Modeling & Identification of Rotary Wing Unmanned Aerial Vehicle

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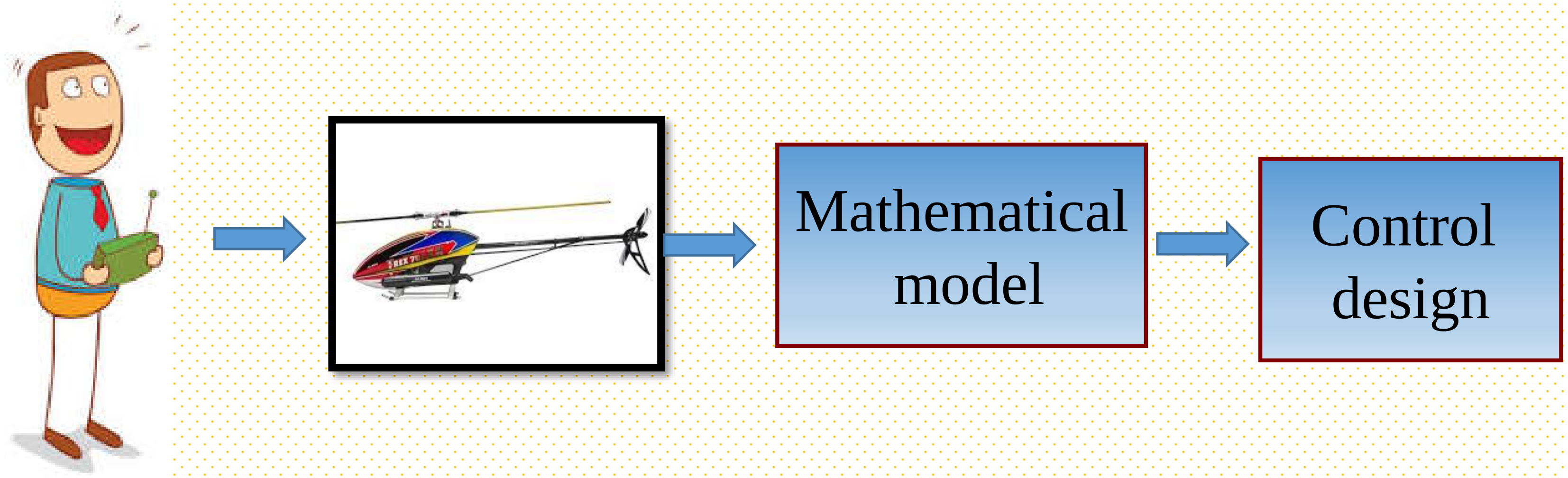
Content

Problem Statement

Development of 6DOF linear state-space model which accurately captures the key dynamics of small-scale unmanned rotorcraft for model based control design.

System identification technique is used to develop the mathematical model using dynamic flight test data.

