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Mr. Andrew Hamilton, Ph.D.
Mechanical Engineer
Monterey Bay Aquarium Research Institute
7700 Sandholdt Road
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Re: Flapping Foil Transient Simulation data analysis (L-10-MFF-01)

Dear Andy:

This letter reviews transient results for three Flapping Foil Computational Fluid Dynamic (CFD) simulations recently completed by Airflow Sciences Corporation (ASC). These simulations model the transient seawater motion around a rotating and translating standard NACA 00015 foil. Three different motion profiles, provided by MBARI, were simulated for a period of 600 seconds using a time step of 0.05 seconds.

Background

MBARI is involved with the design of a *Station Keeping Buoy* that utilizes wave motion to generate power to maintain its position. The wave motion is utilized via a foil attached to the buoy to maintain a desired buoy location. MBARI has been simulating the buoy's full motion by approximating the fluid forces on the foil via published steady state lift and drag correlations. Since the fluid motion around the foil is somewhat transient, MBARI is interested in evaluating the validity of this steady state assumption.

Method

The method adopted for evaluating the steady state assumption is to simulate the transient fluid motion around a foil motion predicted by MBARI's simulations based on that assumption. ANSYS-Fluent version 6.3.26 was used to calculate the lift and drag forces on the foil based on the predicted transient fluid motion. The predicted lift and drag forces were compared to the published steady state data and the differences were evaluated.

Results

Three buoy motion profiles were submitted to ASC for evaluation: 1) BuoyA2 Hs3 Ls15 Lc0.4 dt0.05 tf600, 2) BuoyA2 Hs3 Ls5 Lc0.4 dt0.05 tf600, and 3) BuoyA2 Hs3 Ls1.7 Lc0.4 dt0.05 tf600. It is ASC understanding that each of these motion profiles represent different wave motions expected to be experienced by the buoy.

The transient simulation results were documented via 12000 frame animations that were provided electronically. Some example frames from the Case 1 animation are included, see Figures 1-3. Note that the fluid velocity color contours are in the absolute reference frame and the line graphs on the right show the predicted instantaneous left and drag coefficients along with the published steady state line graphs. It is interesting to note that the third frame shown indicates very close correlation to the steady state assumption, whereas the other two frames show a notable deviation from the steady state curves.

To further analyze the level of correlation between the steady state lift and drag data and the CFD data, a 50 second segment of the full data set provided by MBARI was evaluated. Figures 4-6 present four stacked line graphs for evaluating the foil motion data and the level of correlation. The topmost line graph presents the difference between the NACA data and the CFD prediction. Values of zero indicate good agreement between the two different drag force methods (steady state and transient CFD).

The second graph from the top shows two lines: foil attack angle and the foil pitch rate. The foil angle of attack is in degrees and the scale on the left should be used to evaluate this data. The foil pitch rate is presented in rad/s as provided by MBARI, see the scale on the right of the line graph. Note that there are regions where the foil pitch rate is zero yet the angle of attack is varying since the angle of attack is a function of the foil translational motion.

The bottom two line plots detail the Cartesian fluid forces applied to the foil. The force based on the NACA data is presented with the CFD predicted force.

To help evaluate the degree of correlation between the CFD drag predictions and the NACA data, a histogram plot was generated for each, see Figure 7-9. The histogram plots were generated by evaluating the magnitude of the difference between the CFD lift/drag predictions with the NACA data. The magnitude error between zero and 5 was broken down into 40 groups. The error for all 12,000 integration points where then sorted into these groups and presented as a histogram bar graph. For an ideal correlation, we would expect 12,000 points with an error magnitude of zero.

These histogram graphs indicate that a significant number of the 12,000 integration points deviate noticeably from the steady state drag assumption. In general, these graphs seem to indicate that the drag coefficient correlations are much better than the lift correlations.

Figures 9-11 show an integration of the work performed by the foil. Work is assumed to be the total force applied to the foil dotted with the travel of the foil for each time step. Two graphs are presented for each case: one based on forces from the NACA data and the second based on the CFD predicted forces. Note that the NACA and CFD line graphs grow at different rates for each of the cases. This steady deviation between the two methods indicate that the differences between the CFD force predictions and the NACA data does not lead to canceling.

