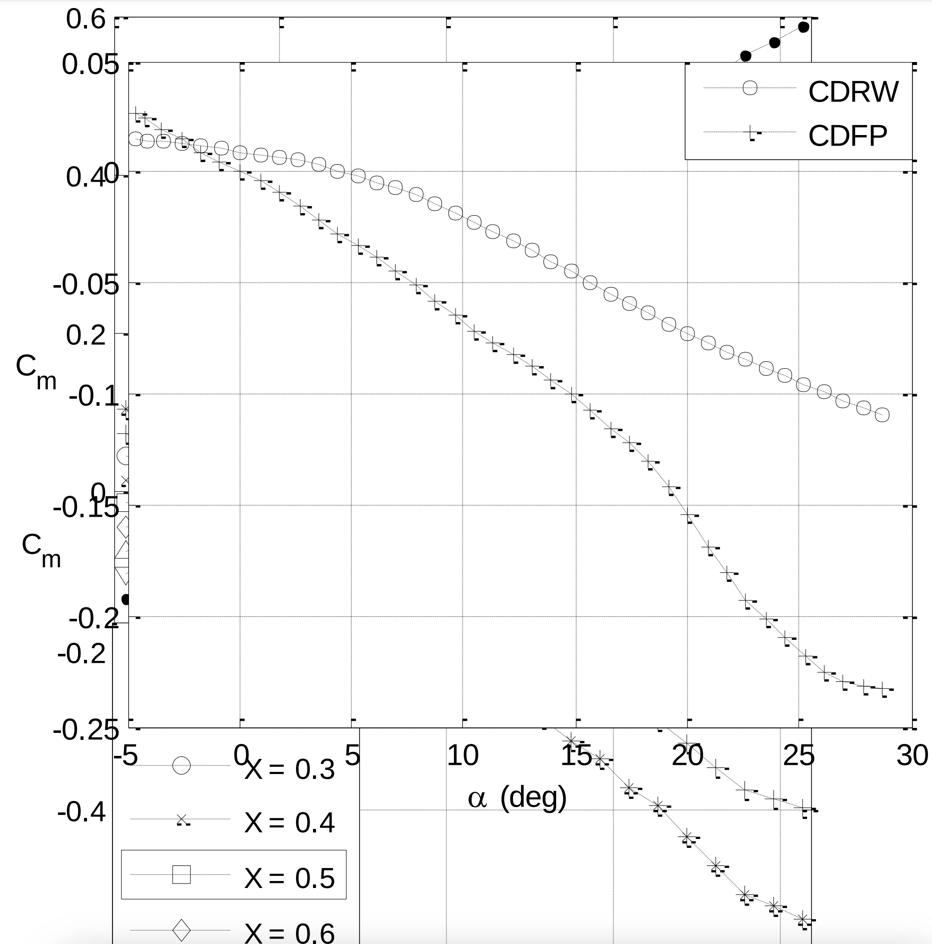


Parameters	CDFP	CDRW
C_{L_0}	0	0.067
C_{D_0}	0.035	0.020
C_{L_α}	3.273	2.981
$C_{L_{max}}$	1.022	0.923
α_{stall}	20.89^0	19.51^0
k	0.16	0.12
e	0.69	0.92