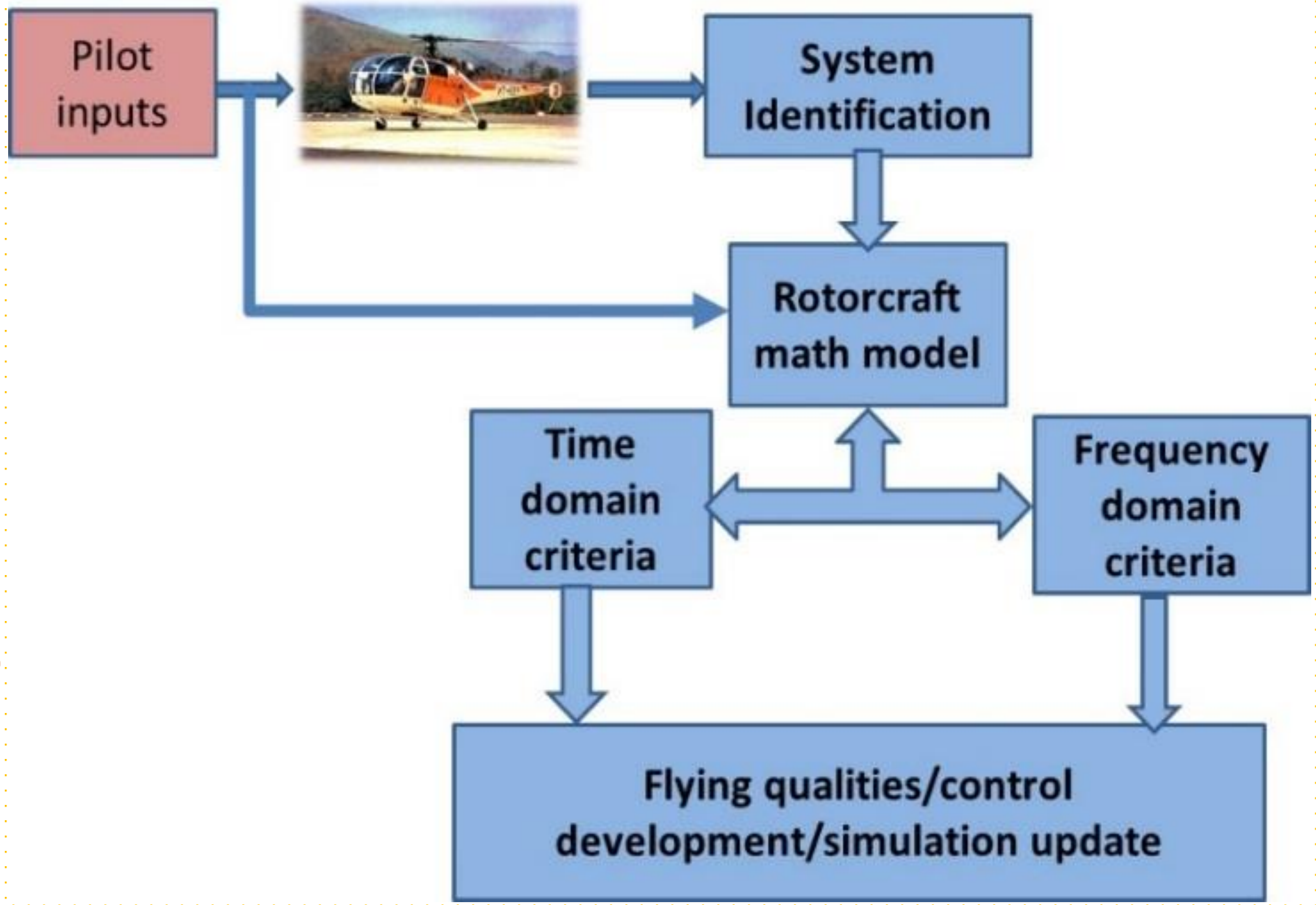


Challenges

- Design & execution of maneuverers which excites the modes of the vehicle.
- Reduced signal to noise ratio in the measurements.
- Unstable behaviour, tests needs to be carried out with autopilot.
- Determining the structure of the model.
- Good understanding of rotor aeromechanics.
- Highly non linear model across the operating conditions.
- Model identification at Low speed (hover).

Approach

- Specially designed control inputs are applied.
- Tools for data processing.
- Sophisticated methods of system identification.
- Mathematical model based on the application.
- Model acceptance criteria.
- Model validation and release to user.



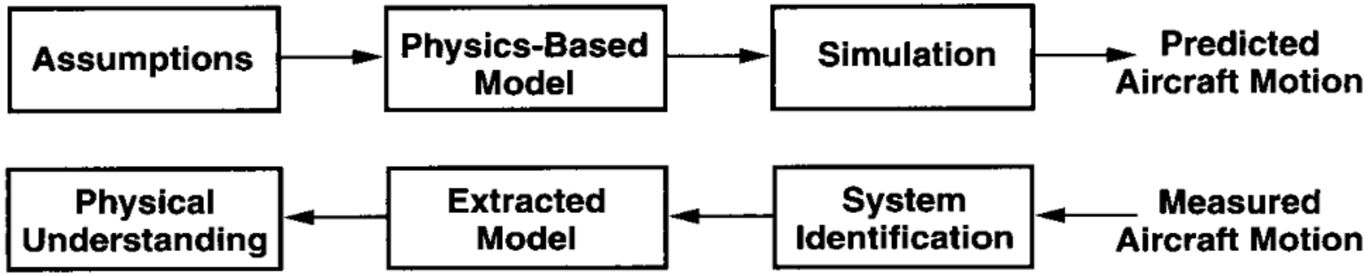
Rotorcraft Model Development

Different approaches

- Wind tunnel testing.
- Nonlinear generic models.

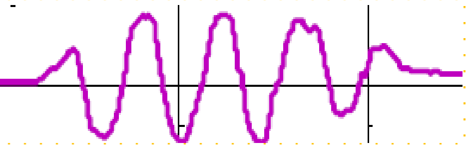
  Uses 1st principles to build up models of the helicopter using knowledge and assumptions of the physical characteristics of each component aspect of the helicopter.

- Derivative models from the flight test data using system identification techniques.

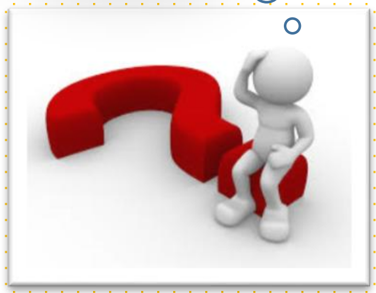


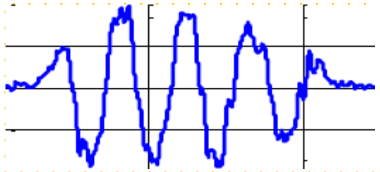
Simulation vs system identification.