Conclusion

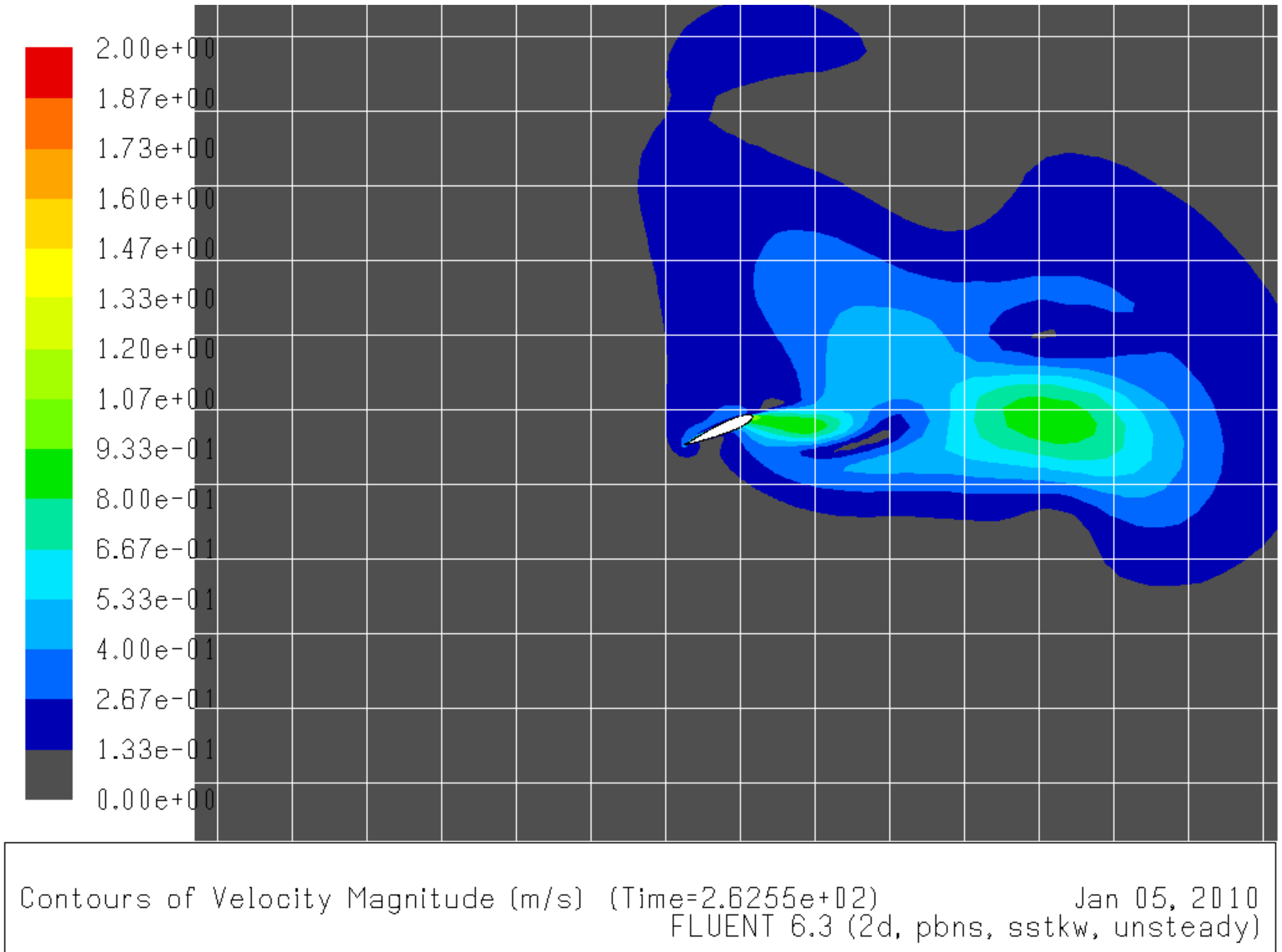
Three transient CFD simulations of a rotating/translating foil have been performed. The motion profile assumed for the foil was based on simulation results provided by MBARI. Each simulation was run for 12,000 time steps and animations were generated to visually evaluate the fluid motion in the vicinity of the foil. Drag and lift forces predicted by the CFD analysis have been compared to published NACA lift and drag data. The lift and drag correlations indicate that there are some areas which show good agreement between the two methods of approximating the foil forces. The statistical analysis detailed in Figures 7-9, however, shows that most of the solution integration points are not approximated well by the steady state assumption. Based on this information ASC is recommending that a coupling method be used to improve the buoy modeling tool.