Aerodynamic Model → WIND TUNNEL TESTING → **Generated Aerodynamic Database**

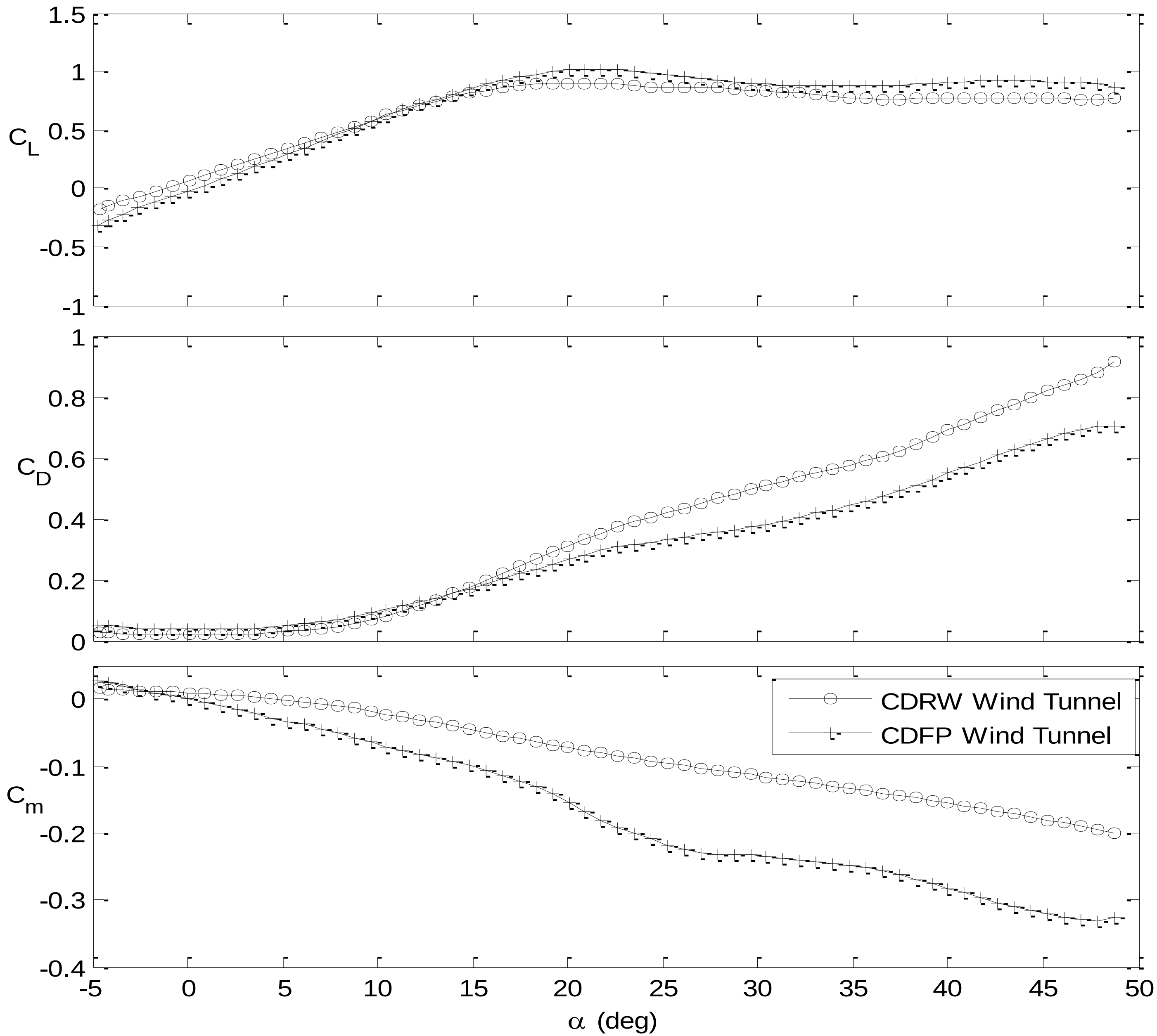




Parameters	***CDFP***	***CDRW***
$\left(\frac{L}{D}\right)_{max}$	*6.62*	*11.59*
$\alpha_{(\frac{L}{D})_{max}}$	*7.8⁰*	*6.1⁰*
$C_{L_{(\frac{L}{D})_{max}}}$	*0.46*	*0.39*
$C_{D_{(\frac{L}{D})_{max}}}$	*0.067*	*0.032*