Modeling & Identification



Input u(t)





Output y(t)

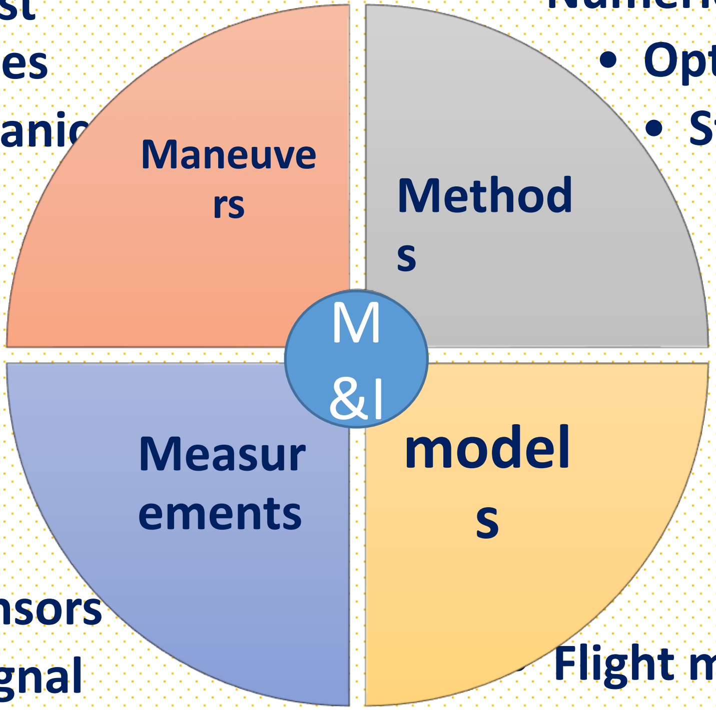
$$
\begin{aligned}
\dot{x}(t) &= f\,[x(t), u(t), \beta] \\
y(t) &= g[x(t), u(t), \beta] \\
z(t_k) &= y(t_k) + Gv(t_k)
\end{aligned}
$$

To determine the unknown parameters β such that model response Y matches measured response Z.

QUAD-M Process

- **Flight test techniques**
- **Flight mechanics**

- **Numerical techniques**
- **Optimization**
- **Statistics**



- **Sensors**
- **Signal conditioning**

- **Flight mechanics**
- **Control theory**

Interdisciplinary task which needs domain expertise.

Steps in Rotorcraft System Identification

Data preprocessing and sensor characterization	• Filtering ,Manuever extraction, Kinematic consistency checks.
Non Parametric identification	• Frequency domain analysis using phase , magnitude and coherence. • Model order at different frequency range.
Rotorcraft model development	• Model structure with sufficient degrees of freedom for the application to be developed.
Parameter estimation	• Using time domain identification techniques such as Output Error, Extended Kalman Filter for State Space Modeling. • Transfer function modeling.
Model Validation	• Apply frequency domain and time domain critertia,statistical measures.

