CFD-BASED IDENTIFICATION OF HYDRODYNAMIC COEFFICIENTS FOR A RUDDER

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SUMMARY

For a moving rudder, the forces are generally not in phase with the angular position, instead, there are contributions to the forces correlated with both the angular velocity and acceleration. These contributions are nonlinear and dependent on the forward speed. In this work was evaluation the forces, and mainly the lift force variation with the time dependent characteristics of the rudder. The simulations include variation in forward speed, maximum rudder amplitude and frequency (giving shaft rates up to 1000 degrees/s). The force coefficients for each forward speed, amplitude and frequency are identified based on the simulations. Dynamic effects on the lift force is important and can with good accuracy be expressed as simple functions of forwards speed and shaft rate. This works even with irregular rudder motions typical for a torpedo as the new light weight torpedo.

1 DEFINITIONS AND ABBREVIATIONS.

CFD	Computational Fluid Dynamics		
NLT	New Lightweight Torpedo / Torpedo 47[i]		
ρ	Density of fluid		[kg/m^3]
L_{ref} / S_{ref}	Reference length / Reference Area		[m ; m^2]
U_{ref}	Reference velocity		[m/s]
α / $\dot{\alpha}$ / $\ddot{\alpha}$	Rudder angle ; rate ; acceleration		[rad ; rad/s ; rad/s^2]
F	Force in velocity coordinate system		[N]
Q_∞	Dynamic pressure,	$\frac{1}{2}\rho \cdot U_{ref}^2$	[Pa]
C_L	Lift force coefficient,	$\frac{F_L}{Q_\infty S_{ref}}$	[-]

2 PURPOSE

The main objective of this work was to analyse the transient forces, with focus on the lift force, on the torpedo rudder for conditions representative for normal operating conditions. An important outcome was also a description of the transient behaviour in a way possible to implement in the time simulator used both for design of the control system and scenario simulations.

3 CFD ANALYSIS

3.1 Basics

All CFD analysis are carried out using ANSYS CFX[ii]. The equation formulation used is the unsteady RANS, Reynolds-Averaged-Navier-Stokes with a standard k-ω turbulence model. The fluid properties are assumed constant which means an incompressible and isothermal fluid. The post-processing, force identification and plot generation are done using Matlab[iii].

3.2 Geometry

The geometry used is almost identical to the actual rudder, one out of four, on the new light weight torpedo for the Swedish Navy. This means a maximum chord of 0.10 m and a span of 0.086 m. The profile is a NACA 0015 where modifications made to make the rudder fit into the tail behind the pumpjet unit. The calculation domain consist of a cylinder with radius of 0.8 m and a length of 3.0 m. The inflow is located 1.0 m upstream from the shaft centre.

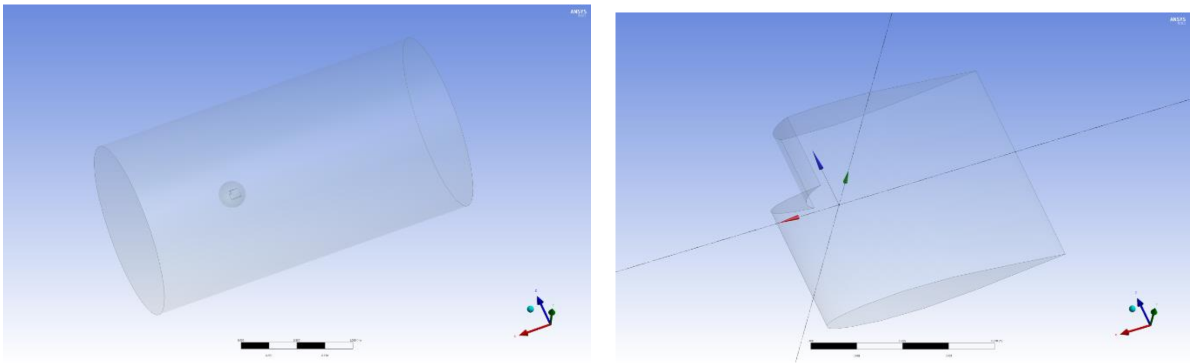

Figure 1Geometry: Complete domain / Rudder with coordinate system

X axis / horizontal axis	Negative in flow direction
Y axis / vertical axis	Positive upward
Z axis / transverse axis	Positive to the right (starboard)
Rudder angle	Body angle in X-Y plane relative to fluid flow. Positive if leading edge pointing up creating positive force in the Y-direction

3.3 Environmental conditions

All simulations are carried out using fresh water with a temperature of 15 degrees Centigrade. This gives a fluid density of 999.1 kg/m^3 and a kinematic viscosity of 1.14 10^{-6} m^2/s.