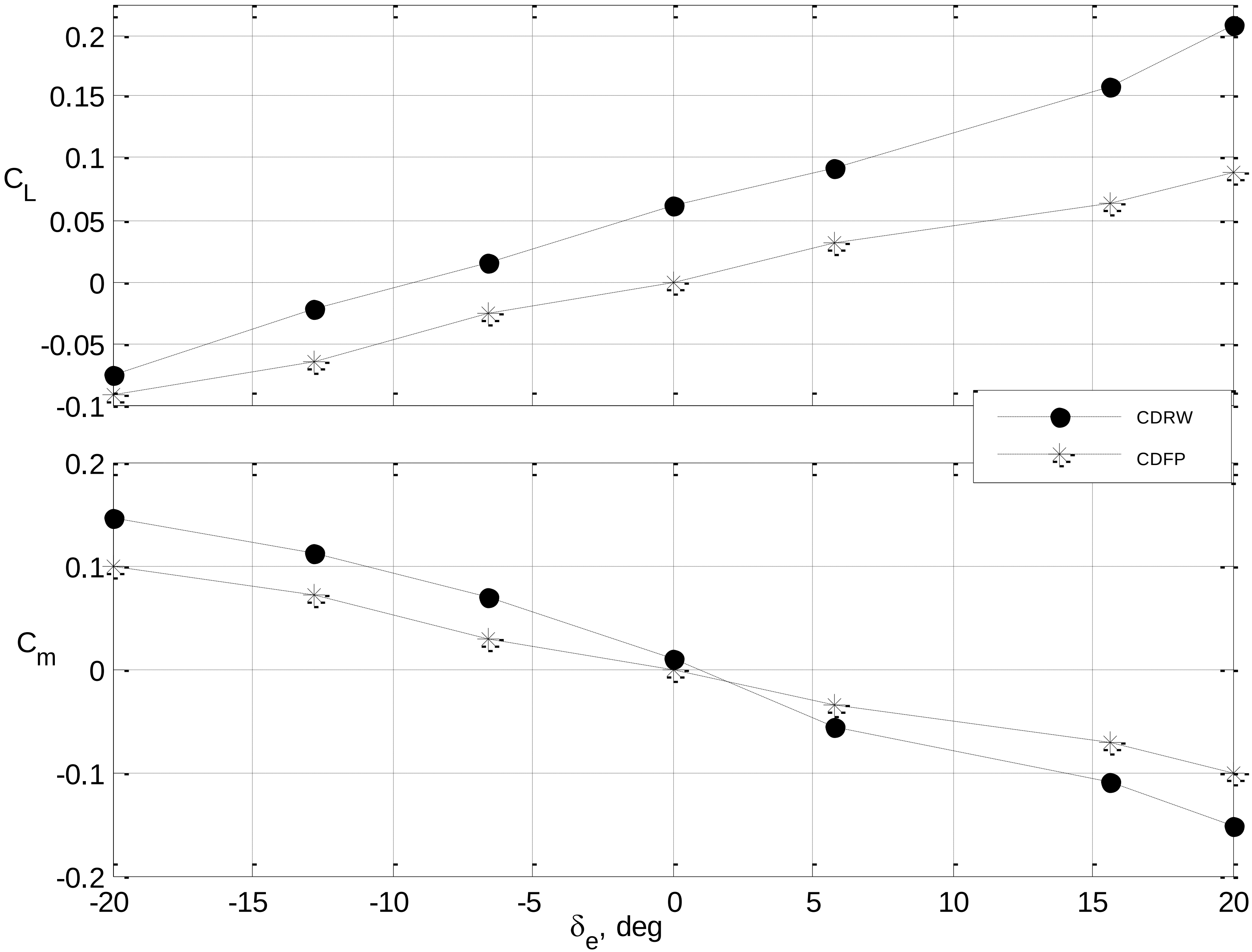
Parameters	***CDFP***	***CDRW***
C_{m_0}	*0*	*0.01*
C_{m_α}	*-0.383*	*-0.239*