Tools used @ each stage

Data preprocessing

&

Sensor characterization

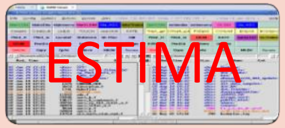
MATLAB

Non Parametric identification

MATLAB

Model development &

Parameter estimation



MATLAB

Model Validation

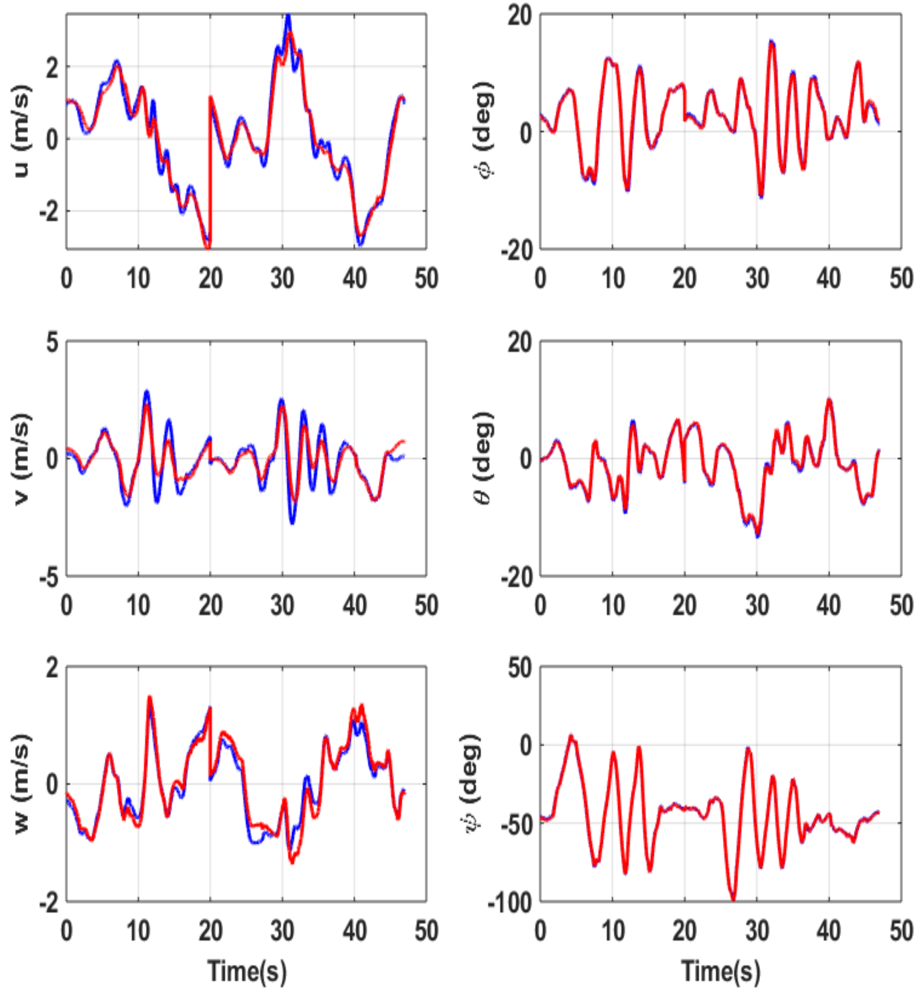
MATLAB

Documentation

MATLAB

Data Preprocessing & Sensor Characterization

- Data Acceptance: Coherence of input – output
- Signal Filtering : accelerations
- Data check independent of system identification to ensure that the measurements are error free and consistent
    - Also called flight path reconstruction (FPR)
    - Estimation of calibration errors (bias, scale factor, time delay errors…)
- Basis for verifying compatibility of measurements is the use of kinematic relationships



Model Formulation

- Non parametric modelling
- Transfer function modelling
  - SISO models

$$T(s) = \frac{(b_0 s^m + b_1 s^{m-1} + \cdots + b_m)e^{-\tau_{eq}s}}{(s^n + a_1 s^{n-1} + \cdots + a_n)}$$

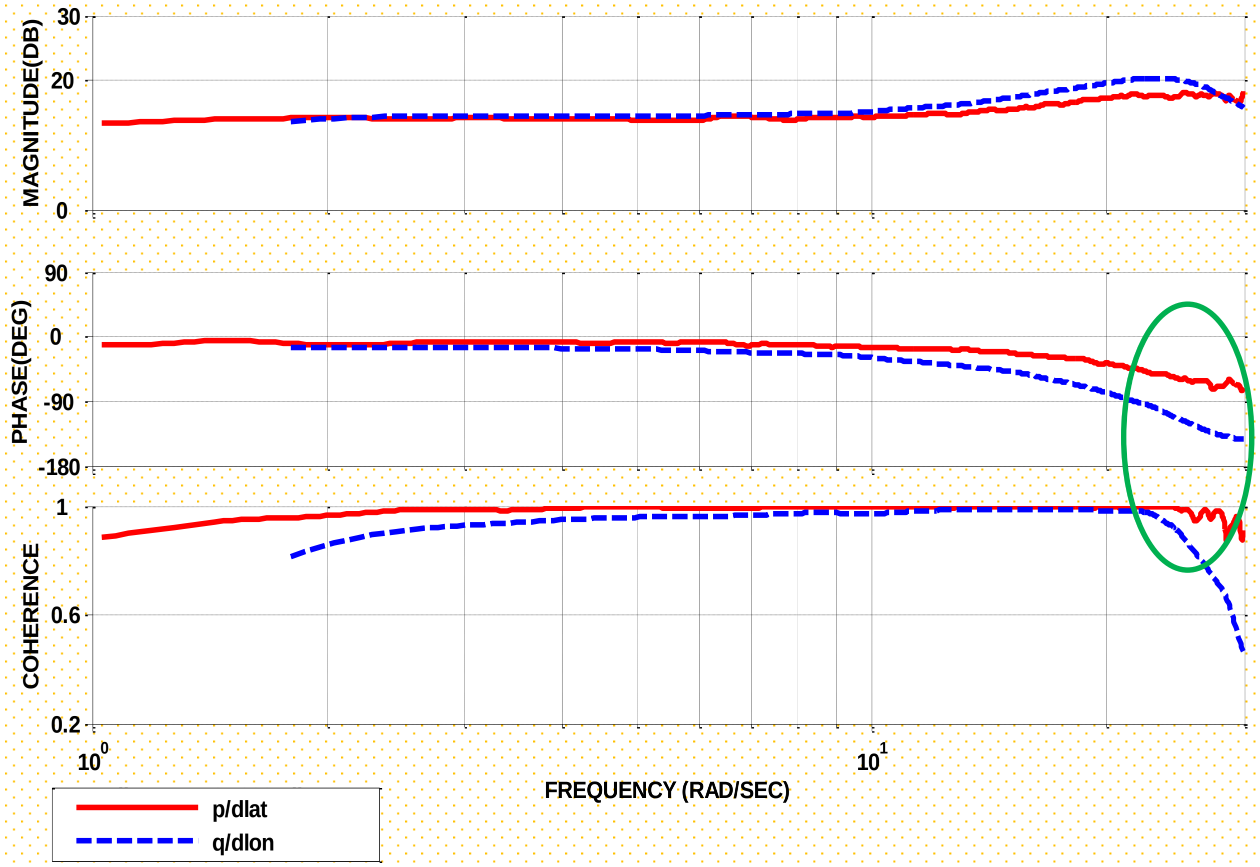
- State space modelling
  - MIMO models

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$
$$z(t_k) = y(t_k) + Gv(t_k)$$

✓ Least no. of parameters which characterize the system.
✓ Initial values for MIMO modelling
✓ Pole-zero modelling of on axis response
✓ Numerator–denominator polynomials
✓ Black box modelling