3.4 Boundary conditions

All CFD simulations are carried out with the following boundary conditions

Inflow	Constant normal velocity (CFX “inflow”)
Outflow	Constant average pressure (CFX “outflow”)
Outer	Constant total pressure (“Total Head”) A condition where the static pressure on the boundary is updated for each time step dependent on the velocity.
Body	Smooth walls. Standard wall model

The inner part is modelled as separate rotating part using CFX “transient rotor” condition at the interface to the stationary outer part. The angular rate of the inner part is given as a function of time. In the practical case the rudder is located behind the pumpjet on the torpedo and the flow is fully turbulent from start. At the inflow the turbulence intensity is set to “medium” to give a condition representative to this location.

3.5 Numerical model

The numerical model has the following properties

Number of nodes/elements	$1.06\ 10^{6}$ / $5.9\ 10^{6}$
Max/Min element side size	$1.0\ 10^{-1}$ m / $1.0\ 10^{-4}$ m (approximate)

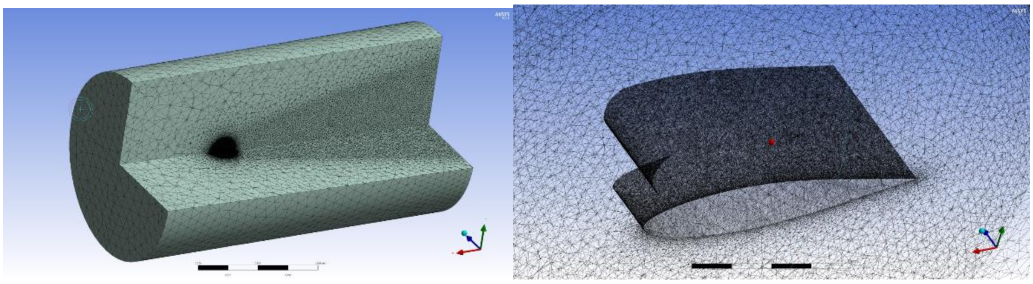

Figure 2 Mesh: Complete domain / Rudder

3.6 Simulation cases

The complete set of simulation consists of static cases, steady state cases with zero angle of attack, ramp cases, transient cases which starts from the static case and the rudder position is ramped to a given static angle and finally dynamic cases where the rudder motion is defined by a regular sinusoidal function.

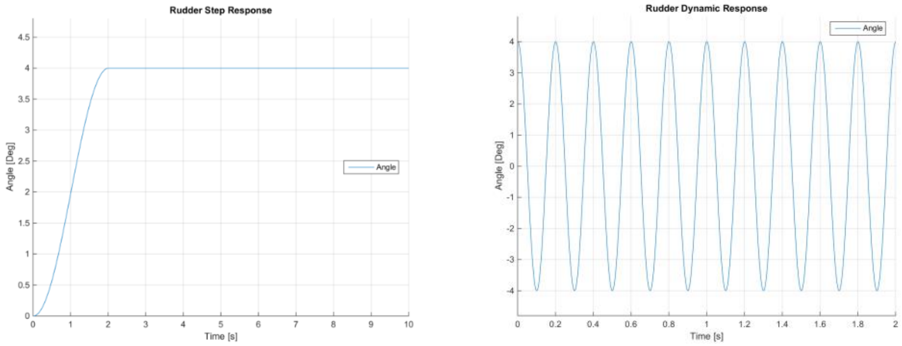

Figure 3 Ramp case: 4 degrees / Dynamic case: 4 degrees 5 Hz

The time step in the CFD simulation varies depending on the frequency and are defined to give time 200 steps for each period where 10 full periods are simulated. The set of cases analysed are combinations of three forward speeds, 2, 10 and 30 knots, four shaft angles, 1, 2, 4 and 8 degrees, and six shaft frequencies, 0.5, 1.0, 2.0, 5.0, 10.0 and 20.0 Hz. The forward speed gives a variation in Reynolds number, Re, from 9.02 10^4 to 1.35 10^6. The reduced frequency, k, based on the semi-chord for the cases goes from 0.01 (30knots/0.5Hz) to 6.1 (2knots/20Hz). This indicates that the cases analysed goes from quasi-steady to highly unsteady.

$$\mathrm{Re} = \frac{U_{ref} \cdot L_{ref}}{\nu} \ , \ k = \frac{\omega \cdot L_{ref} / 2}{V_{ref}} \qquad (1)\ ,(2)$$

3.7 Force calculation

All forces are based on integration of wall pressure and shear forces over the body surface. They therefore represent the hydrodynamic forces acting on the body. Other forces/moments such as inertial forces are not included. The force coefficients are assumed to be dependent on the velocity in free stream, the rudder angular position, the angular velocity, normal referred to as damping part, and the angular acceleration normal referred to as added mass part. Since the rudder is symmetrical in the vertical plane the lift force shall be zero at zero rudder angle. Any lift force in the CFD solution is due to numerical inaccuracy and this has been removed in the analysis. If we neglect the nonlinearities and the zero angle contribution we get:

$$C_L = C_L^{\alpha} \cdot \alpha + C_L^{\dot{\alpha}} \cdot \dot{\alpha} + C_L^{\ddot{\alpha}} \cdot \ddot{\alpha} \qquad (3)$$

For the dynamic cases the following procedure has been used for identification of the coefficients.

