High fidelity modelling for High Altitude Long Endurance Solar Powered Aircraft

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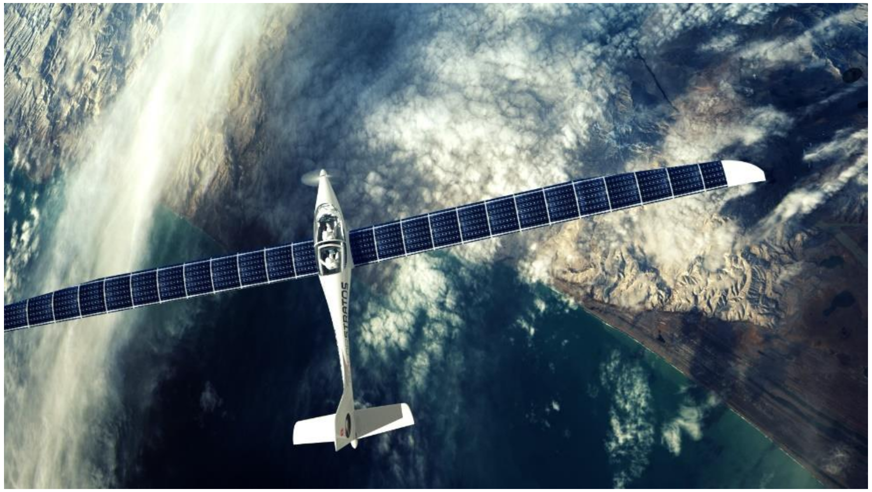
High Altitude Long Endurance (HALE) platforms

- Aerial platforms capable of stratospheric flight for a long period.
- Communication networks to recording of weather and environment.



- Topic: high fidelity modelling procedures for fixed wing platforms.

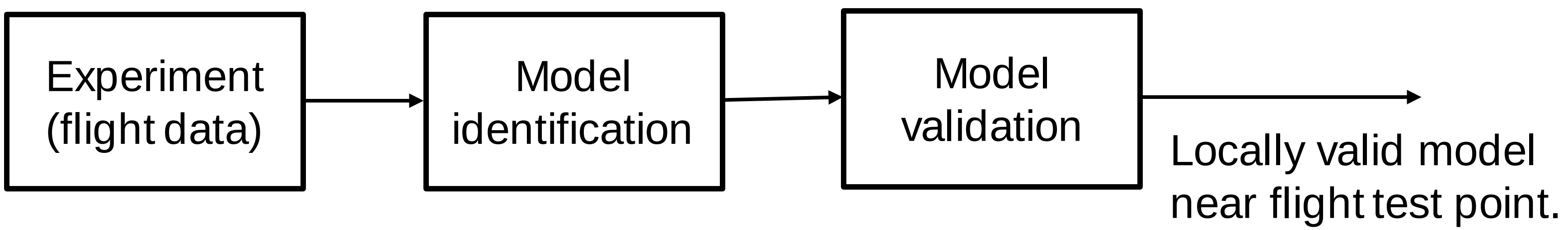
Motivation

- Why high fidelity models?
  - Reduce or avoid in-flight tuning of controller gains.
  - Model based control for landing on mobile platform.
  - Simulation of stratospheric mission.
- Platforms – Elektra 1 and Penguin BE UAV.

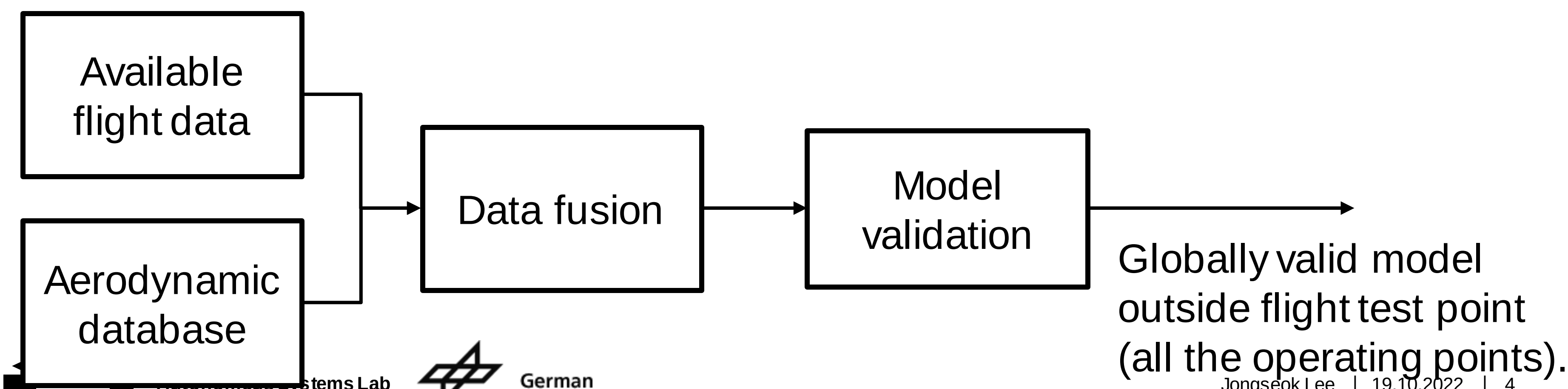
- Approach: local and global system identification.

Motivation

- Local system identification.



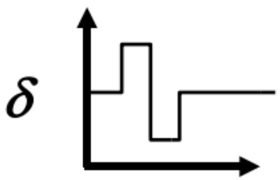
- Global system identification.



Overview

- Motivation.
- Aircraft system identification problem.
- Local system identification - two step method.
- Global system identification - incremental model update.
- Conclusion.

Aircraft system identification problem



Input u

System S

Output y

Given input u and output y find system S

$$m\dot{V} + \omega \times mV = F_{aero} + F_{thrust} + F_{gravity}$$

$$I\dot{\omega} + \omega \times I\omega = M_{aero} + M_{thrust}$$

Aircraft system identification problem

Applying multidimensional taylor series expansion:

$$\widehat{\boldsymbol{F}}_{\boldsymbol{x,aero}} = \mathrm{Fx}_0 + \mathrm{Fx}_\mathrm{u}\boldsymbol{u} + \mathrm{Fx}_\mathrm{w}\boldsymbol{w} + \mathrm{Fx}_\mathrm{q}\boldsymbol{q} + \mathrm{Fx}_\mathrm{de}\boldsymbol{de}$$

$$\widehat{\boldsymbol{F}}_{\boldsymbol{z,aero}} = \mathrm{Fz}_0 + \mathrm{Fz}_\mathrm{u}\boldsymbol{u} + \mathrm{Fz}_\mathrm{w}\boldsymbol{w} + \mathrm{Fz}_\mathrm{q}\boldsymbol{q} + \mathrm{Fz}_\mathrm{de}\boldsymbol{de}$$

$$\widehat{\boldsymbol{M}}_{\boldsymbol{y,aero}} = \mathrm{My}_0 + \mathrm{My}_\mathrm{u}\boldsymbol{u} + \mathrm{My}_\mathrm{w}\boldsymbol{w} + \mathrm{My}_\mathrm{q}\boldsymbol{q} + \mathrm{My}_\mathrm{de}\boldsymbol{de}$$

- 15 parameters for longitudinal dynamics (linear model).
- Physical quantities related to stability and control.
- Linear Vs nonlinear aerodynamic model.
- Local – one value for parameters; Global - sets of values.

Overview

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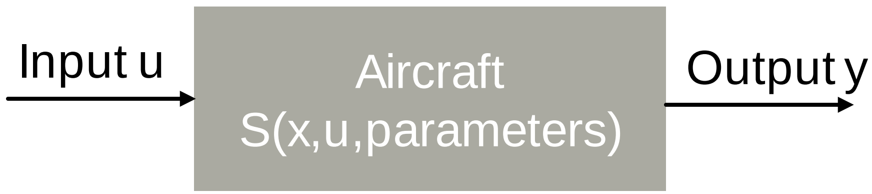
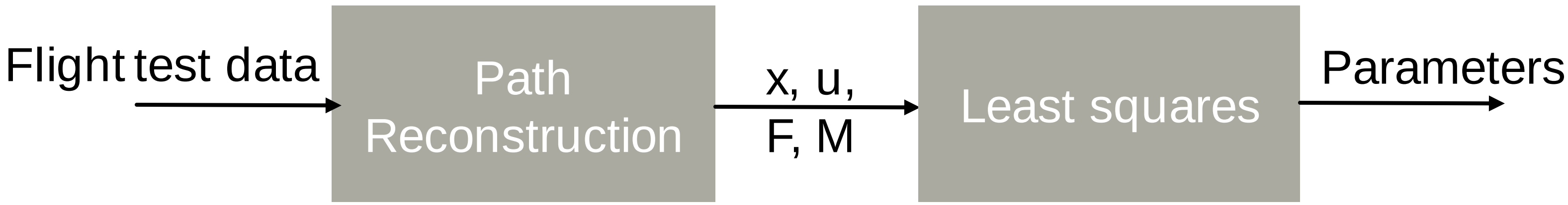
Local system identification - two step method

Approach: $\text{error} = y - S(x, u, parameters)$

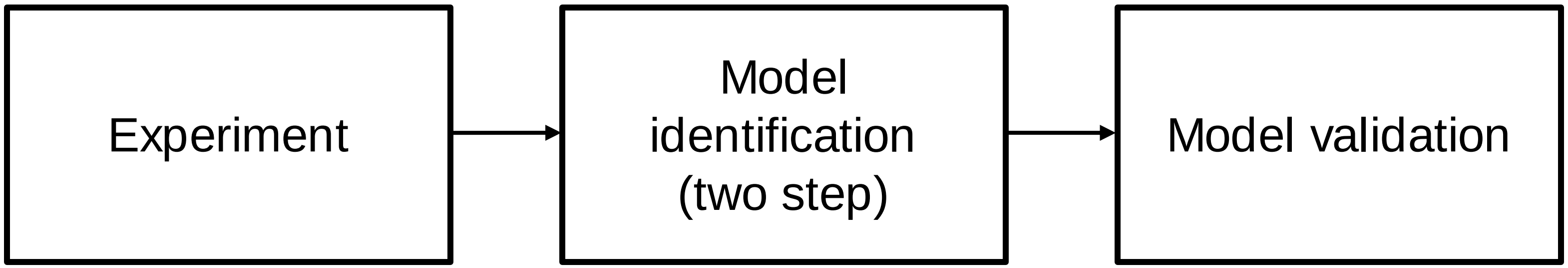




- Linear projection of features.

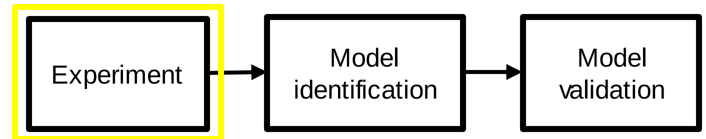
Local system identification - two step method

Procedures:



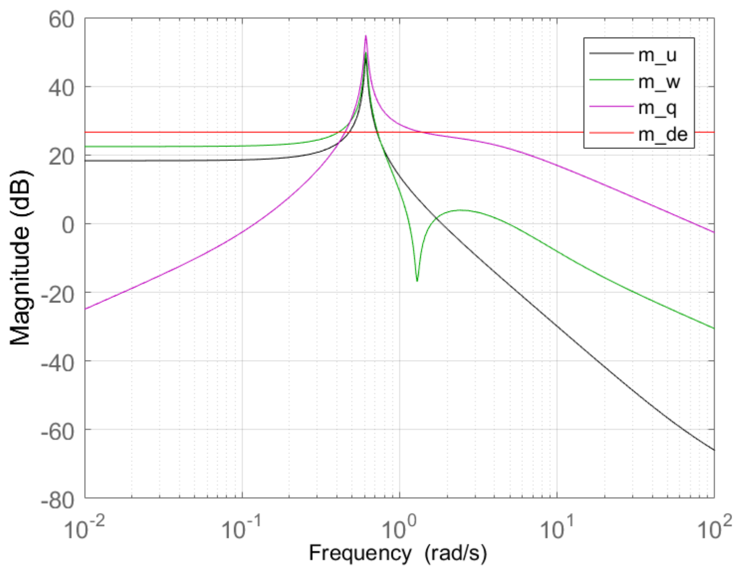
- Experiment: parameter identifiability.
- Reconstruction of path: IEKF estimation and smoothing.
- Parameter identification: linear regression.
- Model validation: statistics and controller synthesis.

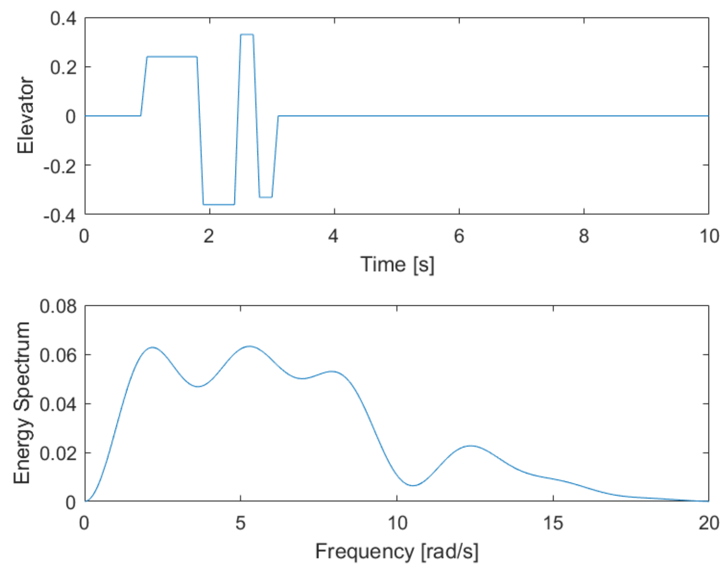
Local system identification - two step method



Input design and experimentation:

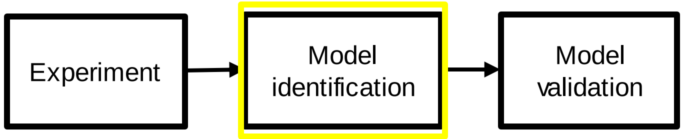
- Parameter identifiability – contribution is visible.