Airflow Sciences Corporation appreciates the opportunity to work with MBARI on this modeling effort and looks forward to helping MBARI improve this modeling tool.

Very truly yours,

Jeffrey D. Franklin, Ph. D., P.E.
Senior Engineer

Case: 1 - Time: 262.5 seconds



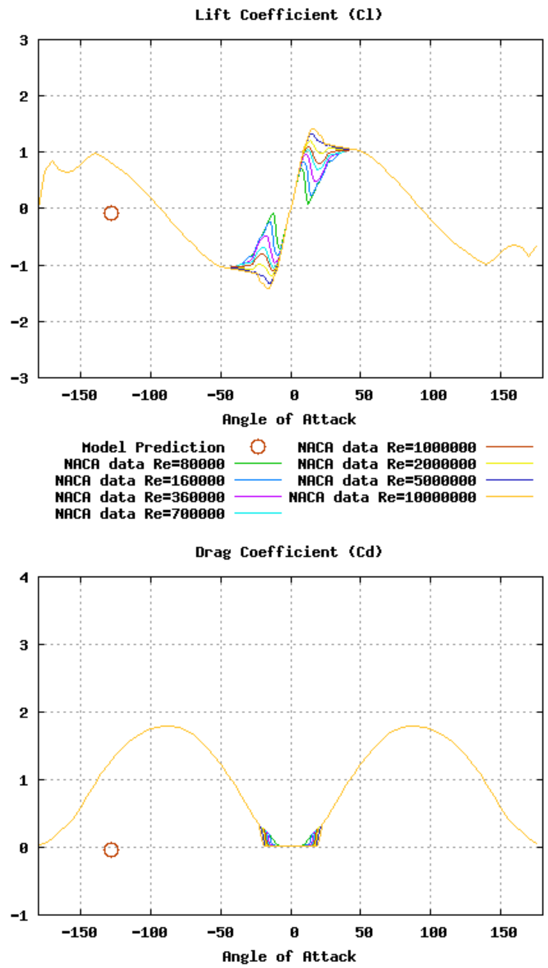


Figure 1

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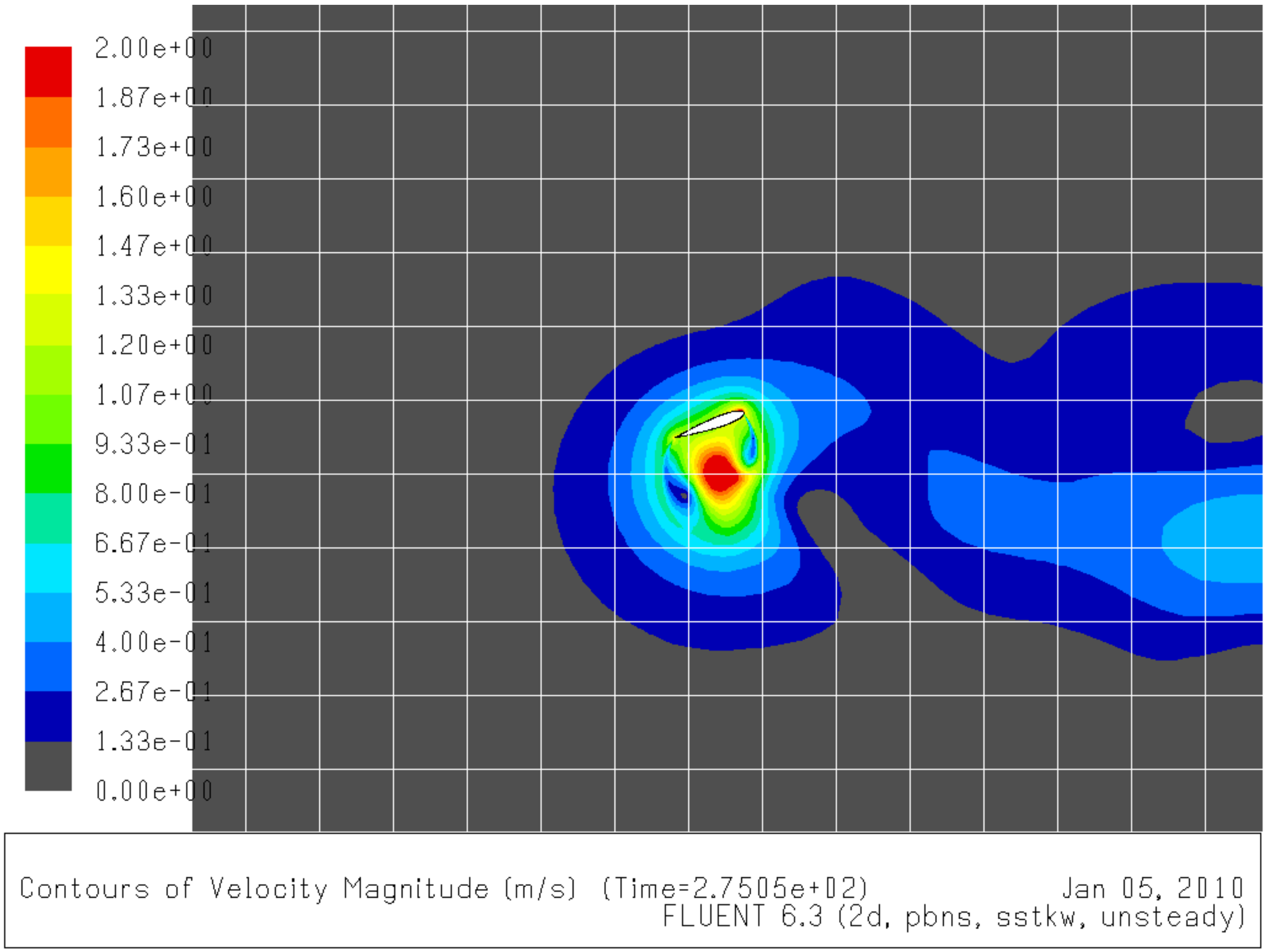
Case: 1 - Time: 275 seconds