- Force coefficients at zero position and at rest. This is identified based on the steady state solution, assumed to be dependent on velocity, and calculated on average of last 50 steps.
- Force coefficients as function of position is calculated from the ramp case taking the average of last half of the simulation. These are assumed dependent on velocity and amplitude
- Force coefficients as function of velocity and acceleration. Identified from the dynamic solution. Least square method applied on 200 points taken from final 5 periods

Since the main purpose of this work was to create input to a time simulation software the force coefficient need to be expressed in a way easily implemented in the code. This means the coefficients shall preferable be expressed as function of forward velocity, shaft position, shaft velocity and shaft acceleration. The results presented are total focused on the lift force since this is the main interest but also since this shows the most complex variation with the independent variables.

4 RESULTS

The regular dynamic results are presented both as Bode plots and time functions, and finally “Irregular dynamic”. First in figure is presented the result on the steady state lift force coefficient as function of angle for the three different speeds. In the figures are presented both the direct result on the total force from the CFD analysis and the influence of each coefficient by adding them to calculate the total force. Here is four cases chosen for each forward velocity: 1 degrees and 4 degrees combined with 1 Hz and 10 Hz. This shows not only the influence from each coefficient but also gives a clear view of the accuracy of the assumption about linearity and the coefficient identification method.

Black	: CFD	Total force from CFD analysis
Blue	: Cf(X)	Force: Position dependent part only
Green	: Cf(X,V)	Force: Position and velocity dependent parts
Red	: Cf(X,V,A)	Force: Position, velocity and acceleration dependent parts