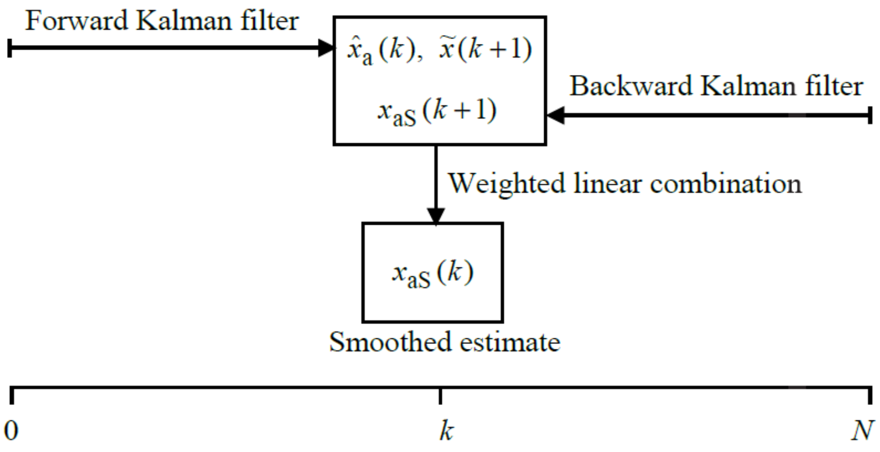
- 2 flights with Elektra 1 and 3 flights with Penguin BE.

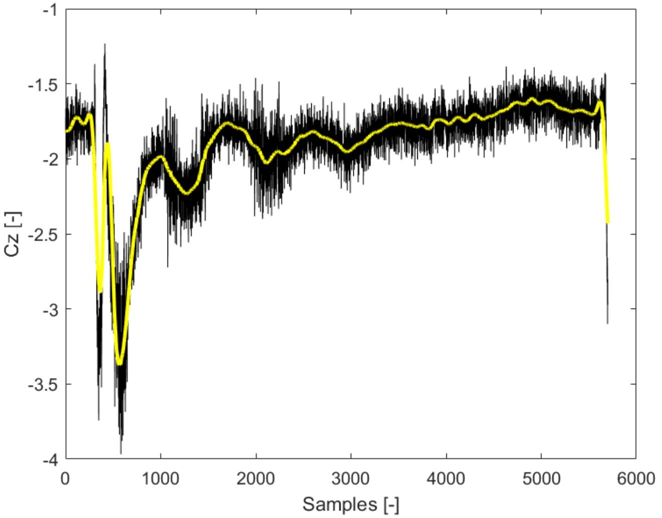
Local system identification - two step method



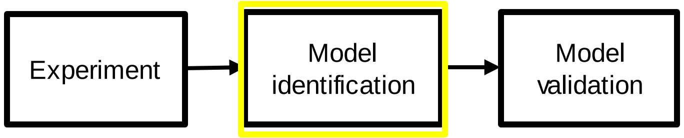
Path reconstruction:

- Smoothened estimate of states, forces and moments.
- Estimation of instrumentation errors.



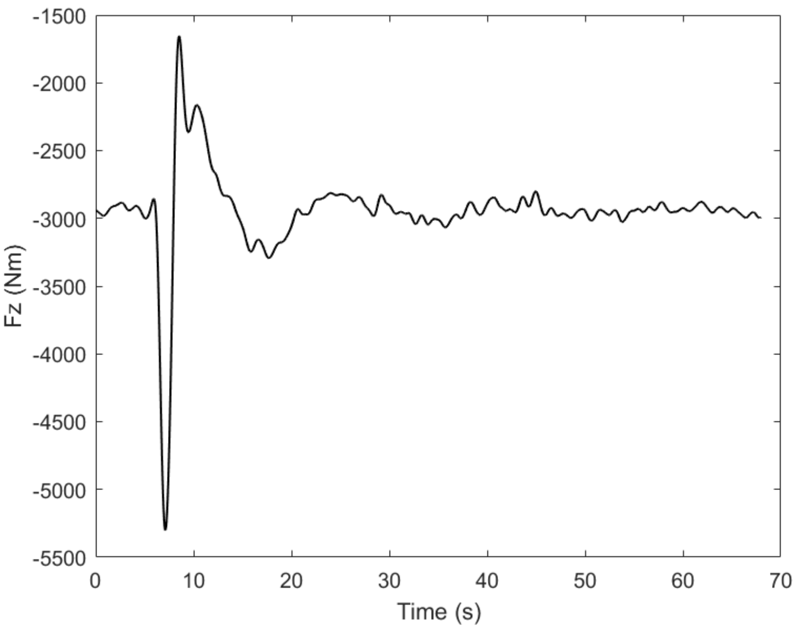


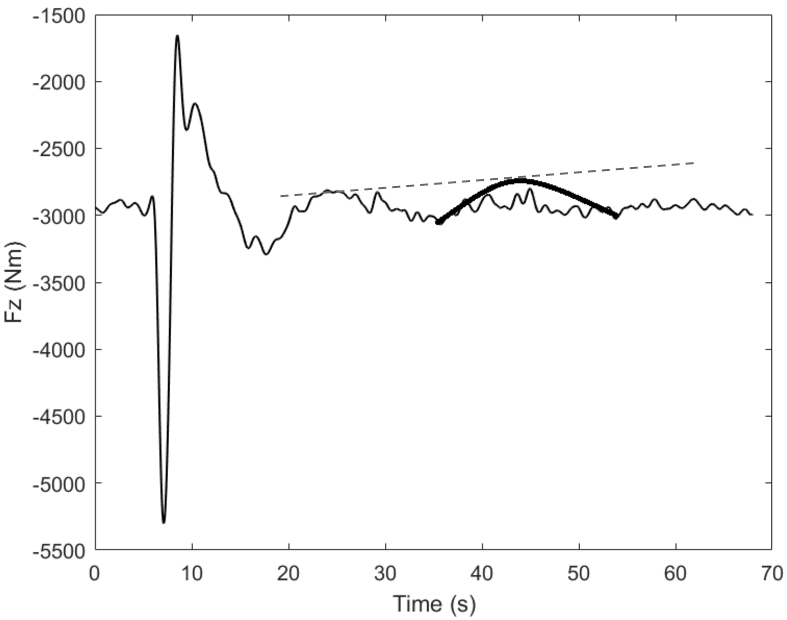
Local system identification - two step method



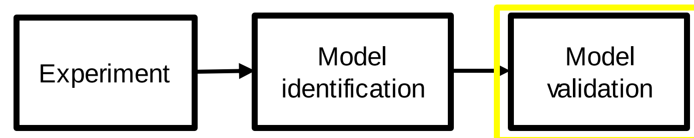
Parameter identification:

- Optimization – linear regression.
- Global minimum may not give correct parameters.
  - OLS Vs WLS Vs NLS Vs CLS.

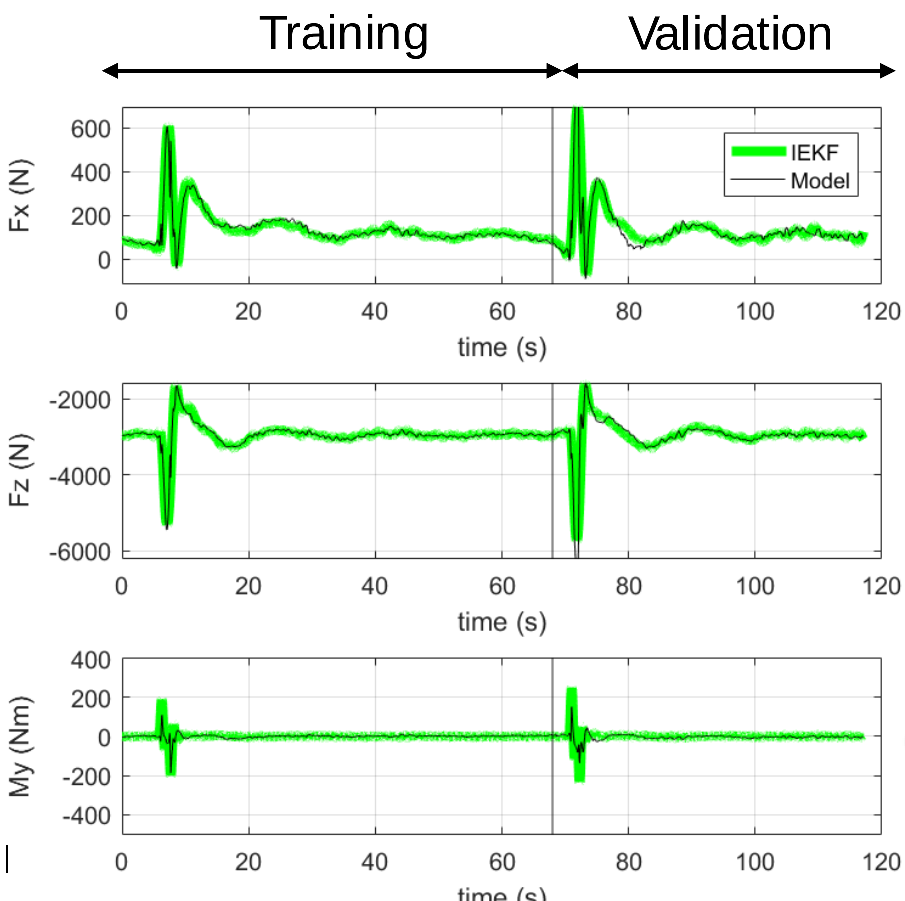




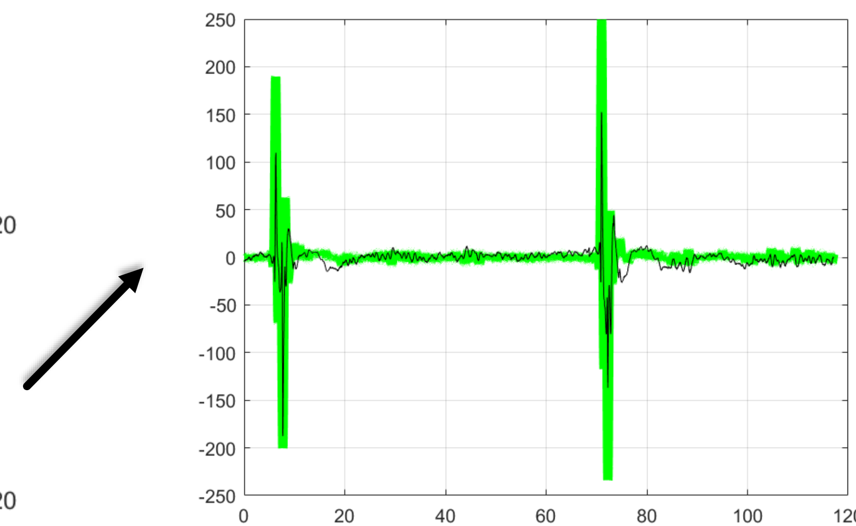
Local system identification - two step method



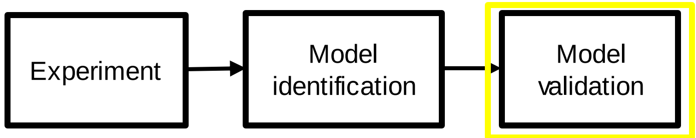
Model validation:



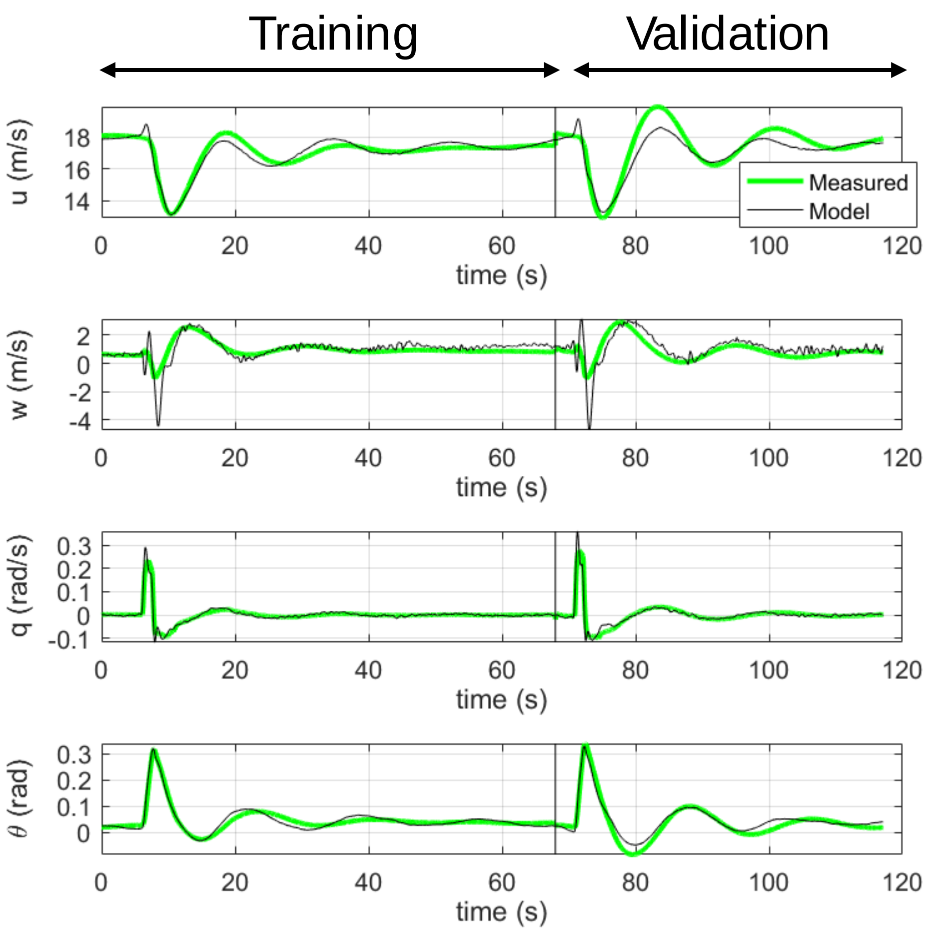
Coefficient	Rsquared [-]	NRMSE [-]
Fx	0.847	0.042
Fz	0.883	0.031
My	0.418	0.036



Local system identification - two step method



Model validation:



State	GOF [-]	TIC [-]
u (m/s)	0.8569	0.0133
w (m/s)	0.5576	0.2301
q (rad/s)	0.8507	0.1985
θ (rad)	0.9061	0.1289

- TIC 0.25 - 0.3 sufficient [Jategoankar 2006].
- Fulfills FAA standards of high fidelity model.