✓ Characterize the whole system
✓ Physics based modelling
✓ Time domain techniques
✓ Frequency domain techniques
✓ On axis as well as cross coupling derivatives

Non Parametric Model Identification



- Input-output relationship of the vehicle dynamics is analyzed from the gathered data using frequency responses and coherence.
- Provides an excellent in sight to selecting the order of the model in the frequency range of interest
- Can be used to analyze the handling quality and stability margin of the vehicle

Helicopter State Variable Model

$$\dot{x} = Ax + Bu$$

$$x = \begin{bmatrix} w & u & q & \theta & \vdots & p & r & v & \varphi & \vdots & \beta_a & \beta_e \end{bmatrix}^T$$

$$u = \begin{bmatrix} \delta_c & \delta_a & \delta_e & \delta_p \end{bmatrix}^T$$

$$A = \left[\begin{array}{c|c|c} \text{Long} & x & x \\ \hline x & \text{Lat} & x \\ \hline x & x & \text{Rotor} \end{array}\right]$$

Rotor States

β_a : Long flap angle

β_e : Lat flap angle

Controls

δ_c : Collective

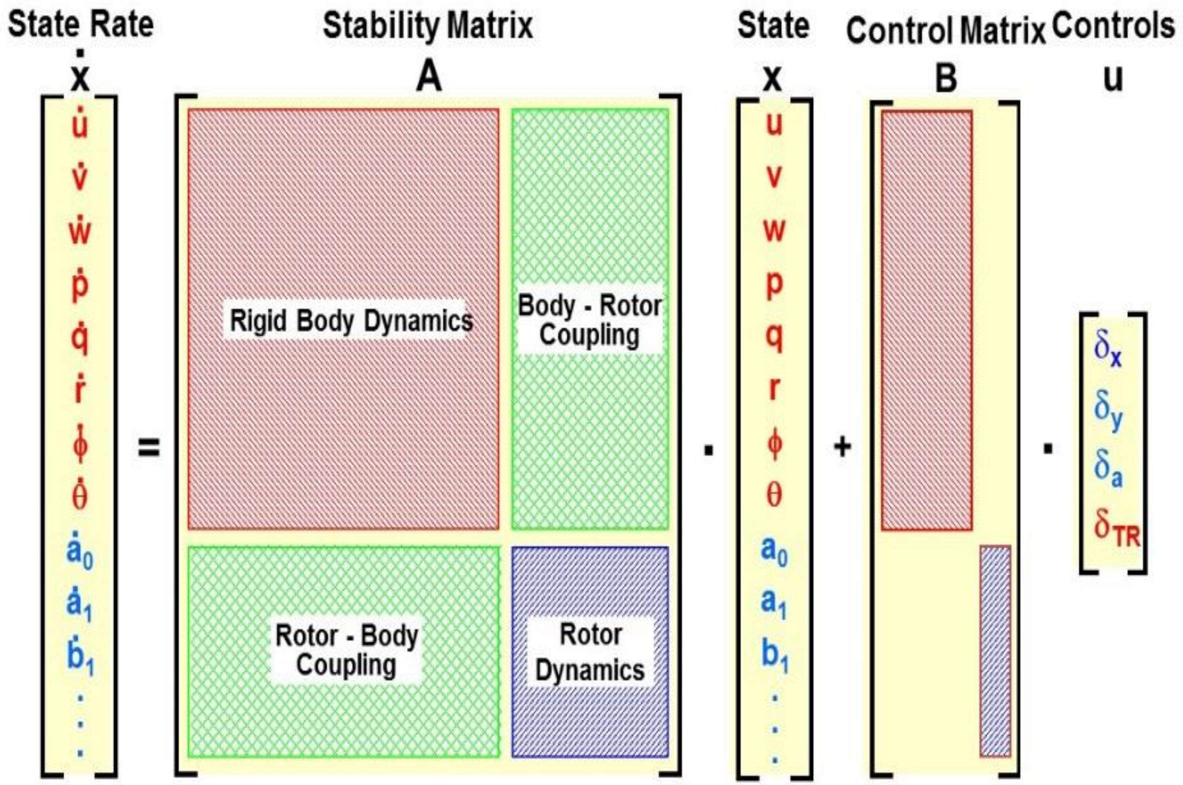
δ_a : Long Cyclic

δ_e : Lat Cyclic

δ_p : Pedal

Advanced Models for Rotorcraft Dynamics

- An appropriate mathematical model which affects both the complexity and the utility of the identified mode
- Models of different order may be used
  - Measurements available
  - Frequency range of application
  - Degree of coupling between the longitudinal and lateral directional motions



- Nearly 60 unknown derivatives
- 6DOF model found to be inadequate at higher frequencies

Time Domain Parameter Estimation

Stabilized Output Error Method and Extended Kalman Filter are used for estimation