WIND TUNNEL TESTING → **Generated High Angle of Attack Aerodynamic Database**



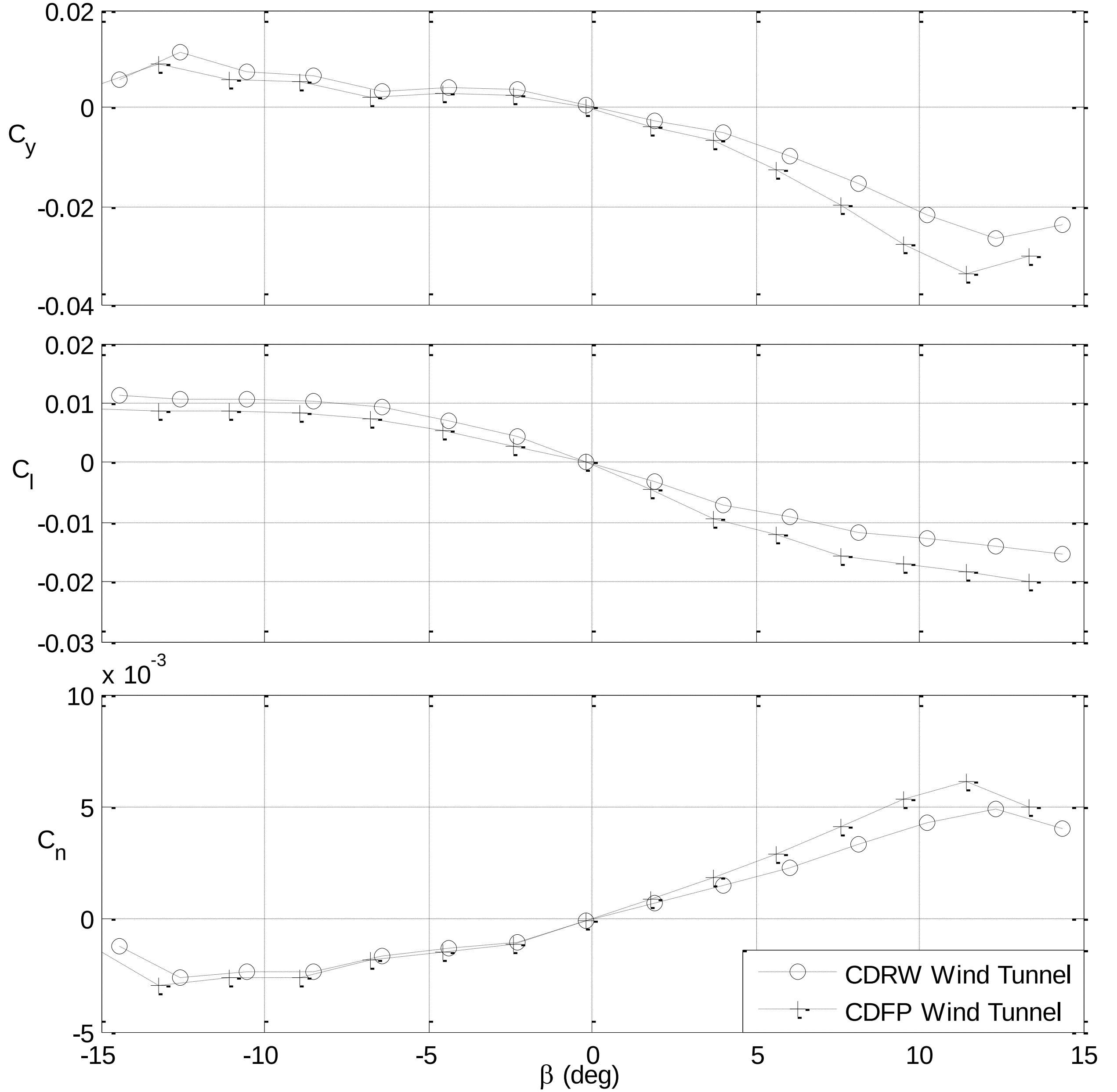
High angle of attack Longitudinal Wind Tunnel data : ***CDRW, CDFP***