4.1 Steady state

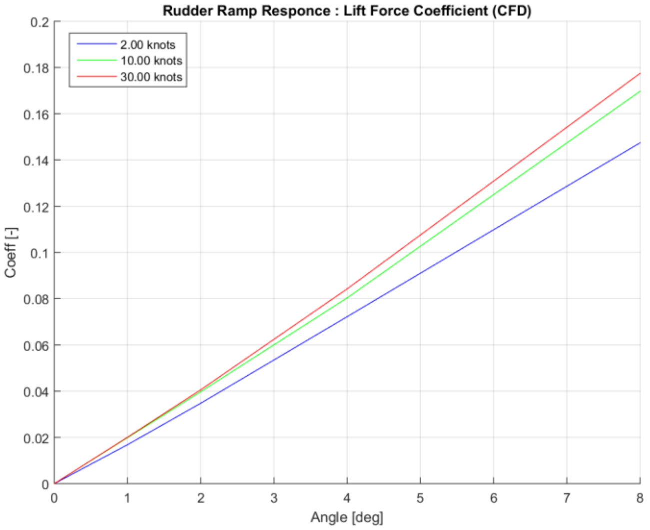

Figure 4 Steady state lift force coefficient variation: 2, 10 and 30 knots

4.2 Dynamic: Bode plots (Amplitude & Phase vs frequency [ω])

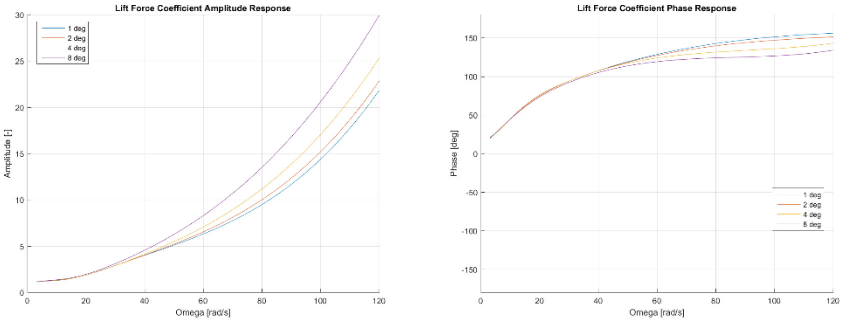

Figure 5 Lift force coefficient variation Amplitude / Phase: 2 knots

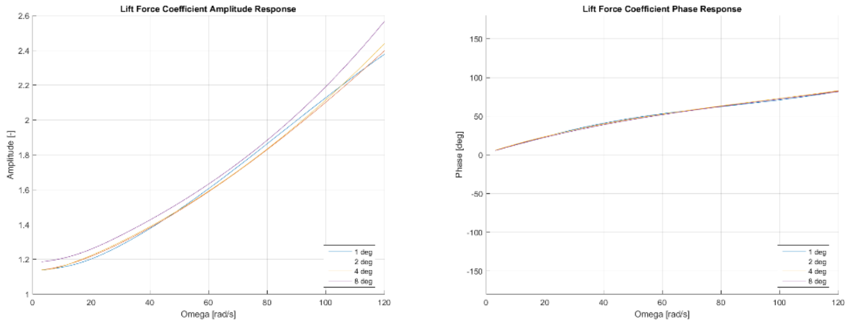

Figure 6 Lift force coefficient variation Amplitude / Phase: 10 knots

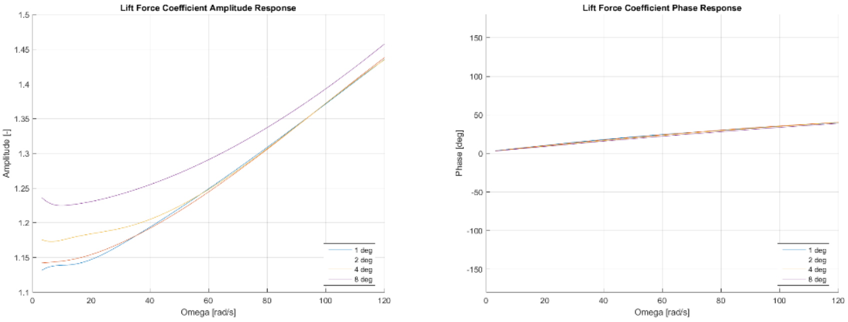

Figure 7 Lift force coefficient variation Amplitude / Phase: 30 knots

4.3 Dynamic: Forces vs phase

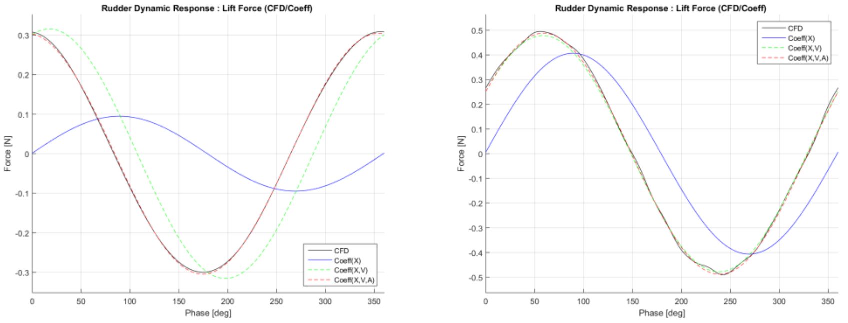

Figure 8 Force vs Phase, (2 knots / 1 deg(Left) & 4 deg / 1.0 Hz)

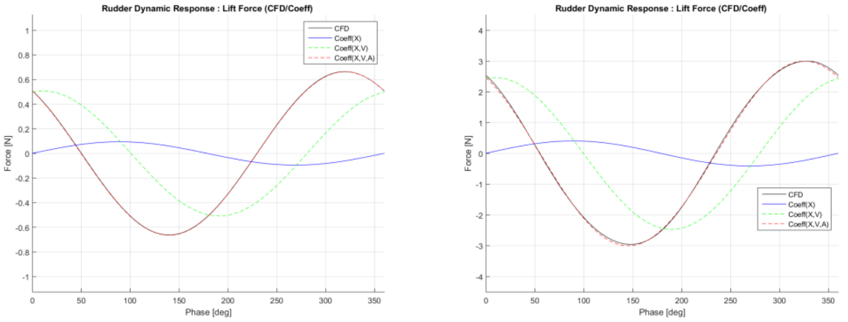

Figure 9 Force vs Phase, (2 knots / 1 deg(Left) & 4 deg / 10.0 Hz)

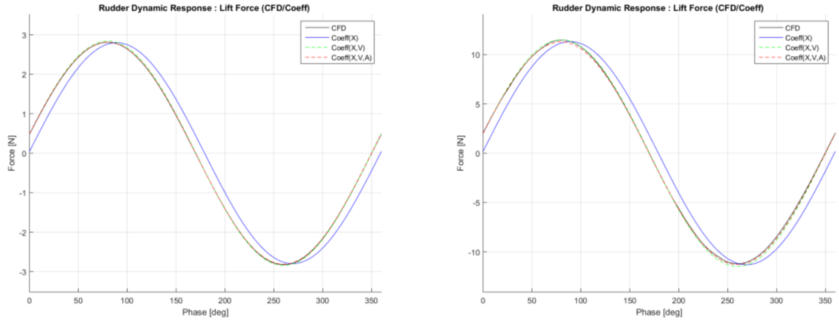

Figure 10 Force vs Phase, (10 knots / 1 deg(Left) & 4 deg / 1.0 Hz)