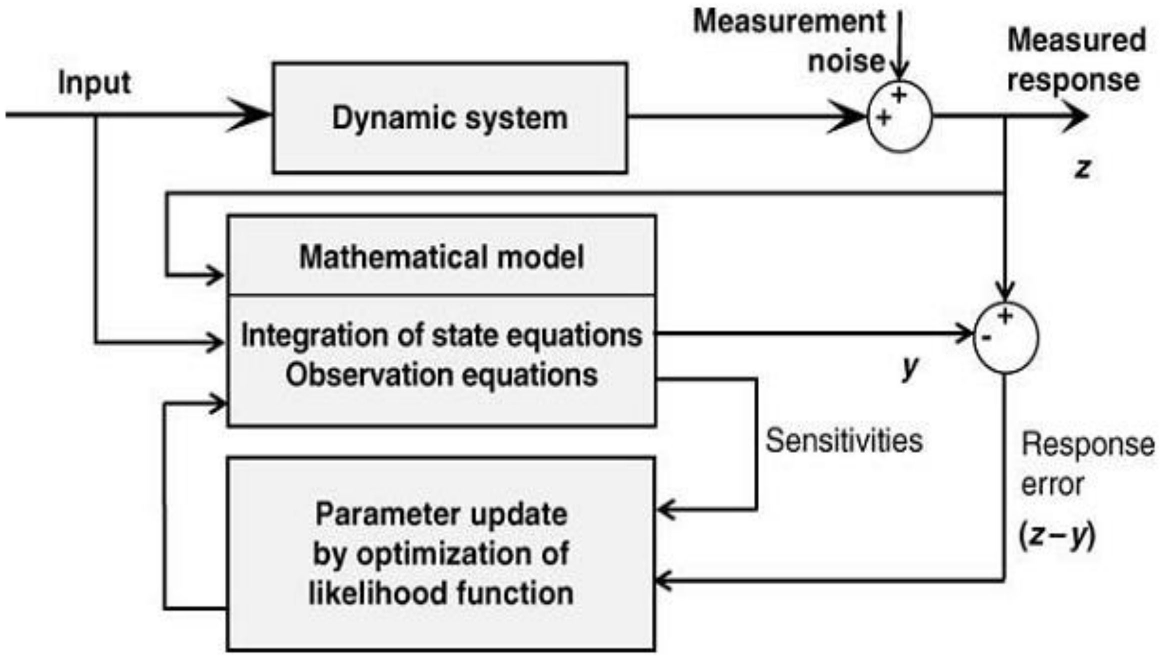
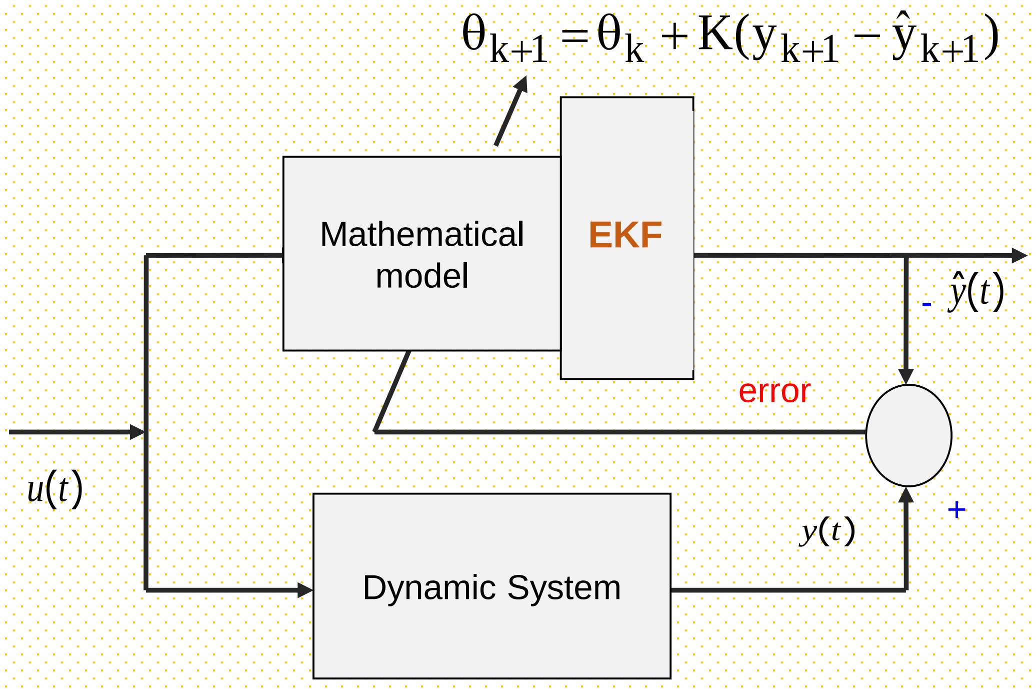


Fig. 4.1 Block schematic of output error method.