Overview

- Motivation.
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- Global system identification - incremental model update.
- Conclusion.

Global system identification – Incremental update

Approach 1: Current practice in the industry.

- Collection of data at all points of flight envelope.

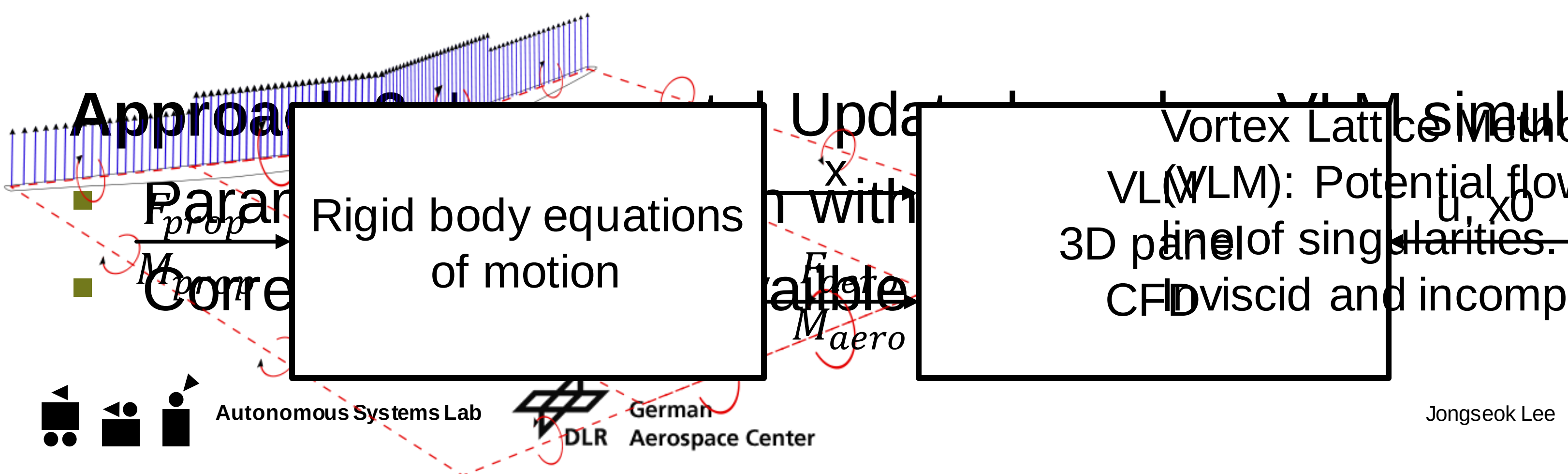
Approach 2: Incremental Update

- Data fusion of aerodynamic database with flight test data.
  - Aerodynamic database using windtunnel & CFD.

Approac… Upda… VLM simulation.

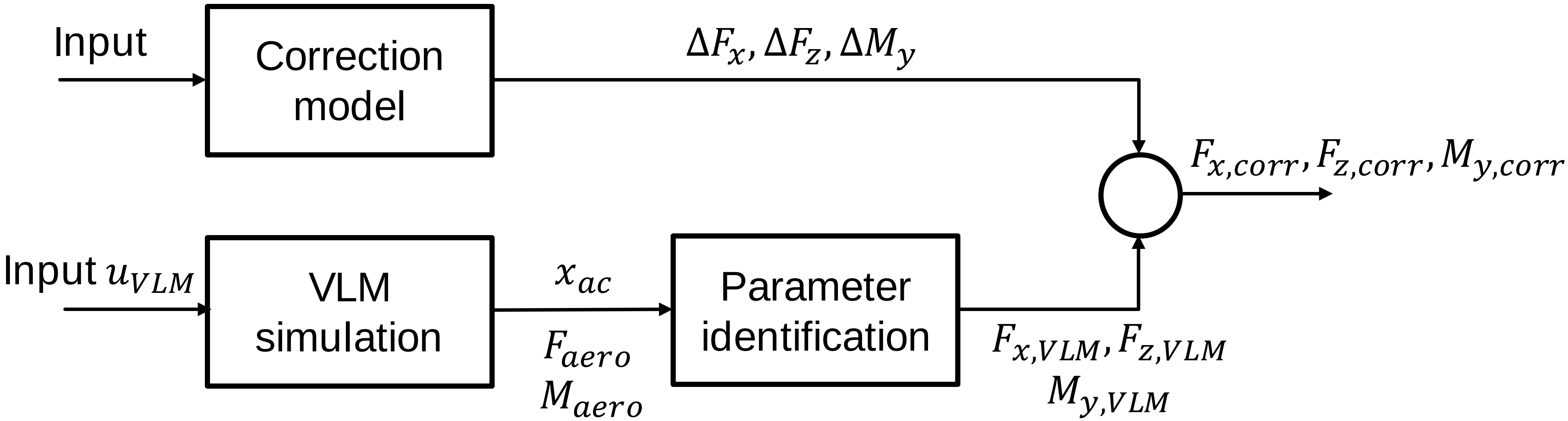
- Para… with
- Corre… able.

Vortex Lattice Method (VLM): Potential flow with a line of singularities.
Inviscid and incompressible.



Global system identification – Incremental update

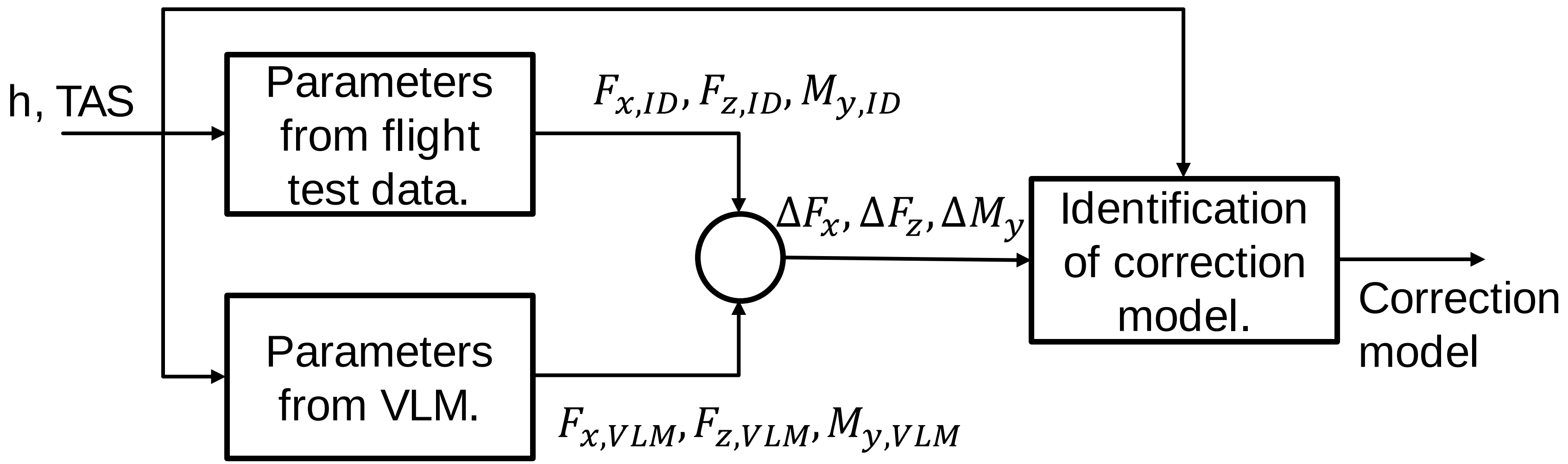
Method: Scheme for global system identification.



- Aerodynamic model outside the region of the flight data.
- Improvement in accuracy.

Global system identification – Incremental update

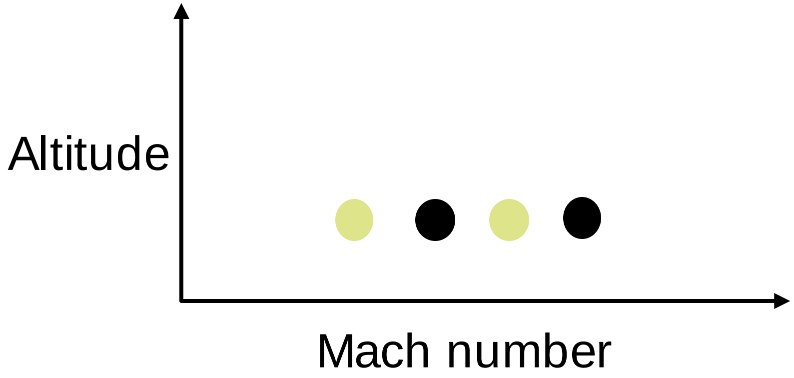
Method: Correction model identification.



- Correction model identification using available flight data.
- Separation of training and validation set via different trim.

Global system identification – Incremental update

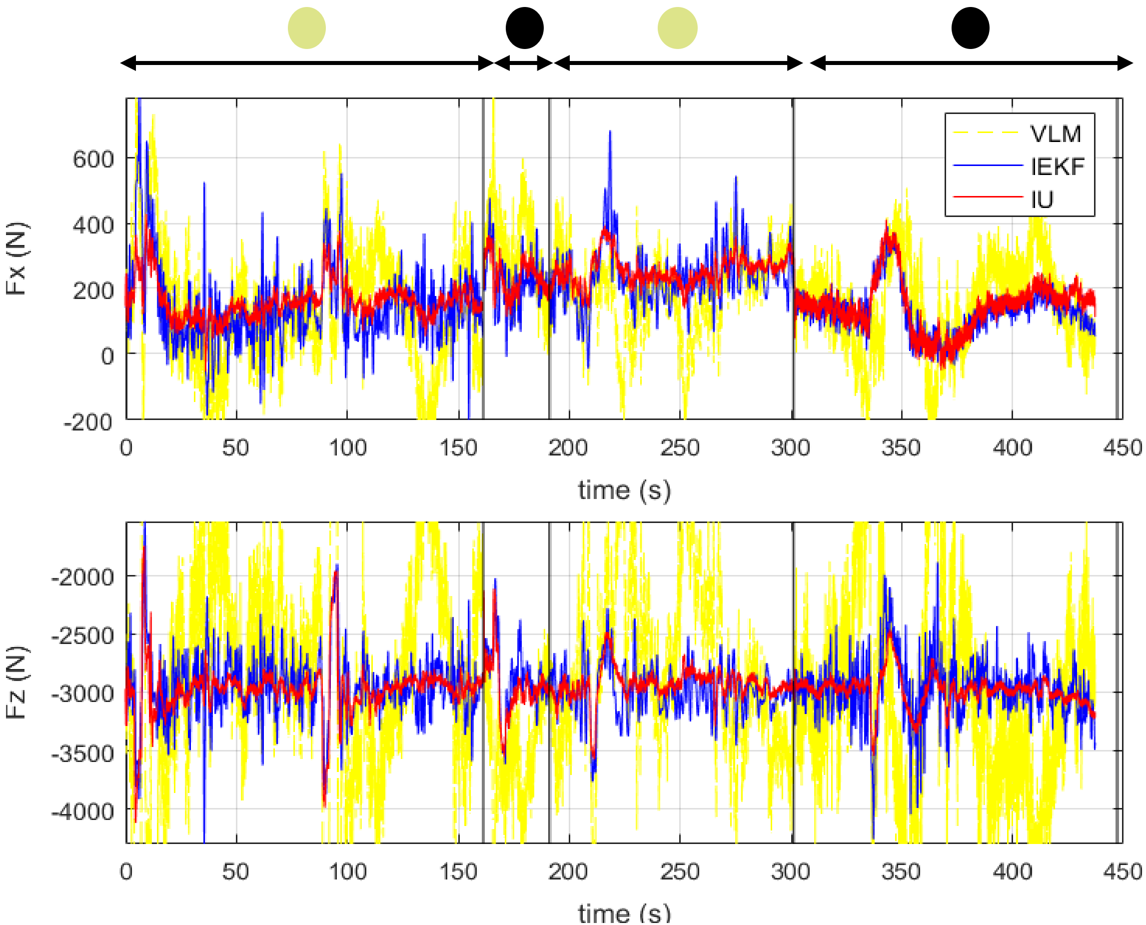
Scope: Preliminary study at low altitude for Elektra 1.



- Identification of correction model at two points ●.
- Validation of correction model at two points ●.

Global system identification – Incremental update

Results: Preliminary study at low altitude for Elektra 1.



Fx	VLM	CVLM
RMSE	146.8	77.86
NRMSE	0.148	0.0789

Fz	VLM	CVLM
RMSE	932.9	212.8
NRMSE	0.338	0.0777

Conclusion

- Local system identification.
  - Two step method implemented and validated.
  - System identification tool chain for 2 fixed wing platforms.
  - High fidelity model according to FAA standards.

- Global system identification.
  - Preliminary study on incremental model update scheme.
  - Within low altitude low velocity region the method proved to work with reduction of NRMSE by 0.5 and 0.2 for Fx and Fz respectively.

Future work

- Local system identification.
  - System identification for flexible aircraft (Elektra 2).