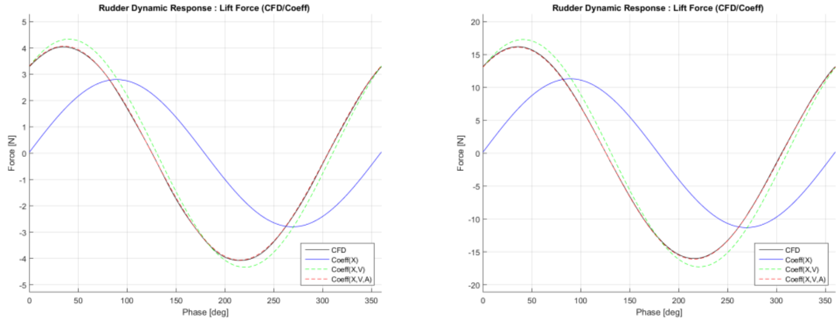

Figure 11 Force vs Phase, (10 knots / 1 deg (Left) & 4 deg / 10.0 Hz)

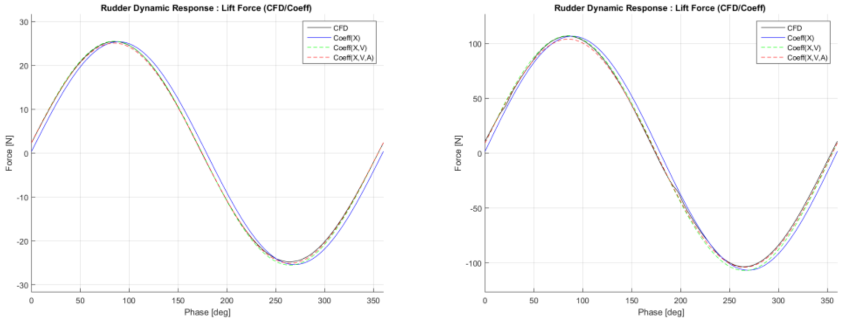

Figure 12 Force as function of shaft position 30 knots / 1 deg(Left) & 4 deg / 1 Hz

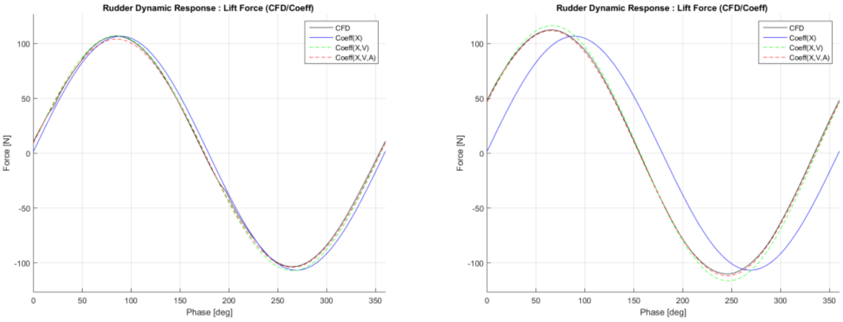

Figure 13 Force as function of shaft position 30 knots / 1 deg(Left) & 4 deg / 10 Hz

4.4 Summary: regular rudder motion

For the medium and high speed cases the phase shift is independent of amplitude and varies only with forward speed and shaft frequency. For the low speed case the relation is more complicated. The amplitude varies with a factor of 10 and compared to 1.5 to 2 for the other speed cases and the phase shift is also much larger even up to 150 degrees at the highest frequency. This indicates a much larger added mass component. This is seen also in the plots with the phase as independent variable. For the 2 knots cases the acceleration depended part is significant but even here is the velocity dependent part dominating.

Based on all these regular rudder motion analysis ONE constant coefficient are calculated for each of the shaft position, shaft velocity and shaft acceleration dependency for each forward velocity. This is done by simple taking the average of the coefficients of the dynamic cases for each speed. The velocity dependent part (Clv), which dominates over the acceleration part (Cla), shows the least standard deviation 1-2% of the mean value for 10 and 30 knots and 10% for 2 knots. This indicates that a more complicated function may be required to cover the 2 knots case with higher accuracy.