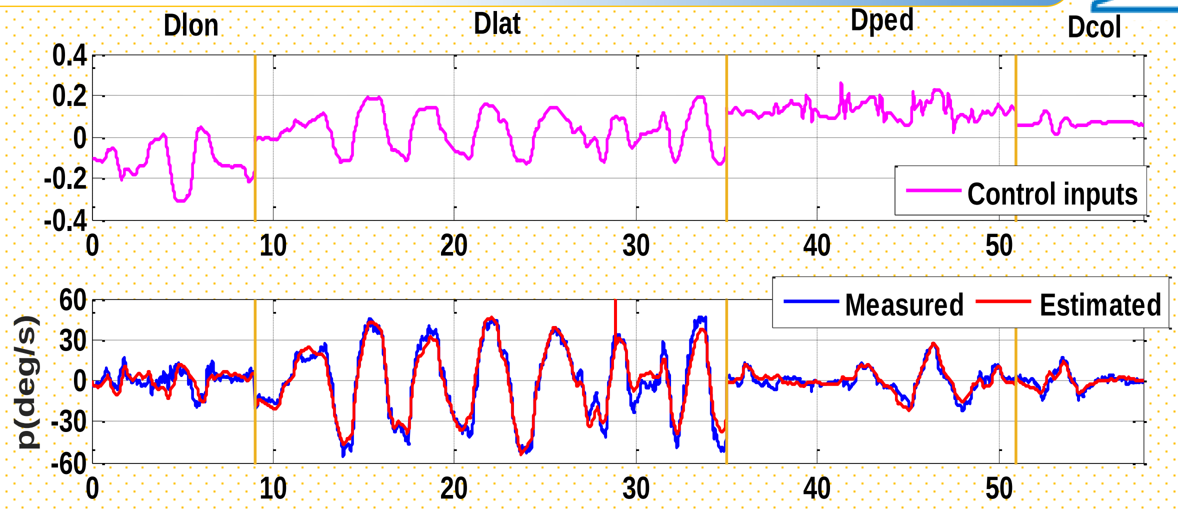
Block diagram of Extended kalman filter

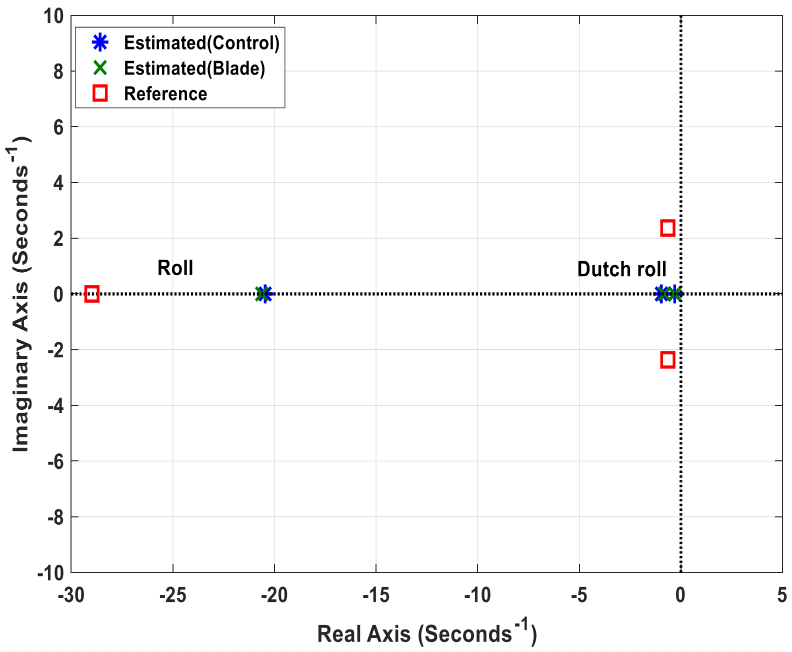
Results

Derivative estimation is carried out using output error method(OEM) and Extended Kalman Filter(EKF).

Stability analysis carried out using Eigen values & Eigen vectors.