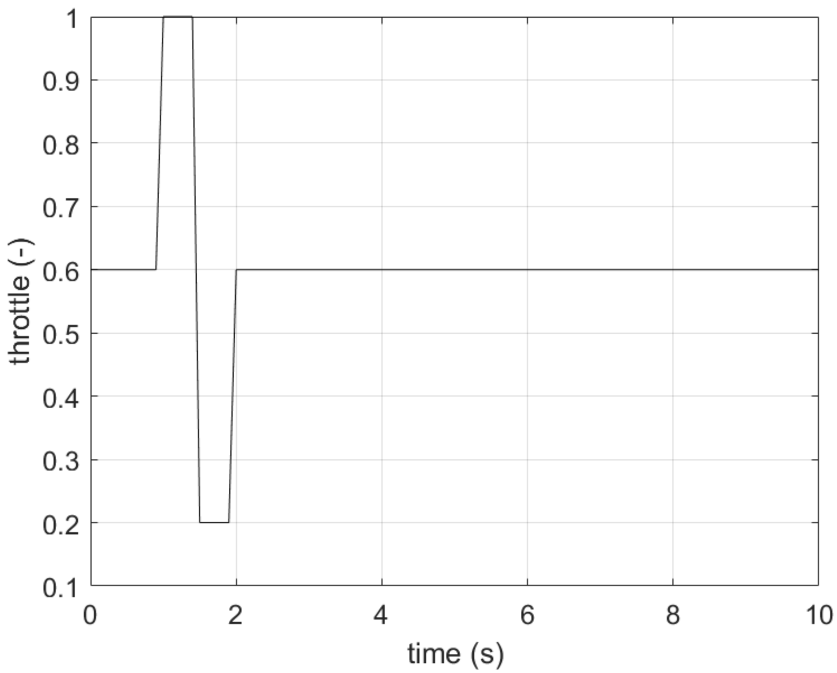
- Global system identification.
  - Wider ranges of velocities.
  - Wider ranges of altitude (Low Reynolds High Mach?).

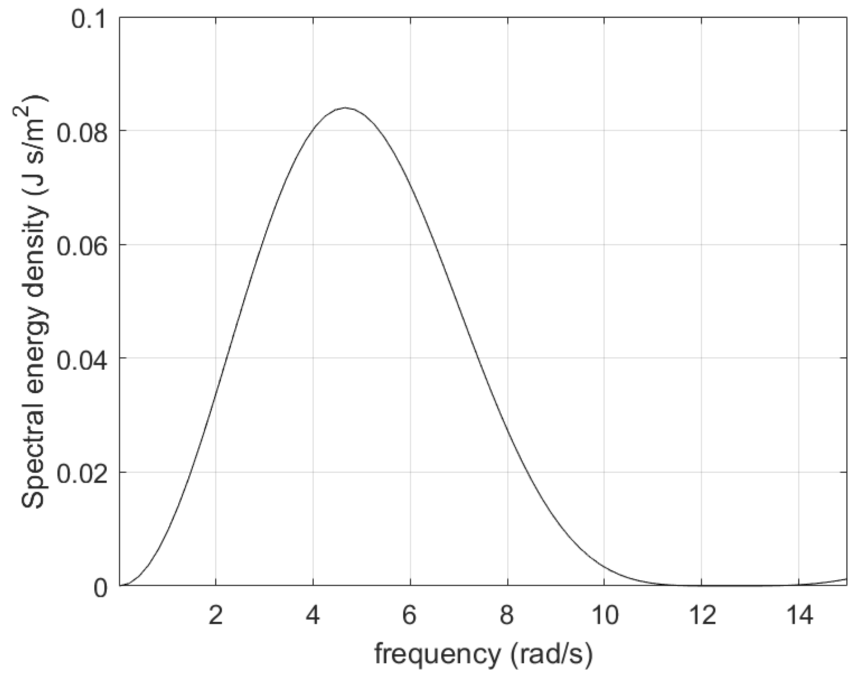
- Fidelity definition for controller synthesis.
  - Step response of the aircraft.
  - Derivation of quantitative requirements?

Questions?