WIND TUNNEL TESTING → **Generated Aerodynamic Database – CDFP & CDRW**

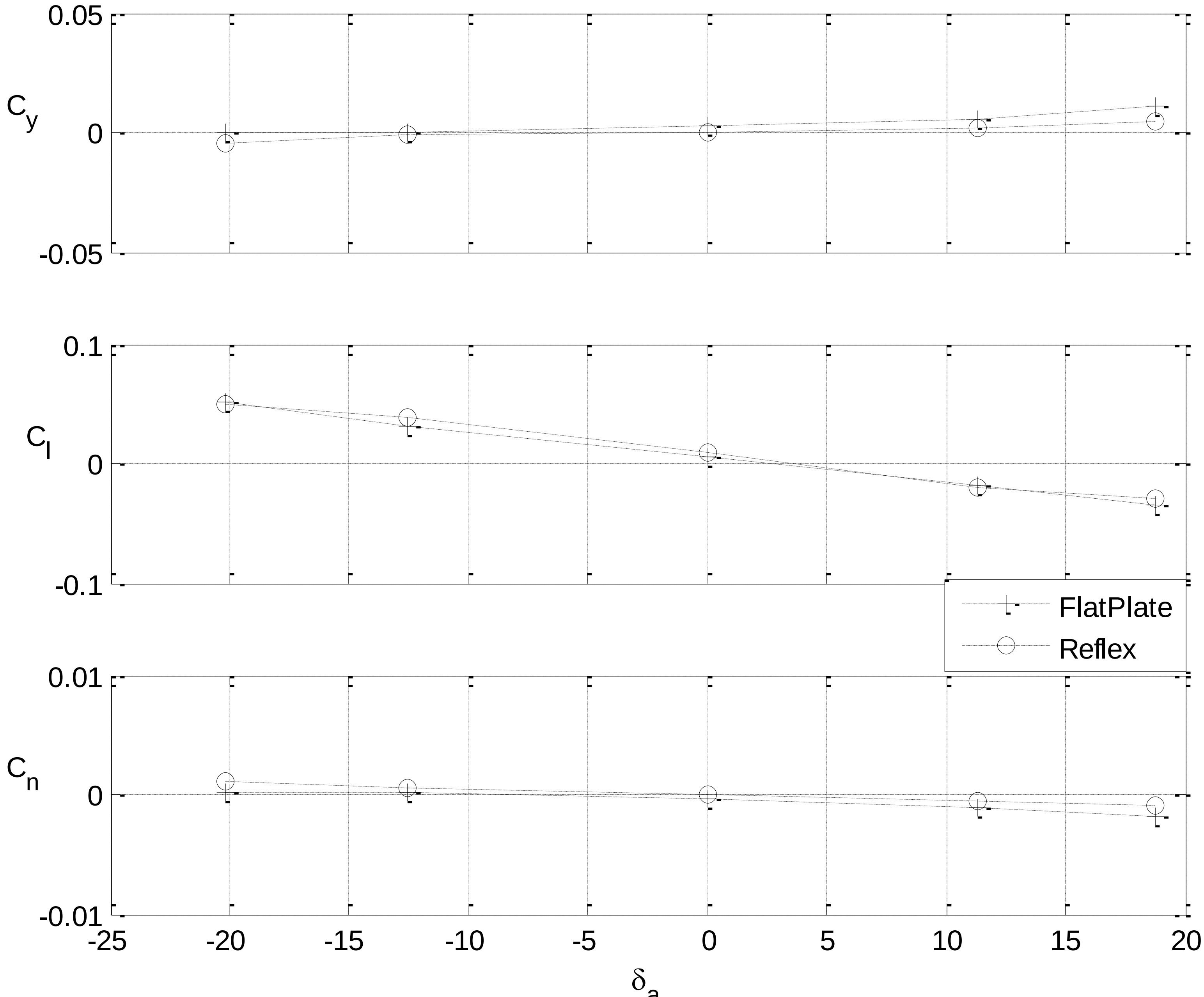


Comparison of variation of C_L and C_m with δ_e of CDRW and CDFP configurations

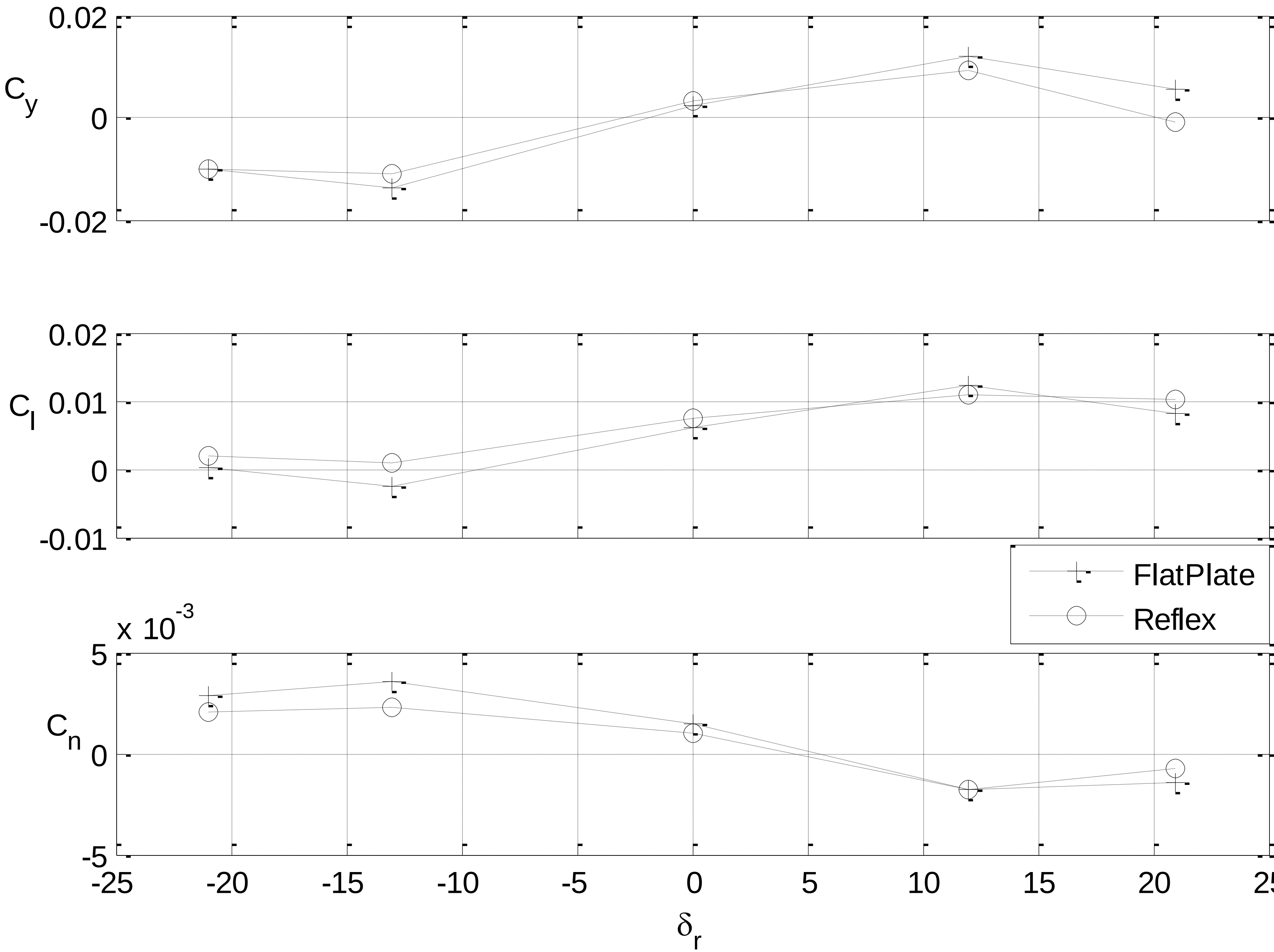
WIND TUNNEL TESTING → **Lateral – Directional Aerodynamic Database**



Variation of C_y, C_l and C_n with β for the CDFP and CDRW UAVs during wind tunnel testing



Variation of C_y, C_l and C_n with δ_a for the CDFP and CDRW UAVs during wind tunnel testing



Variation of C_y, C_l *and* C_n with δ_r for the CDFP and CDRW UAVs during wind tunnel testing

Queries


Thank You
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