Table 1 Mean & Standard deviation values (Std) of the transient lift force coefficients

V[knots]	Clv(Mean)	Cla(Mean)	Clv(Std)	Cla(Std)
2.00	0.104562	-0.000179	0.011242	0.000653
10.00	0.025628	0.000435	0.000193	0.000293
30.00	0.011438	0.000650	0.000333	0.000211

4.5 Irregular rudder motion

The rudder motion of the torpedo is of course not a regular motion with a constant amplitude and frequency. The identified coefficients therefore need to be verified on cases with irregular rudder motions. Four different “irregular” cases have been generated combining the frequencies and amplitudes used in the dynamic cases.

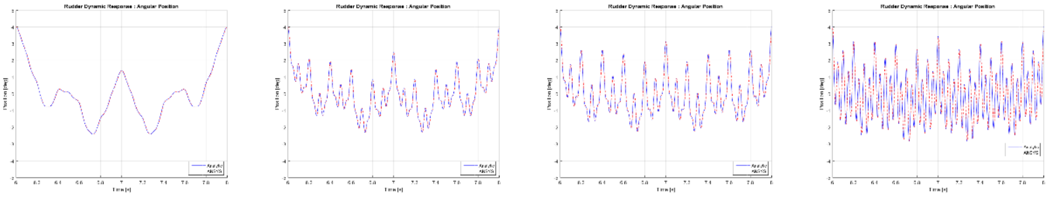

Figure 14 Rudder positions: irregular cases 1- 4, IR1 to IR4

In each figure is given the analytical solution together with the angle reported by ANSYS CFX during the solution. The maximum shaft velocities are for the three cases 25, 100, 150 and 250 deg/s. First we look at the values direct from the averaging process without any adjustments and after that the same values when a simple velocity dependent scale factor function is applied to the shaft rate dependent force coefficient and the added mass is removed. The scale factors applied on the velocity dependent coefficients are 1.00, 0.66 and 0.55 for the 2, 10 and 30 knots forward speed cases.