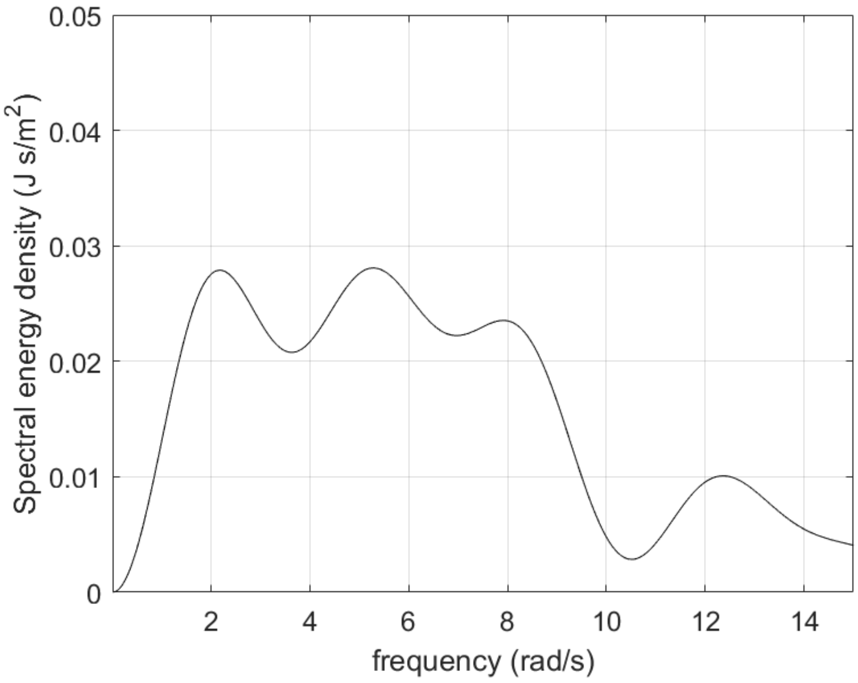
Back up slides

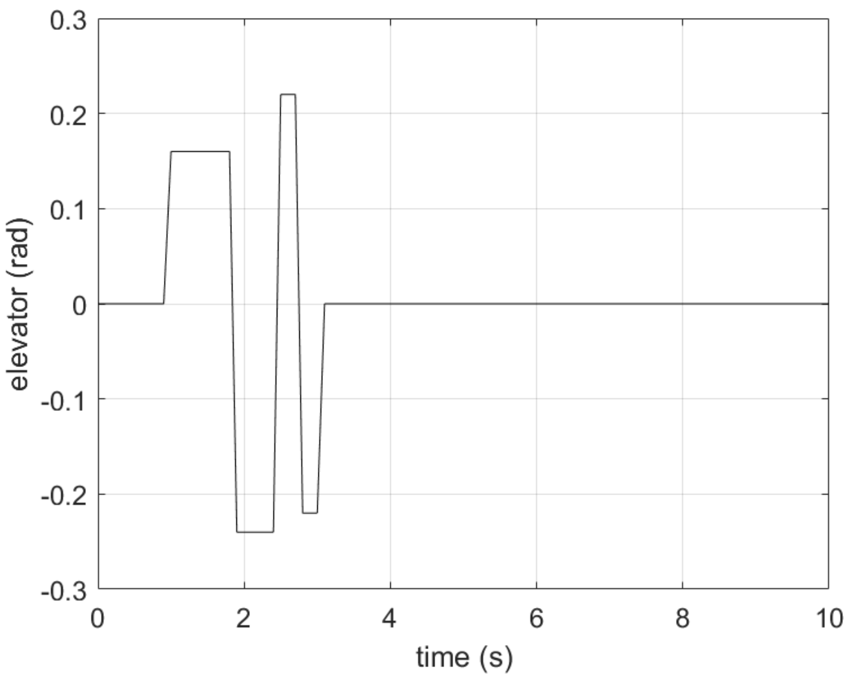
Back up slides – Elektra 1



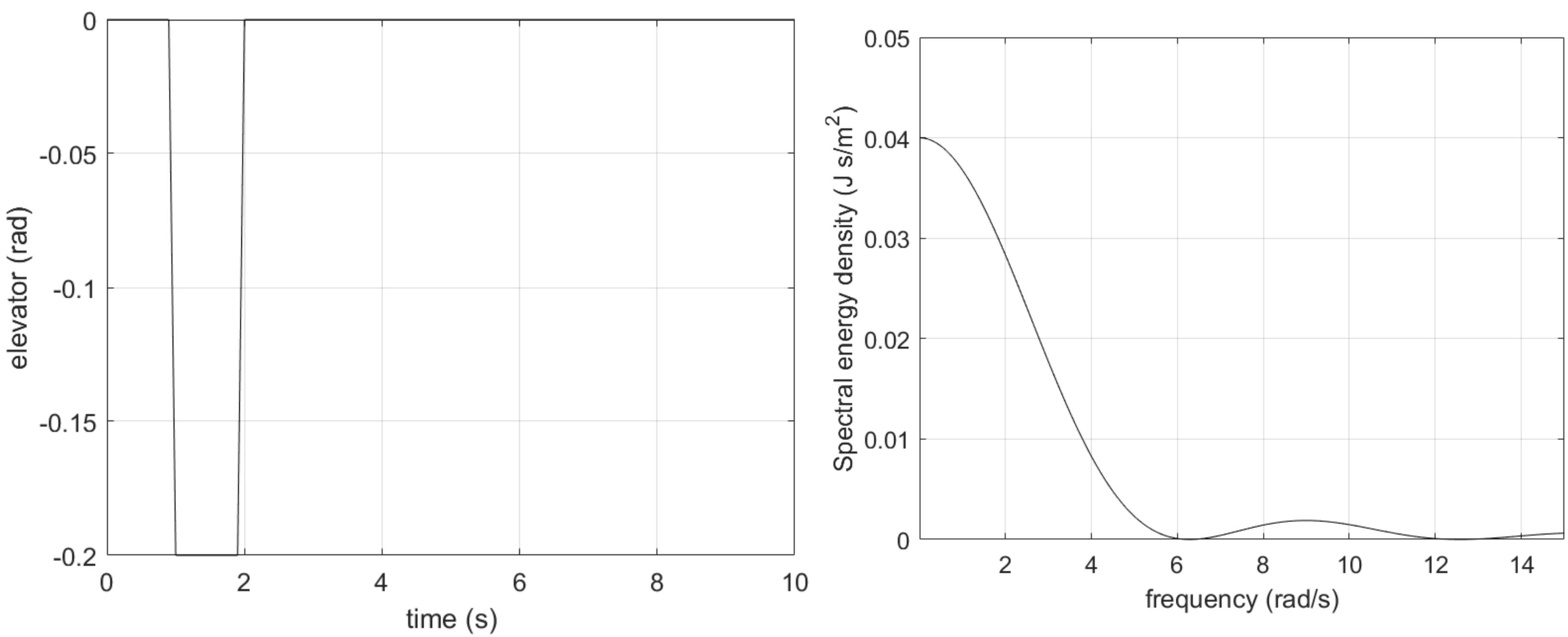


Back up slides – Elektra 1

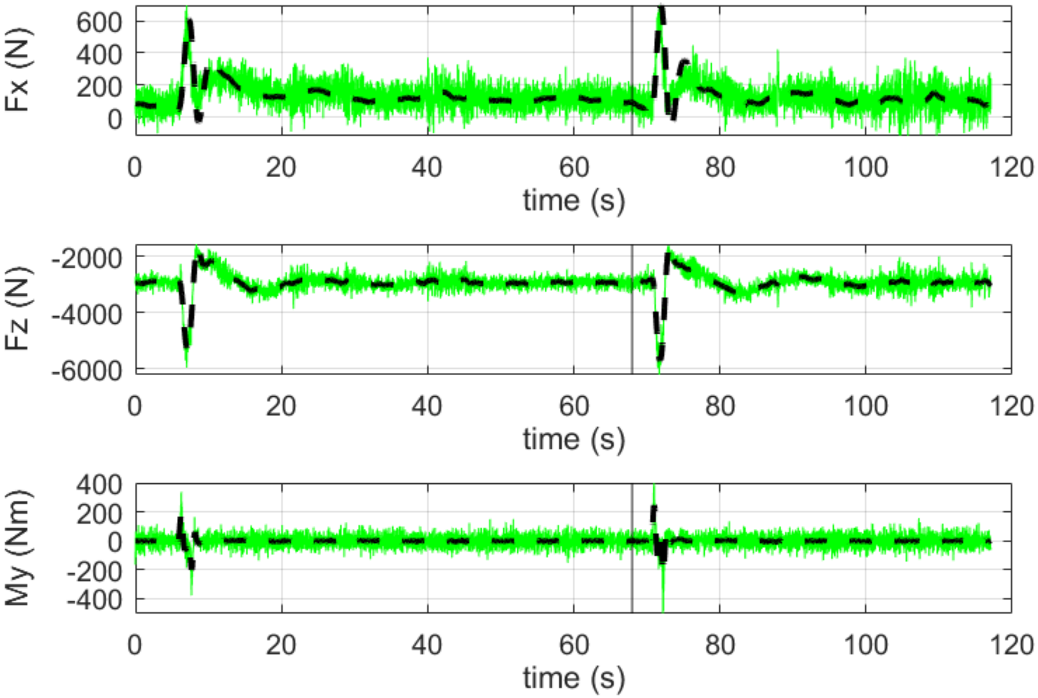


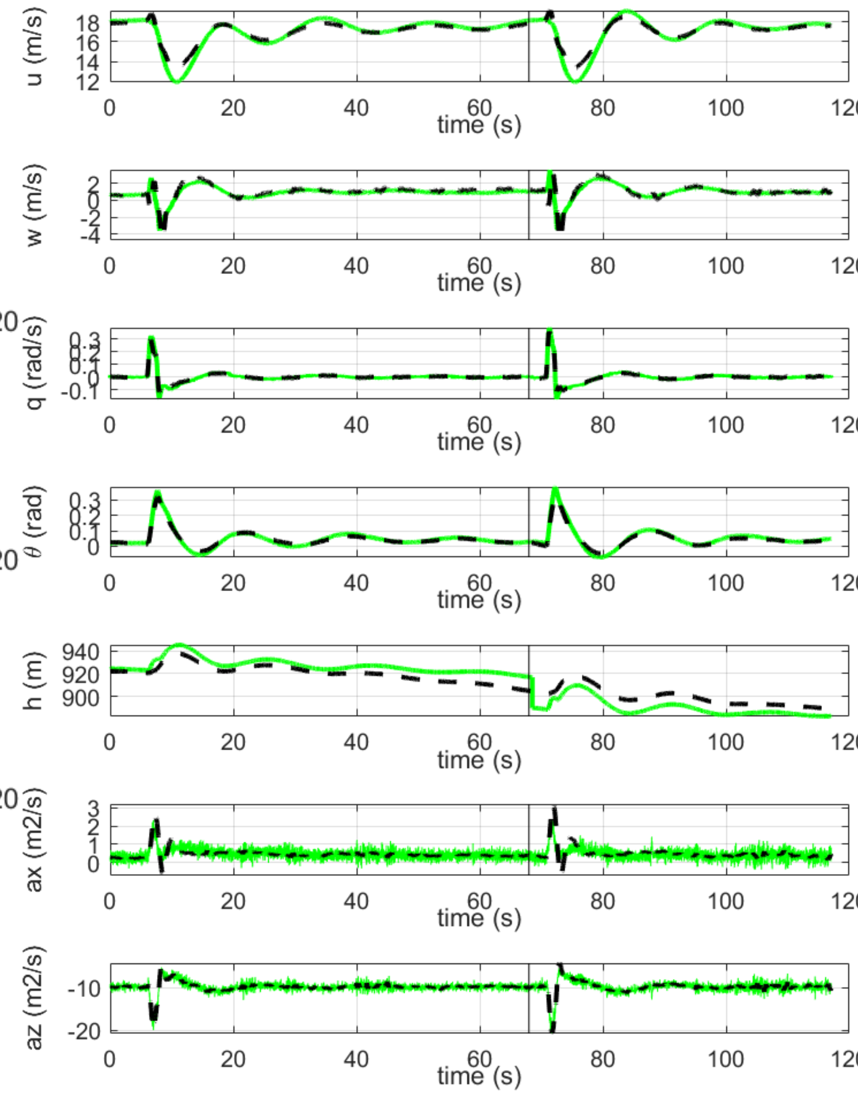


Back up slides – Elektra 1

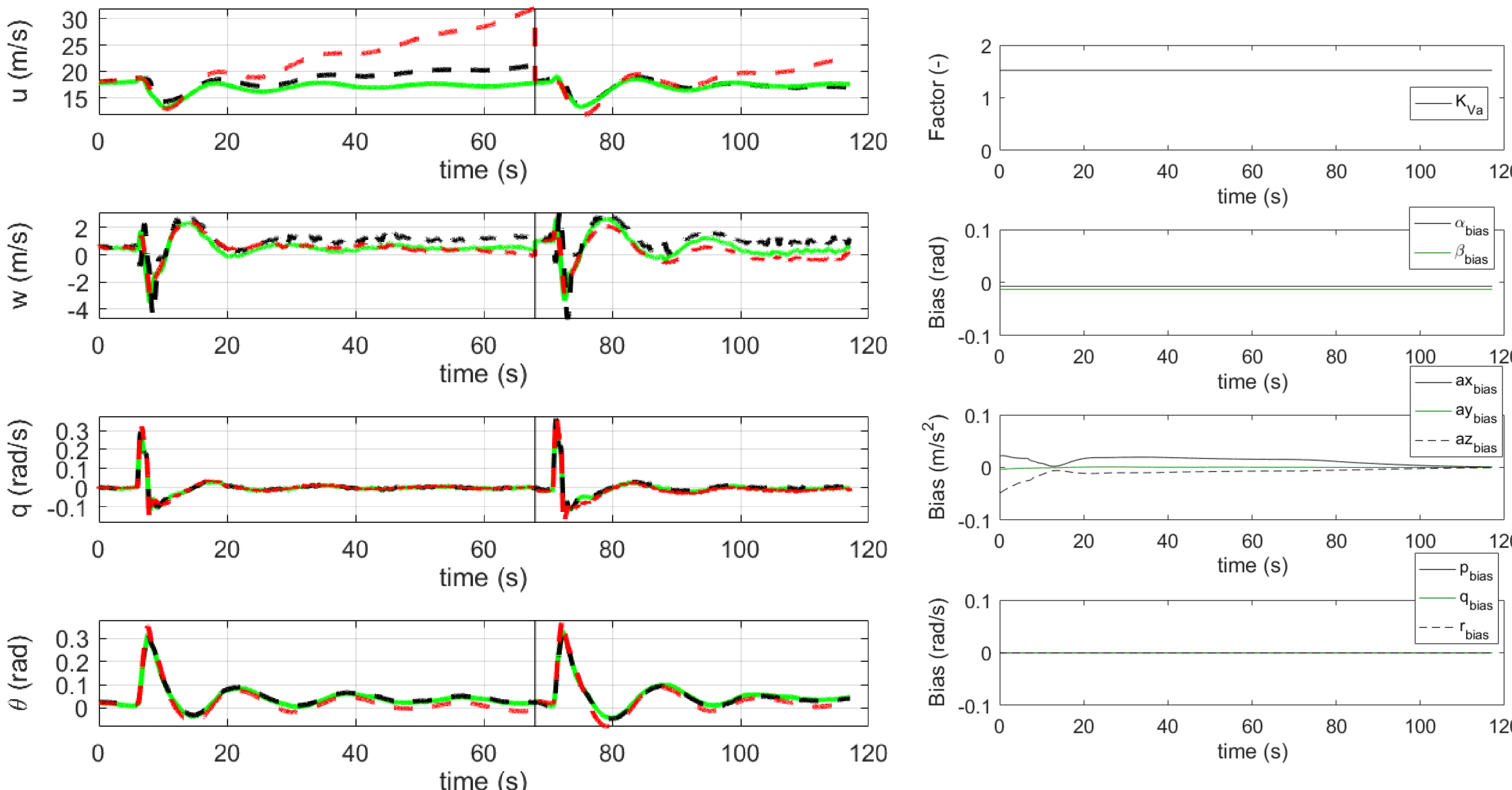


Back up slides – Elektra 1

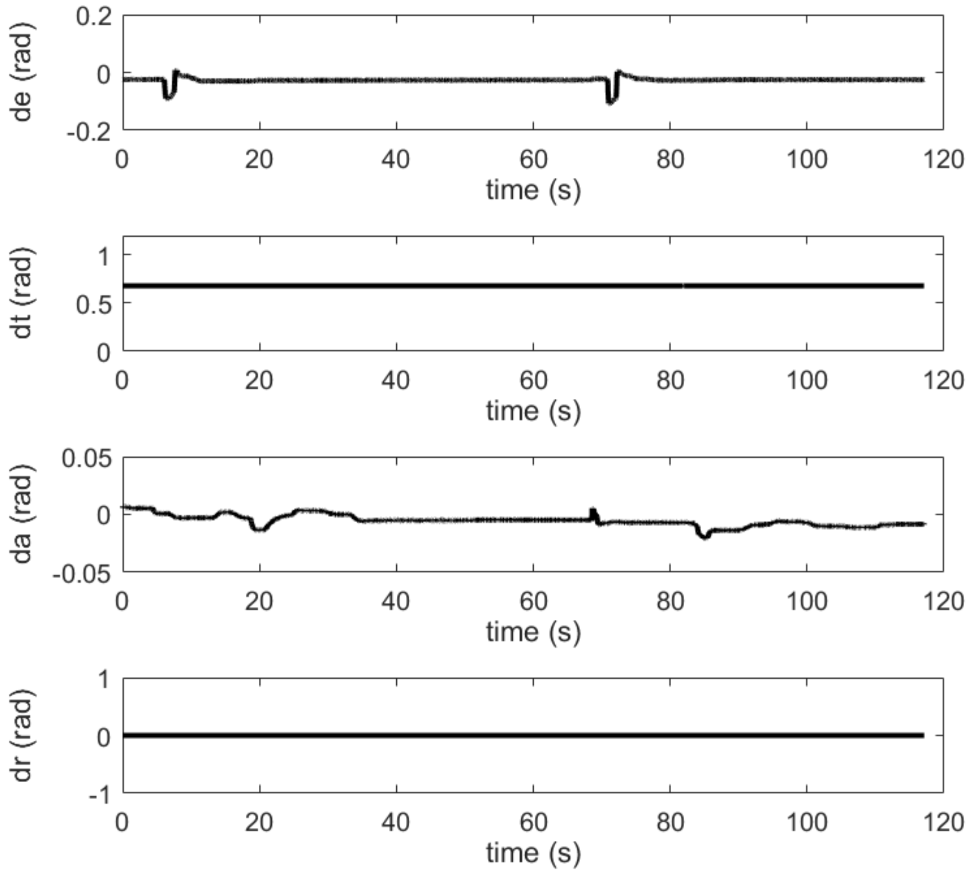




Back up slides – Elektra 1



Back up slides – Elektra 1



Back up slides – Elektra 1

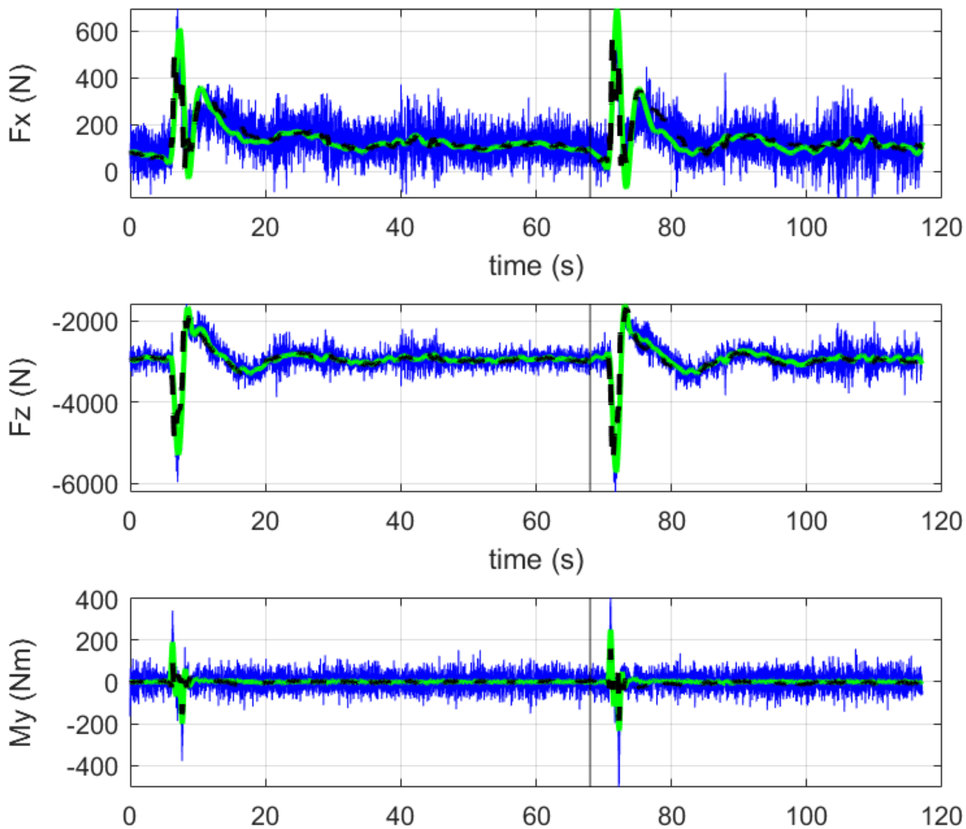


Table 2.5: R-squared, RMSE and NRMSE for forces and moments prediction of linear model.