Derivatives are compared with the values from first principle



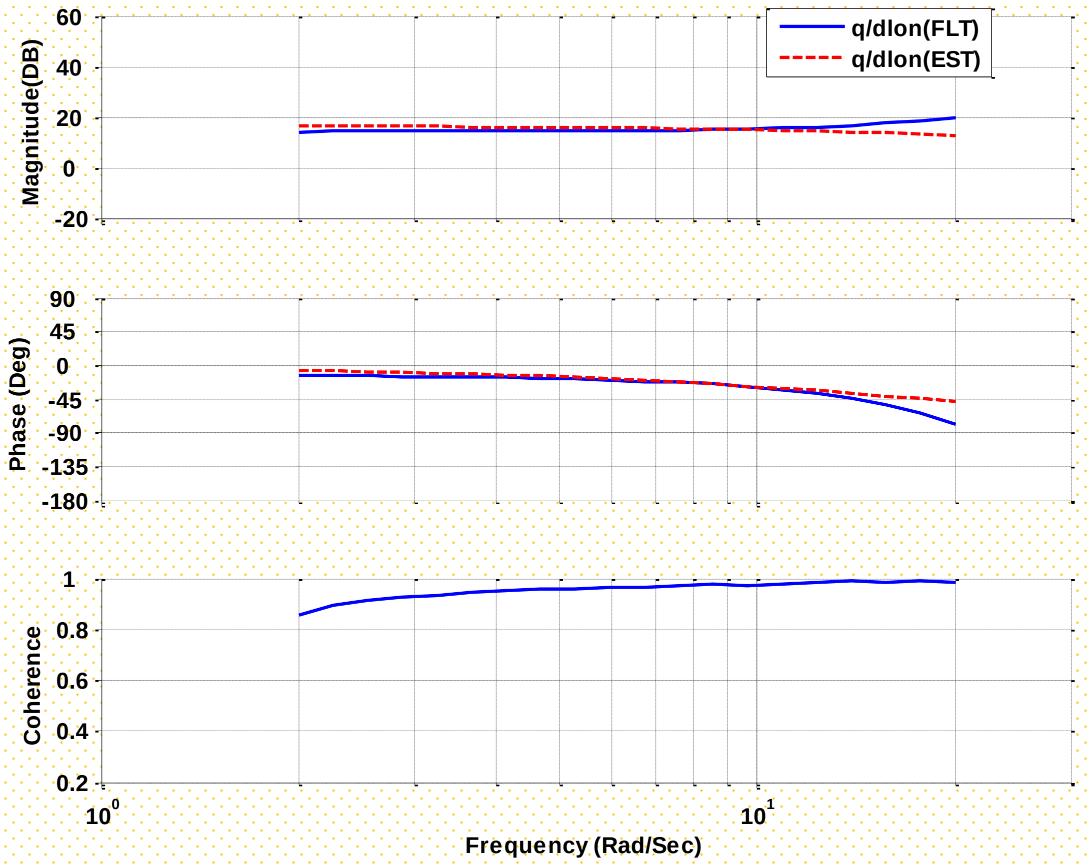


Model validation

- **Complementary dataset** : The trajectories are simulated using the identified model and compared with measured flight data.

- **Statistical analysis** : Computation of standard deviation and Cramer-Rao bounds

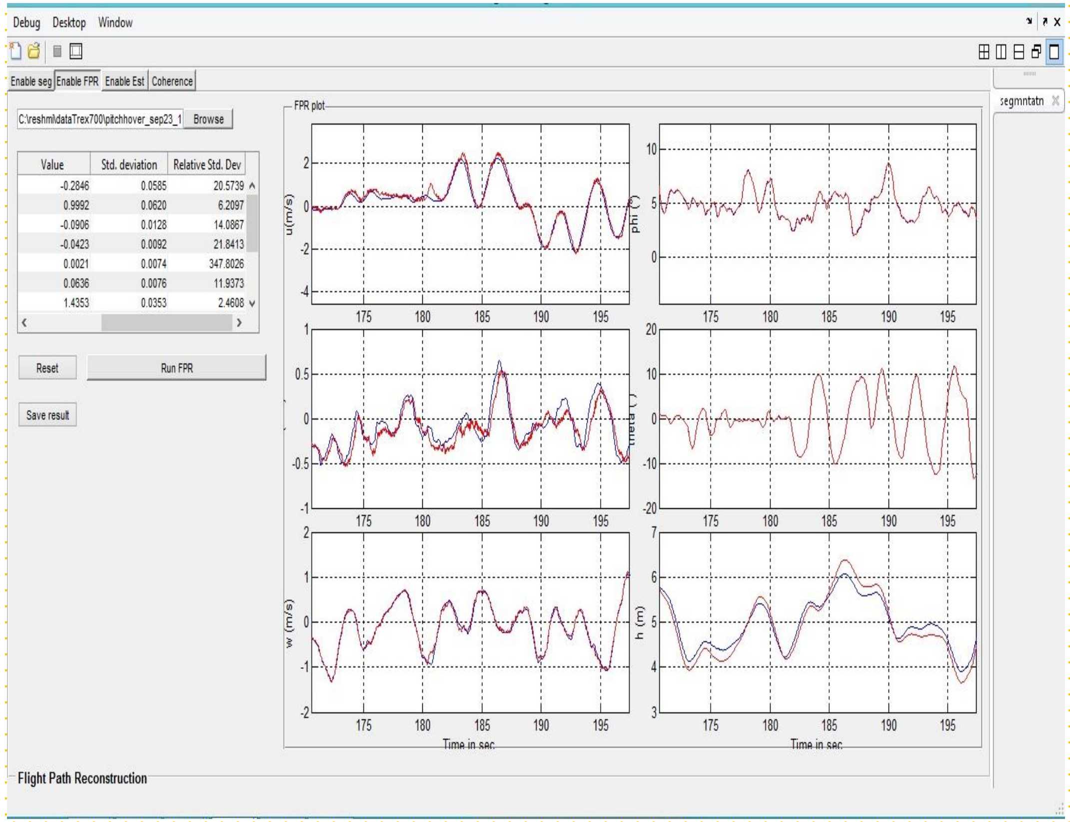
- **Frequency domain validation**: The measured and model predicted responses are compared in frequency domain



Frequency response match for model validation

Key Take Away

- 6DOF State Space model for a small scale UAV rotorcraft was developed using system identification techniques.
- Both time & frequency domain algorithms were used.
- MATLAB® is used extensively in the work for
  - Data processing.
  - SISO modelling &MIMO modelling.
  - GUI based for front end.
  - Result generation & documentation.
- Future work
  - Frequency domain parameter estimation using MATLAB®
  - Development of end to end solution for RUAV identification using MATLAB®.



GUI based for front end