4.6 Irregular rudder motion lift force: Unadjusted

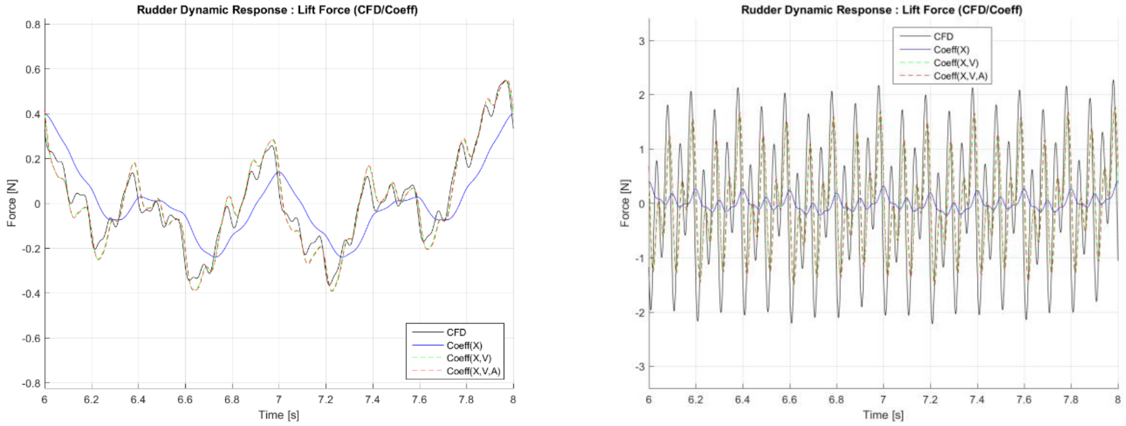

Figure 15 Lift Force 2 knots: IR1 and IR3 irregular case

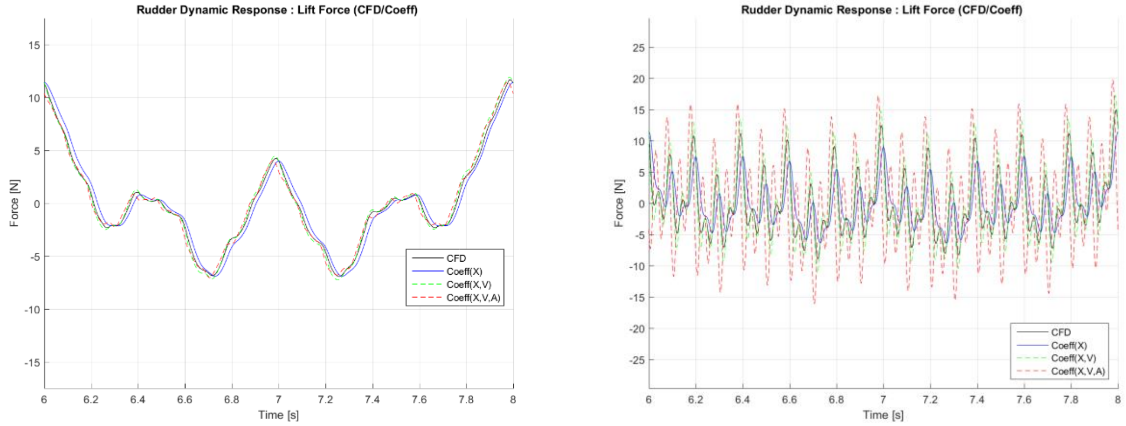

Figure 16 Lift Force 10 knots: IR1 and IR3 irregular case

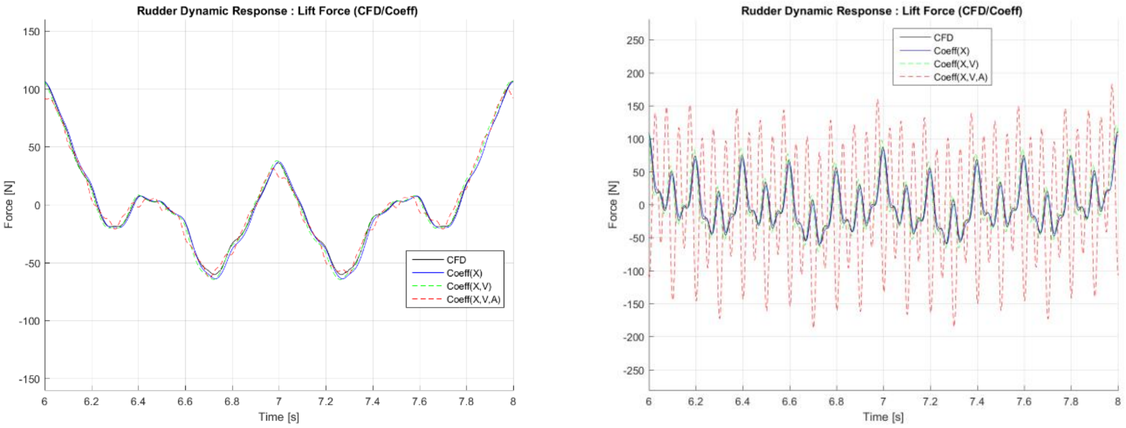

Figure 17 Lift Force 30 knots: IR1 andIR3 irregular case

4.7 Irregular rudder motion lift force: Adjusted

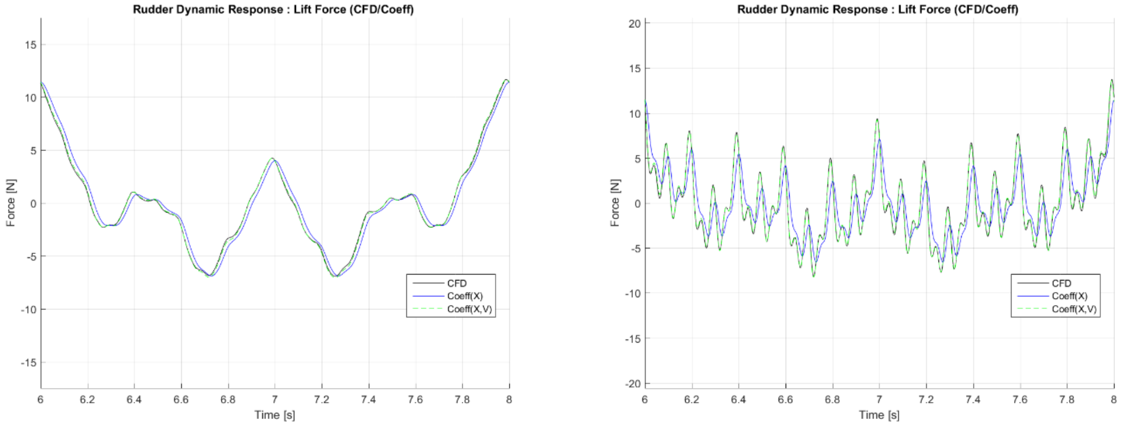