Identification				Validation			
Coef	C_X	C_Z	C_m	Coef	C_X	C_Z	C_m
R^2	0.69	0.79	0.30	R^2	0.65	0.77	0.29
RMSE	41.89	153.7	15.89	RMSE	49.15	178.5	19.29
NRMSE	0.065	0.042	0.041	NRMSE	0.063	0.043	0.039

Back up slides – Elektra 1

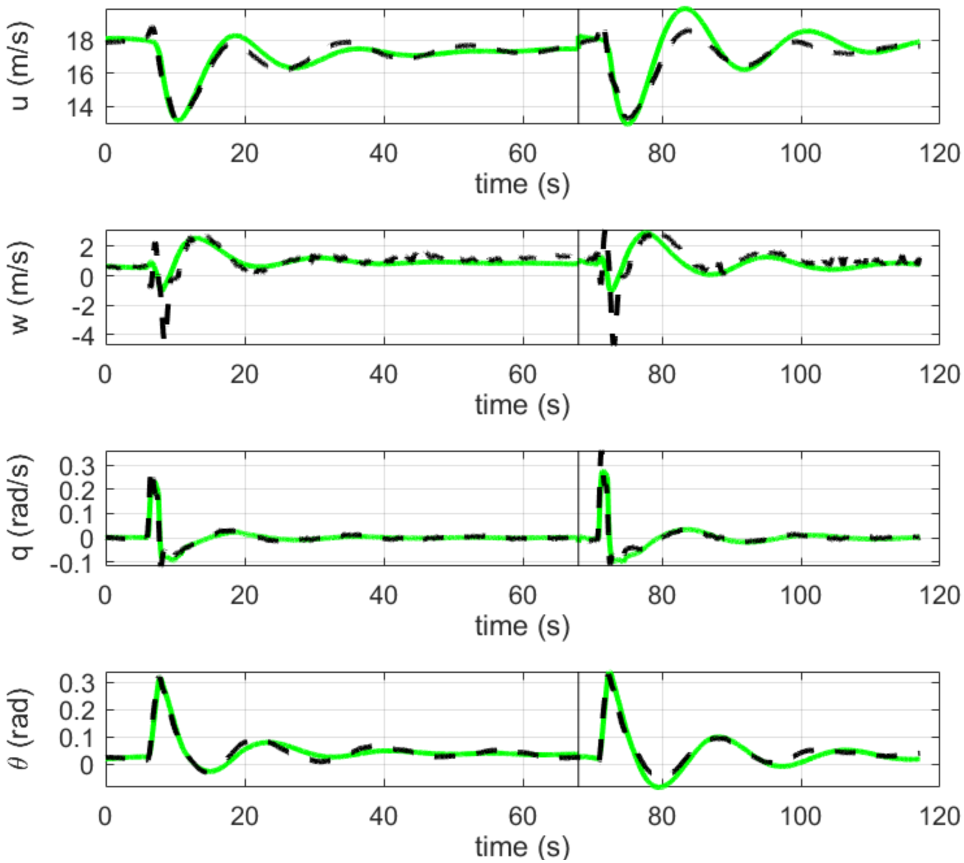
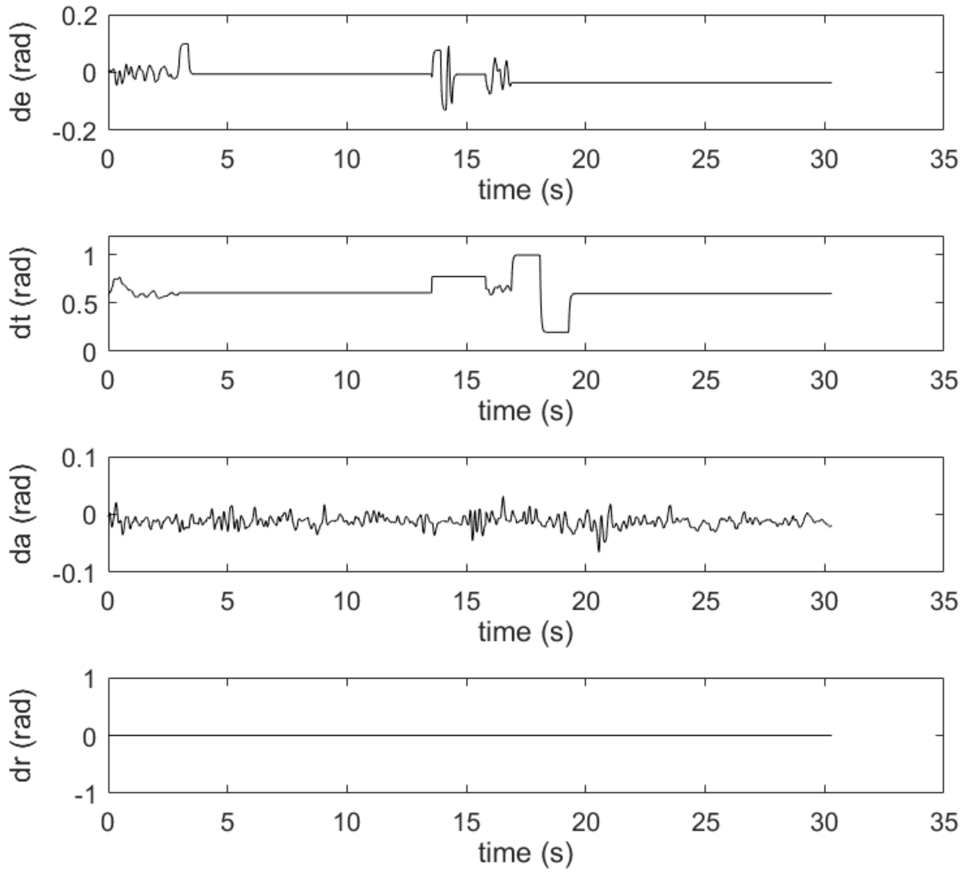


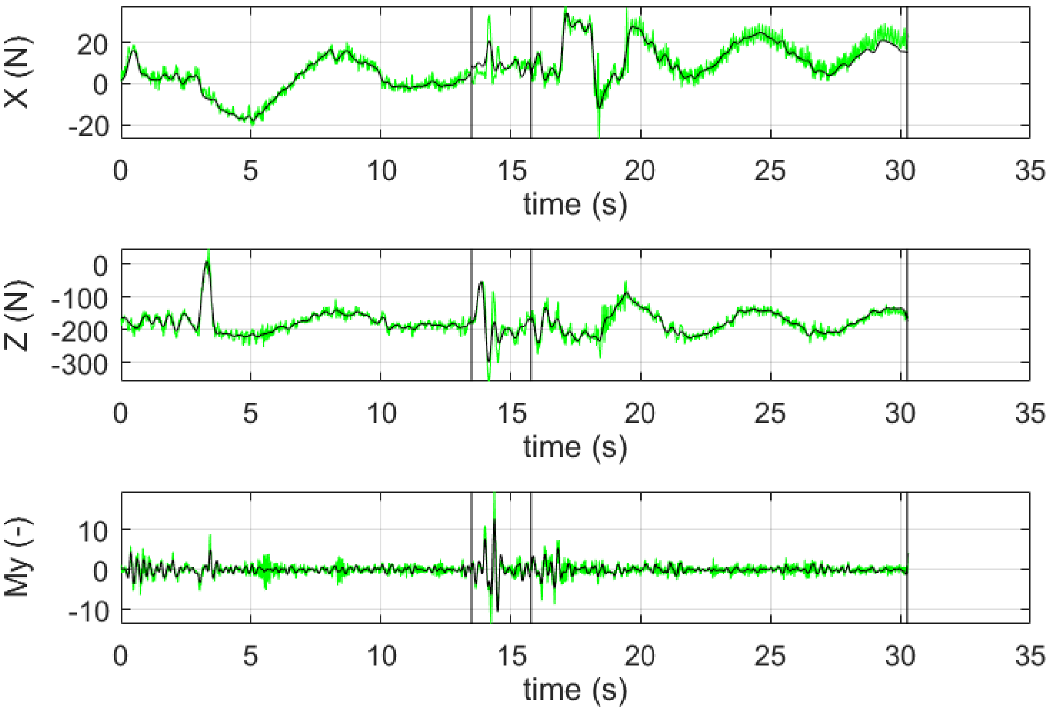
Table 2.7: TIC and GOF values for forward simulation using identified linear model.

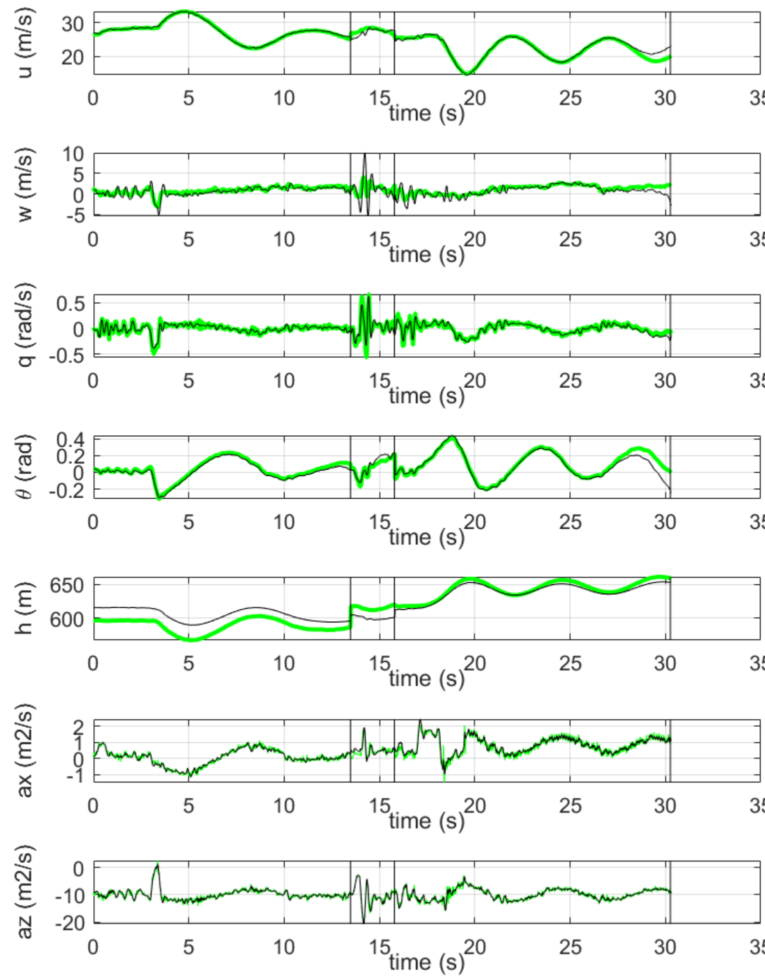
Nonlinear:									
Identification					Validation				
State	u	w	q	θ	State	u	w	q	θ
GOF	0.9037	0.5856	0.8959	0.9323	GOF	0.7156	0.5119	0.8765	0.8981
TIC	0.0094	0.2154	0.1660	0.0971	TIC	0.1872	0.2626	0.1753	0.1239

Back up slides – Penguin BE

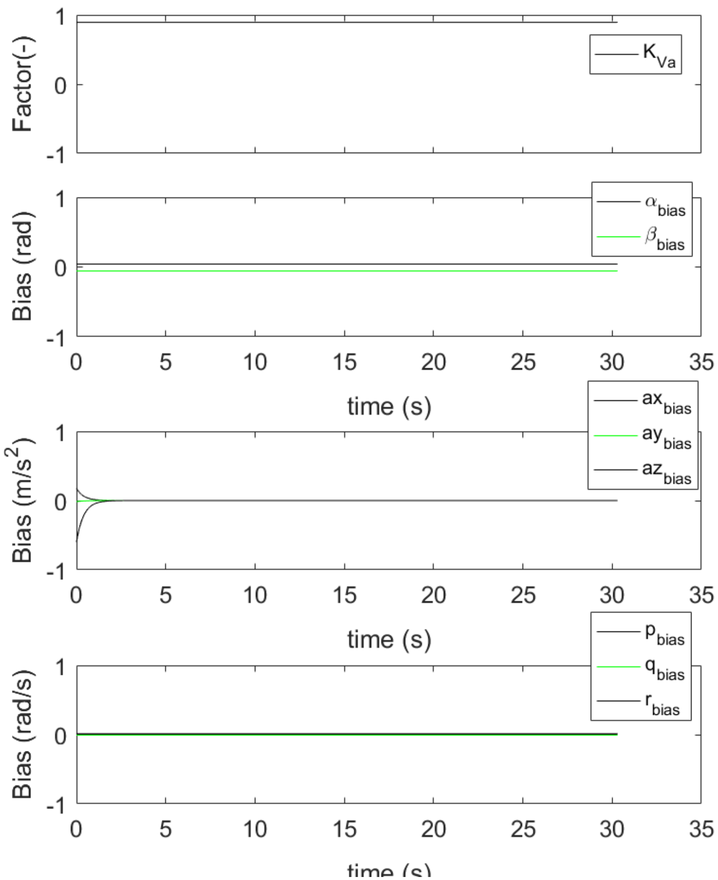


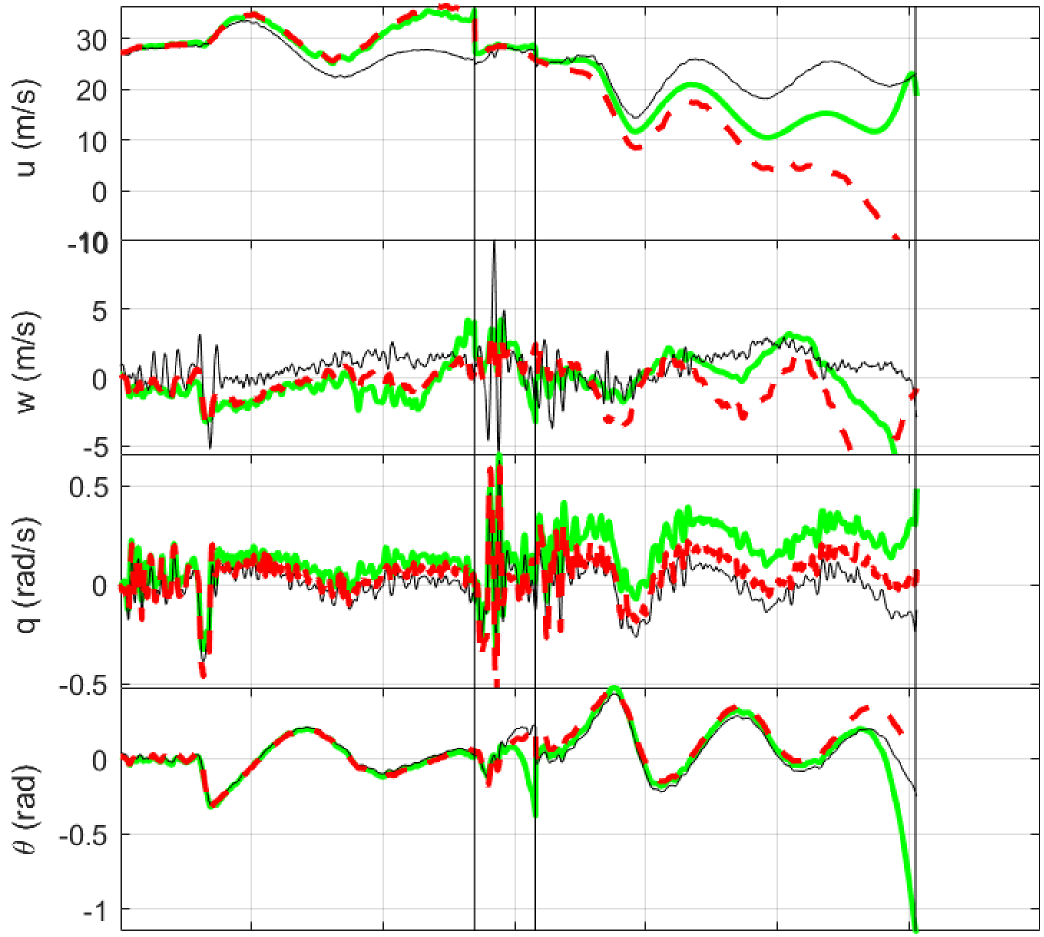
Back up slides – Penguin BE





Back up slides – Penguin BE





Back up slides – Penguin BE

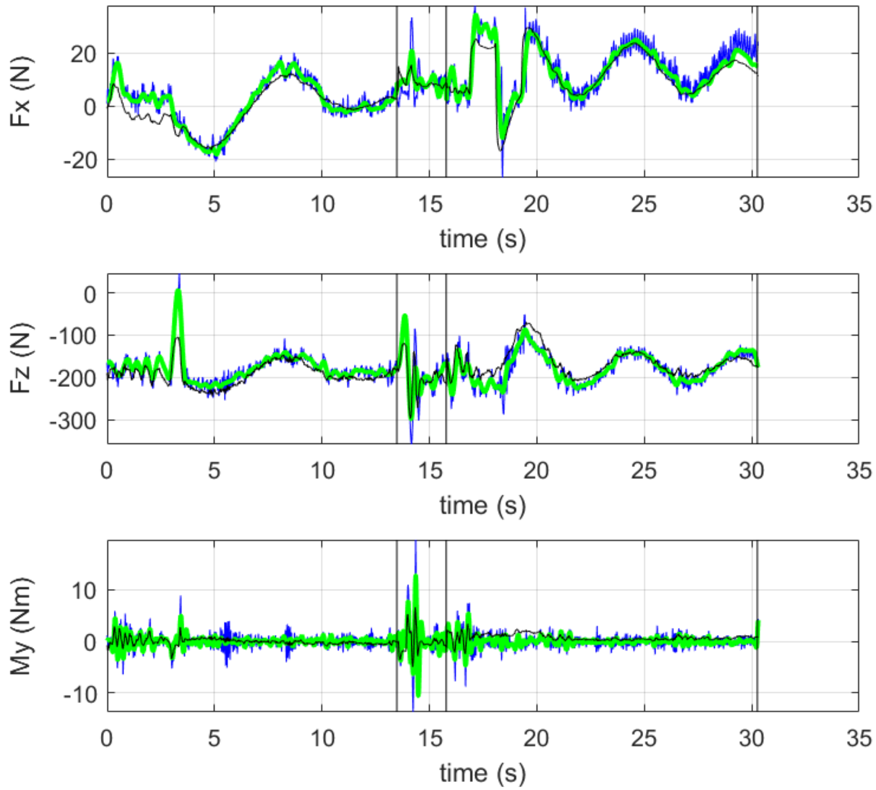


Table 3.12: Averaged R-squared, RMSE and NRMSE for forces and moments prediction of linear model.

Identification				Validation			
Coef	C_X	C_Z	C_m	Coef	C_X	C_Z	C_m
R^2	0.868	0.616	0.422	R^2	0.848	0.665	0.1359
RMSE	3.109	19.779	1.0899	RMSE	4.10	20.63	1.239
NRMSE	0.071	0.067	0.045	NRMSE	0.078	0.067	0.053

Back up slides – Penguin BE

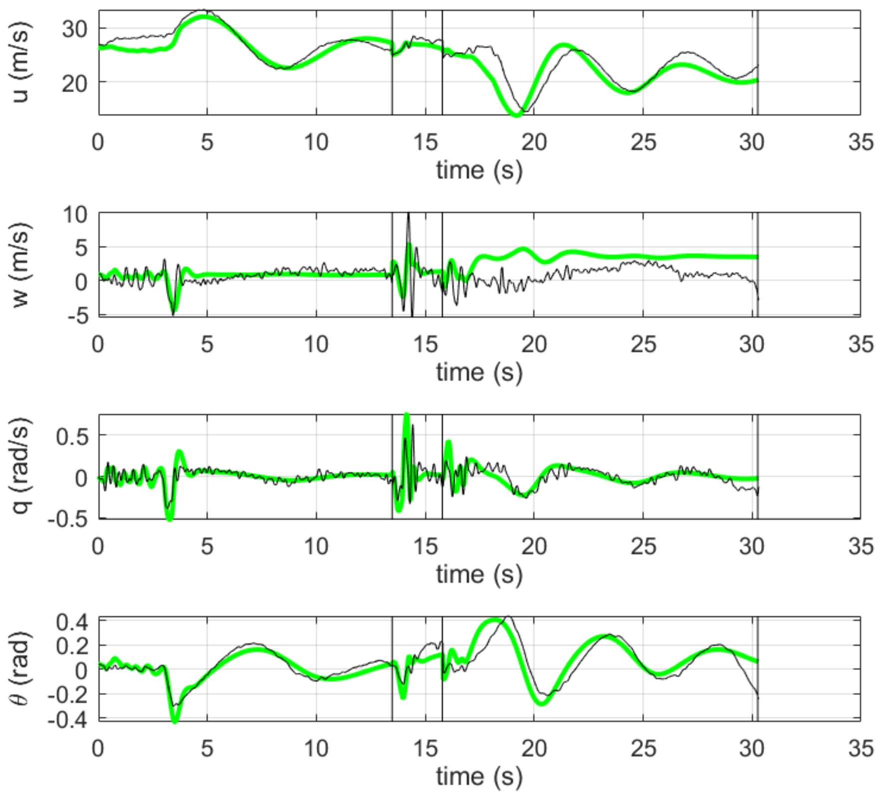


Table 3.14: TIC and GOF values for forward simulation with linear model.

Identification					Validation				
State	u	w	q	θ	State	u	w	q	θ
GOF	0.77	0.72	0.514	0.688	GOF	0.76	0.52	0.52	0.72
TIC	0.03	0.28	0.355	0.254	TIC	0.038	0.453	0.345	0.236

Back up slides – Global

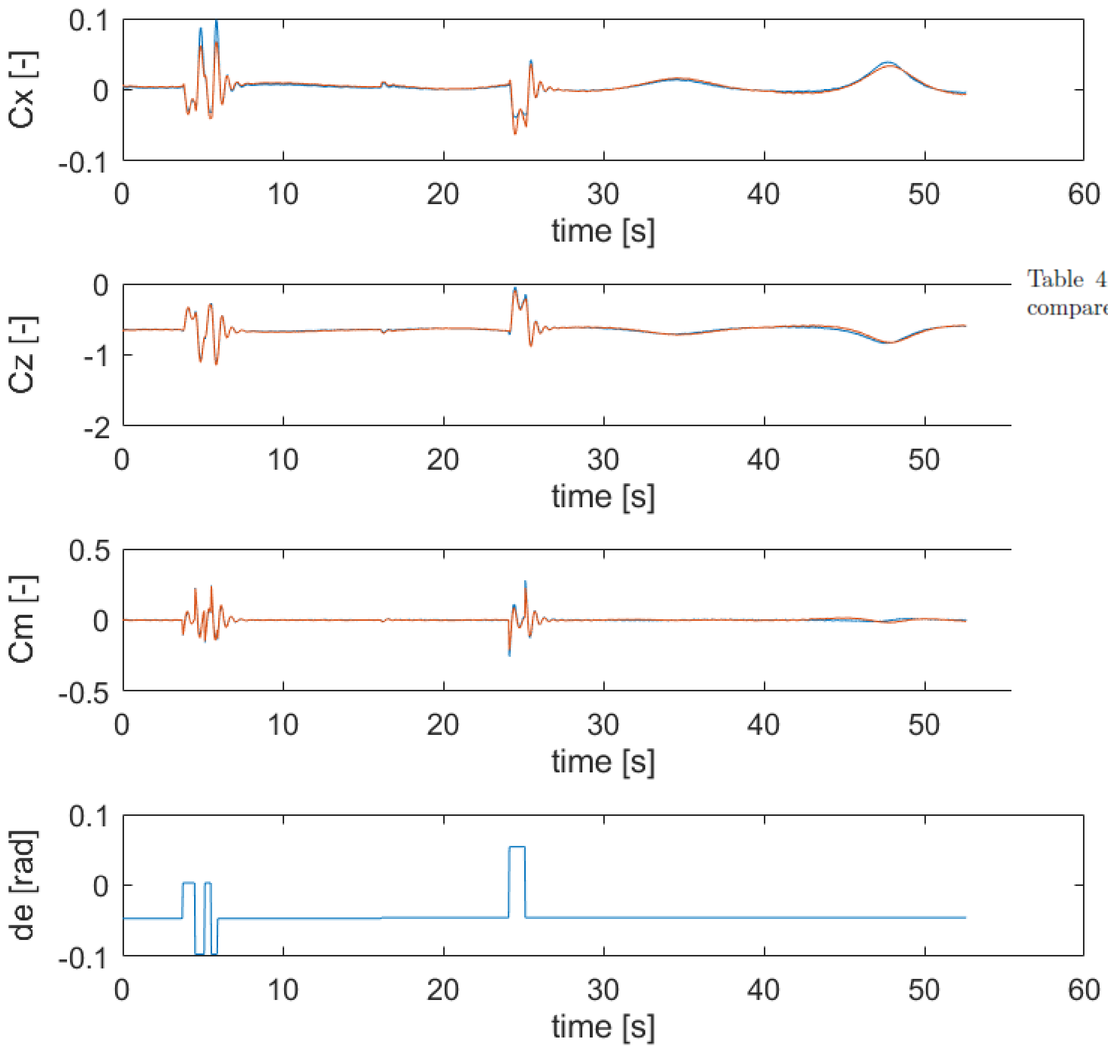


Table 4.1: Identified model parameters using VLM based simulation data (ID) compared to direct output of VLM software (AVL).

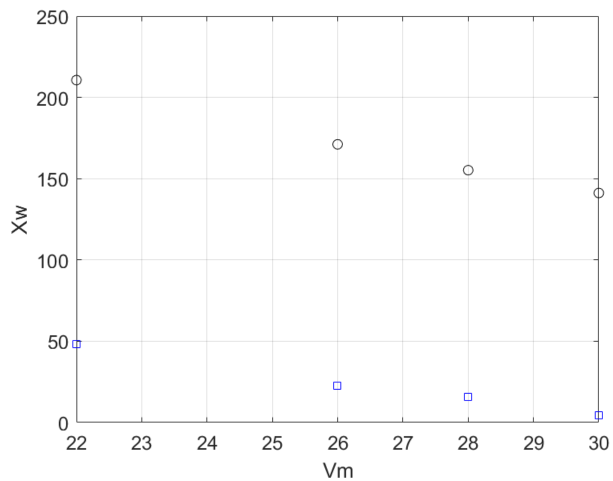
ID:

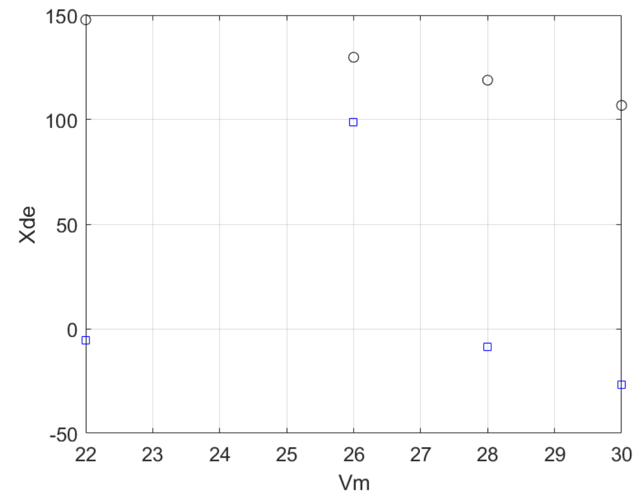
Term	Value	Term	Value	Term	Value
C_{x_u}	-0.004	C_{z_u}	-0.036	C_{m_u}	0.0105
C_{x_w}	0.0405	C_{z_w}	-0.231	C_{m_w}	-0.095
C_{x_q}	0.0026	C_{z_q}	-0.08595	C_{m_q}	-0.196
$C_{x_{de}}$	0.00059	$C_{z_{de}}$	-0.0097	$C_{m_{de}}$	-0.047

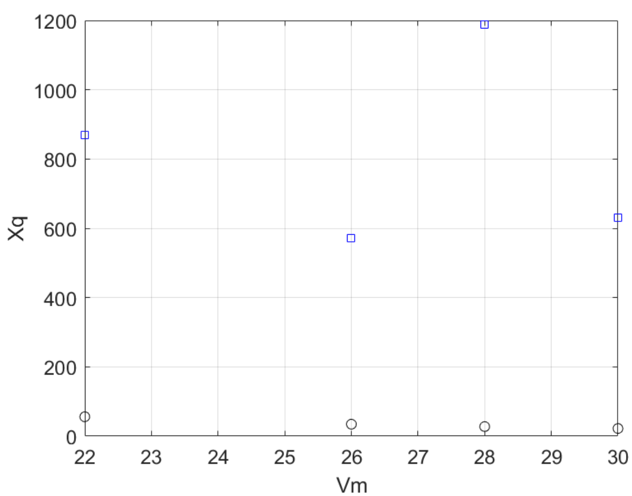
AVL:

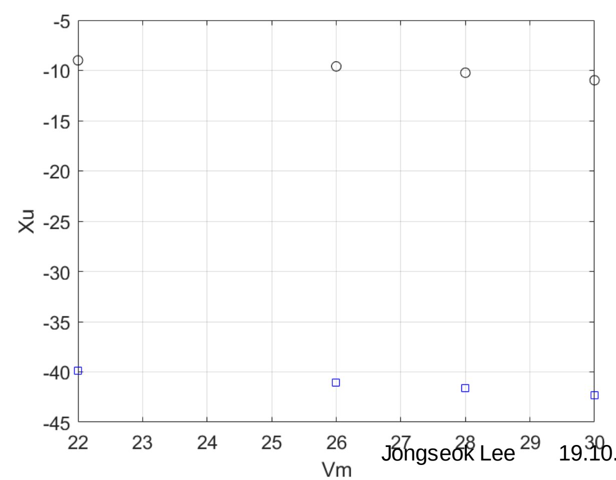
Term	Value	Term	Value	Term	Value
C_{x_u}	-0.004	C_{z_u}	-0.04	C_{m_u}	0.011
C_{x_w}	0.045	C_{z_w}	-0.25	C_{m_w}	-0.105
C_{x_q}	0.0029	C_{z_q}	-0.0955	C_{m_q}	-0.218
$C_{x_{de}}$	0.00054	$C_{z_{de}}$	-0.0088	$C_{m_{de}}$	-0.0431

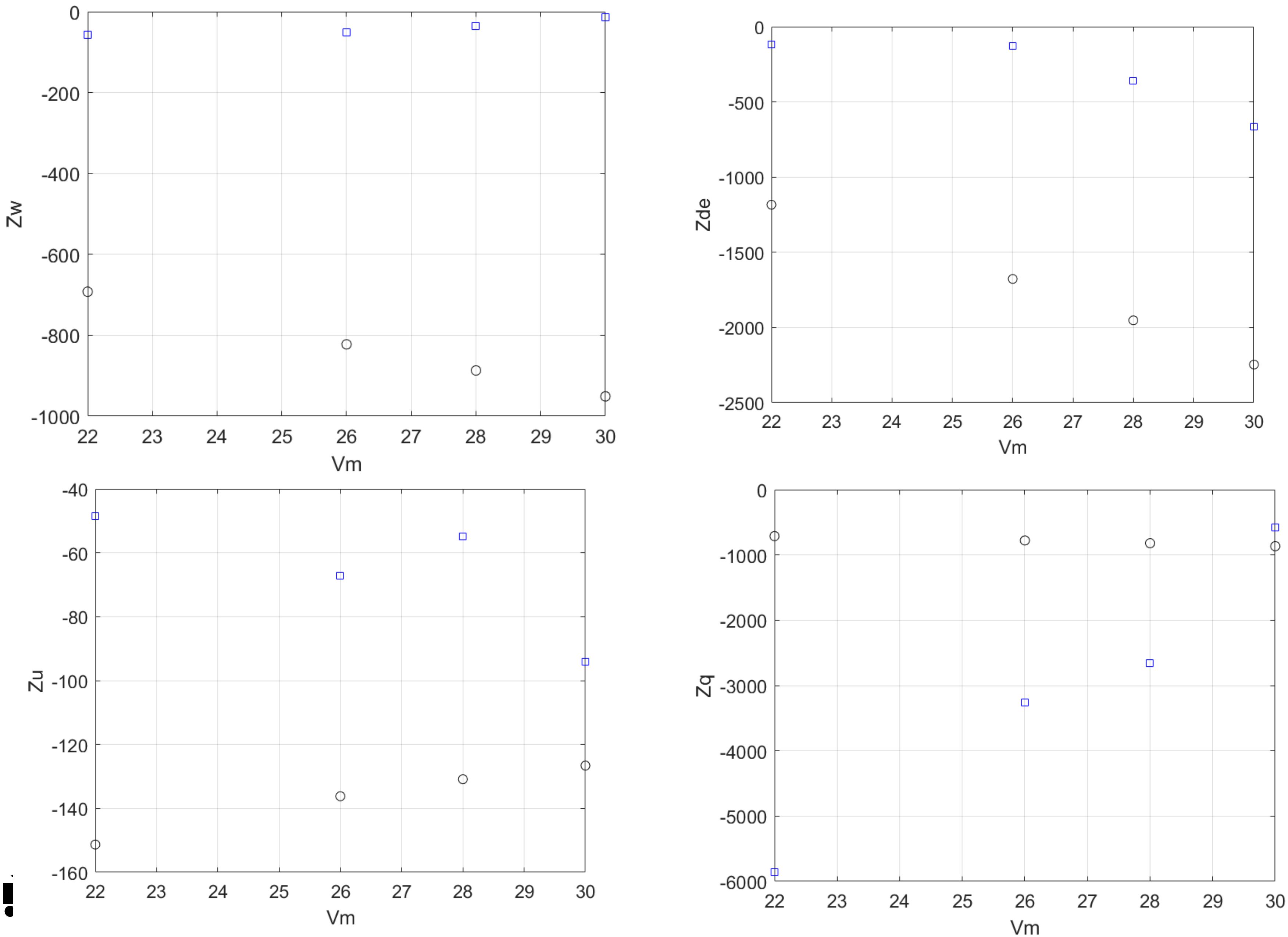
Back up slides - Global

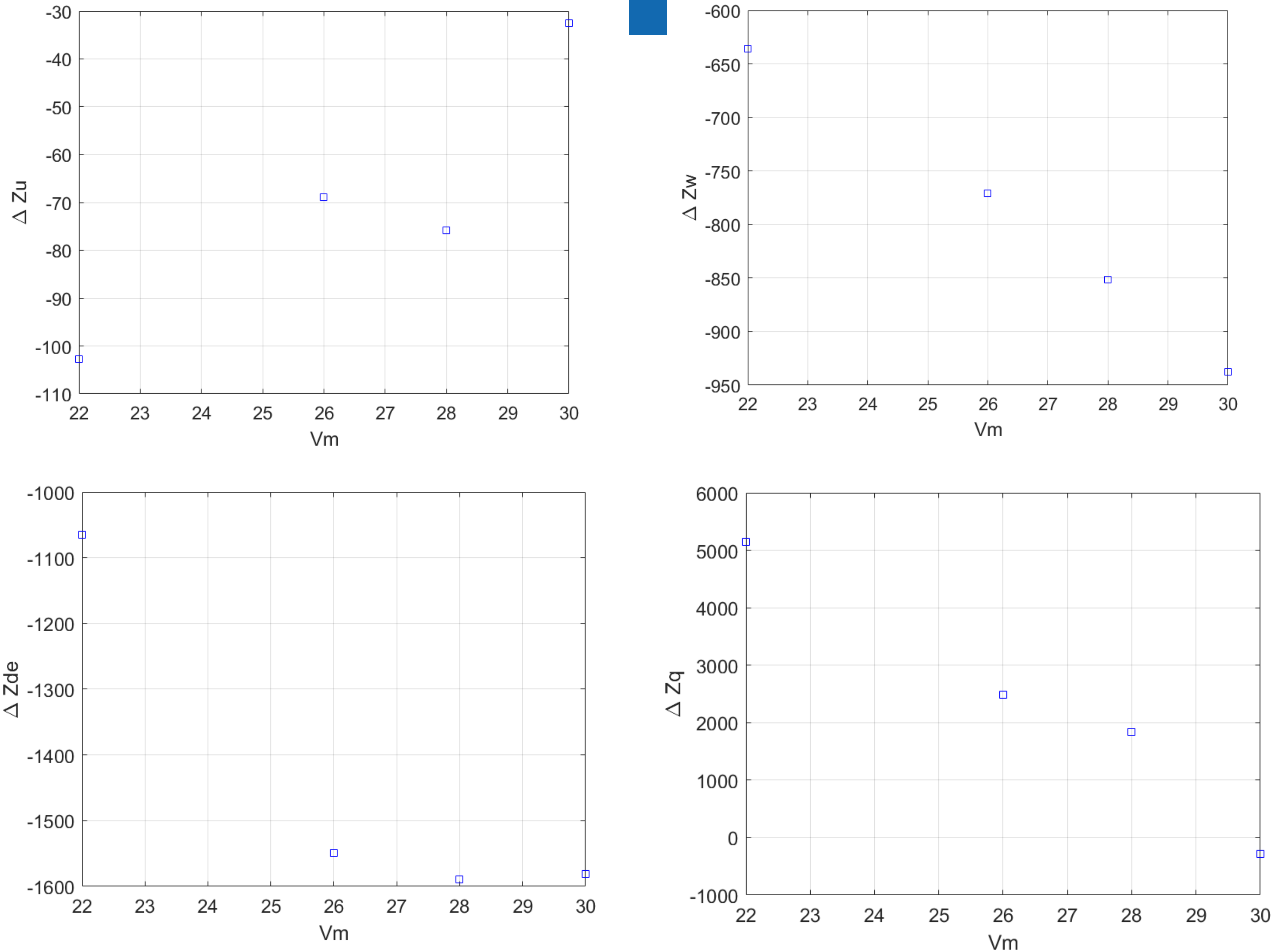




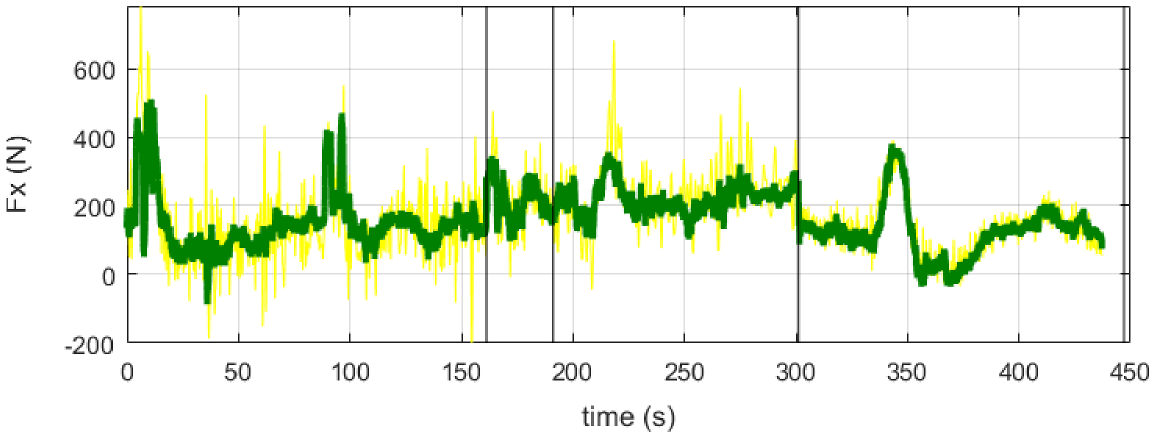


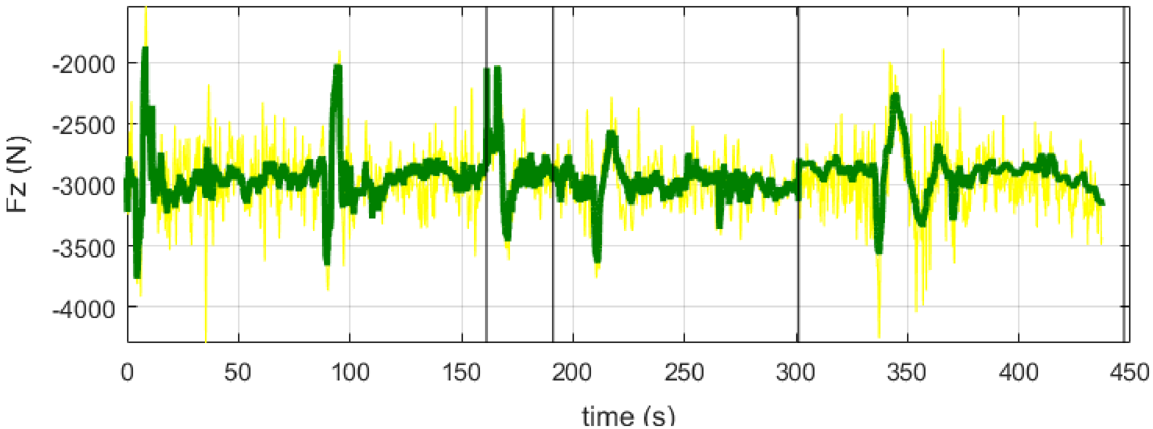



Zw
0
-200
-400
-600
-800
-1000
22 23 24 25 26 27 28 29 30
Vm
Zde
0
-500
-1000
-1500
-2000
-2500
22 23 24 25 26 27 28 29 30
Vm
Zu
-40
-60
-80
-100
-120
-140
-160
22 23 24 25 26 27 28 29 30
Vm
Zq
0
-1000
-2000
-3000
-4000
-5000
-6000
22 23 24 25 26 27 28 29 30
Vm


Δ Zu
Vm
Δ Zw
Vm
Δ Zde
Vm
Δ Zq
Vm

Back up slides - Global





Back up slides

Table 4.6: Case studies with various choice of training and validation set.

Case A	V1	V2	V3	V4	ALL
RMSE F_x	81.671	90.608	73.837	37.251	70.841
RMSE F_y	2.273E2	2.262E2	2.057E2	2.045E2	2.151E2
Case B	V1	V2	V3	V4	ALL
RMSE F_x	80.86	99.391	78.729	50.709	77.422
RMSE F_y	1.697E2	2.262E2	2.236E2	2.4066E2	2.257E2
Case C	V1	V2	V3	V4	ALL
RMSE F_x	86.883	97.78	74.22	37.251	74.033
RMSE F_y	3.710E2	2.359E2	1.884E2	2.0456E2	2.329E2
Case D	V1	V2	V3	V4	ALL
RMSE F_x	83.72	99.39	85.45	83.90	88.115
RMSE F_y	1.802E2	2.262E2	1.884E2	2.1704E2	2.112E2

$$\begin{aligned}
\Delta X_u &= 0.083 \cdot V_m + 29.088 \\
\Delta X_w &= -3.790 \cdot V_m + 246 \\
\Delta X_q &= -57.9 \cdot V_m + 462 \\
\Delta X_{de} &= -4.3 \cdot V_m + 248 \\
\Delta Z_u &= 4.4 \cdot V_m - 201.3 \\
\Delta Z_w &= -36 \cdot V_m + 156 \\
\Delta Z_q &= -552 \cdot V_m + 1729.8 \\
\Delta Z_{de} &= -1.39 \cdot V_m^2 - 17.82 \cdot V_m
\end{aligned}$$