Figure 18 Lift Force 10 knots: IR1 and IR2 irregular case

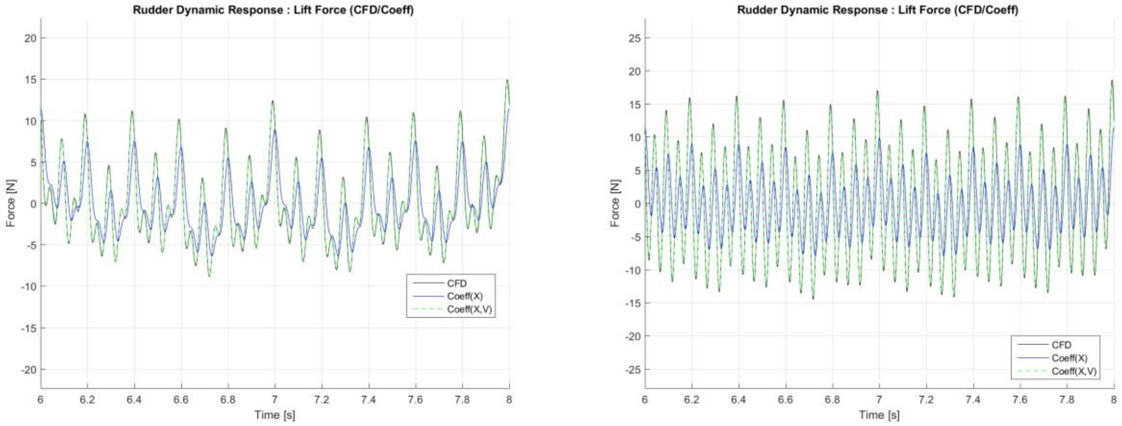

Figure 19 Lift Force 10 knots: IR3 and IR4 irregular case

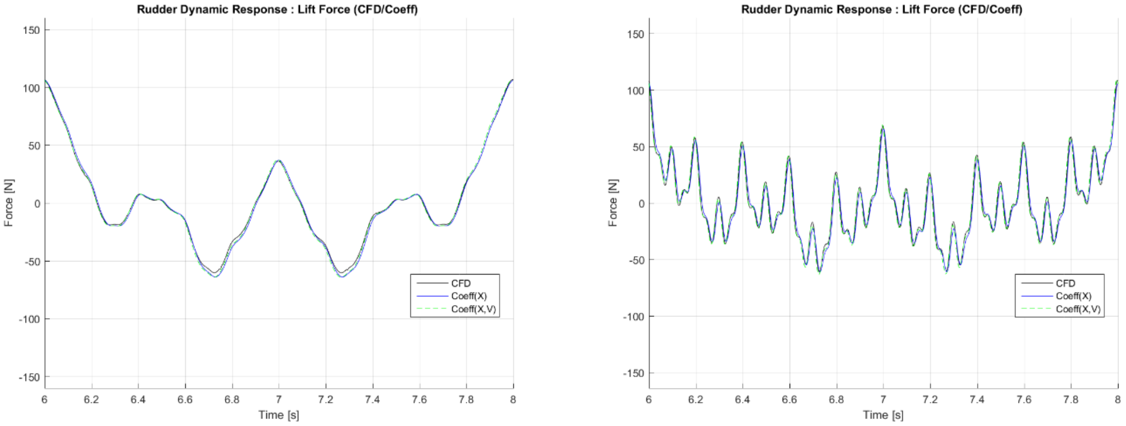

Figure 20 Lift Force 30 knots: IR1 and IR2 irregular case

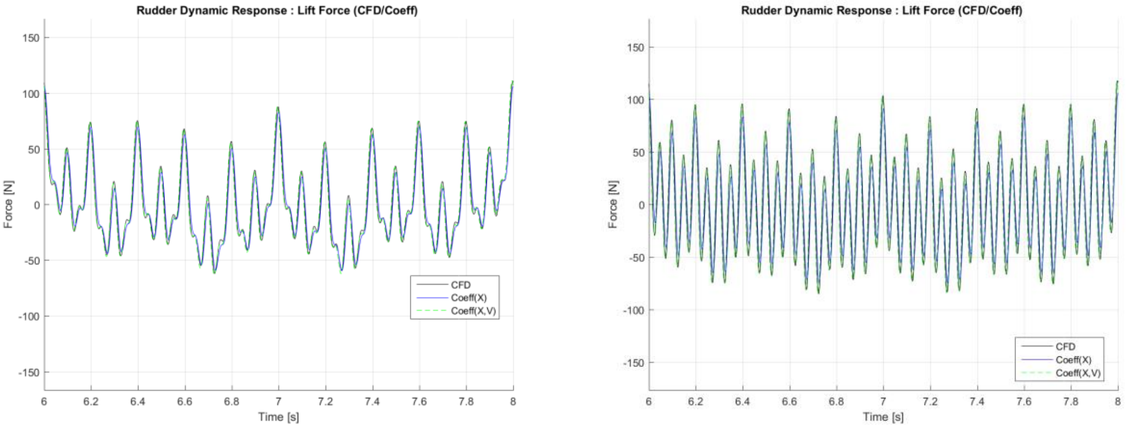

Figure 21 Lift Force 30 knots: IR3 and IR4 irregular case

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