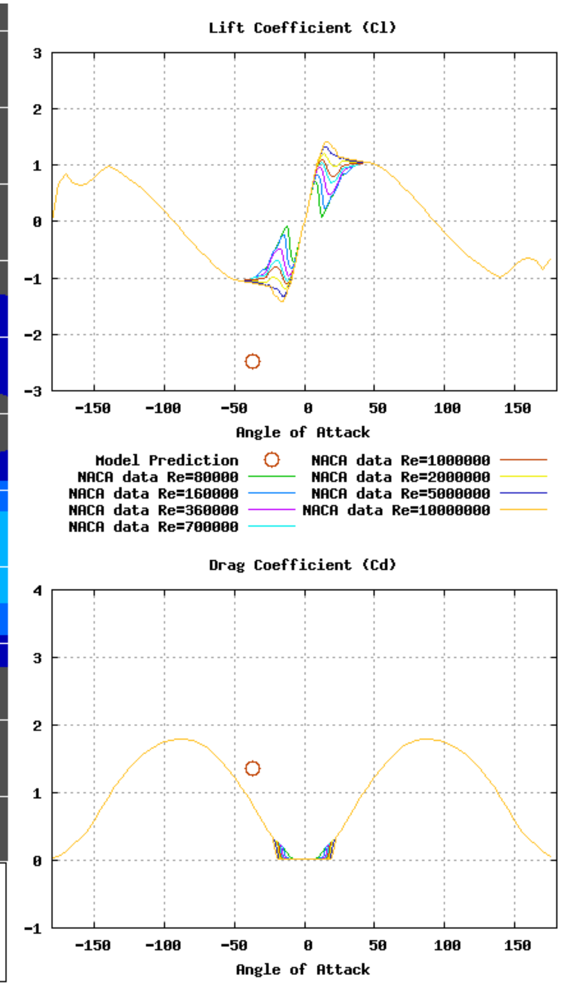


Figure 2

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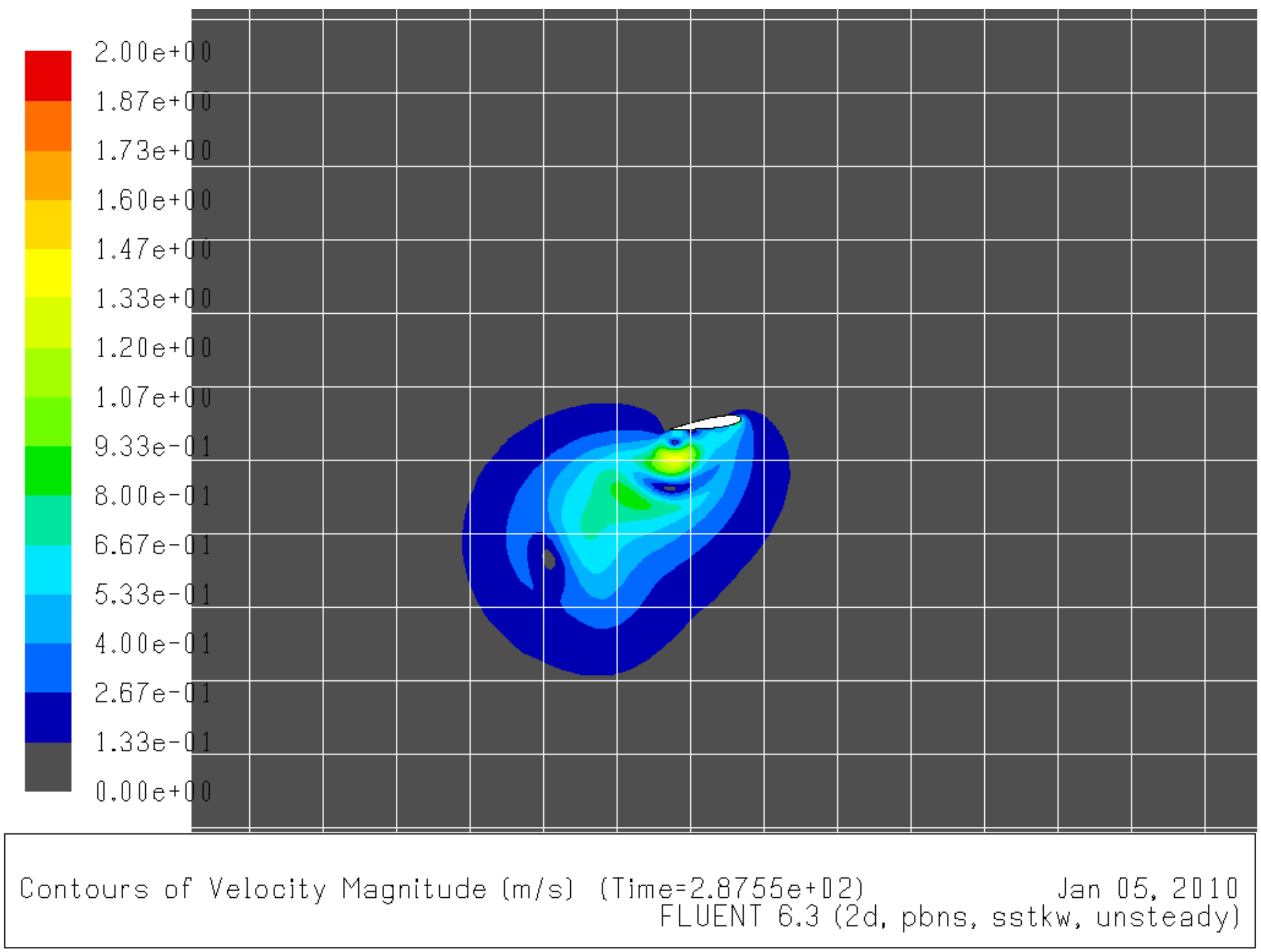
Case: 1 - Time: 287.5 seconds



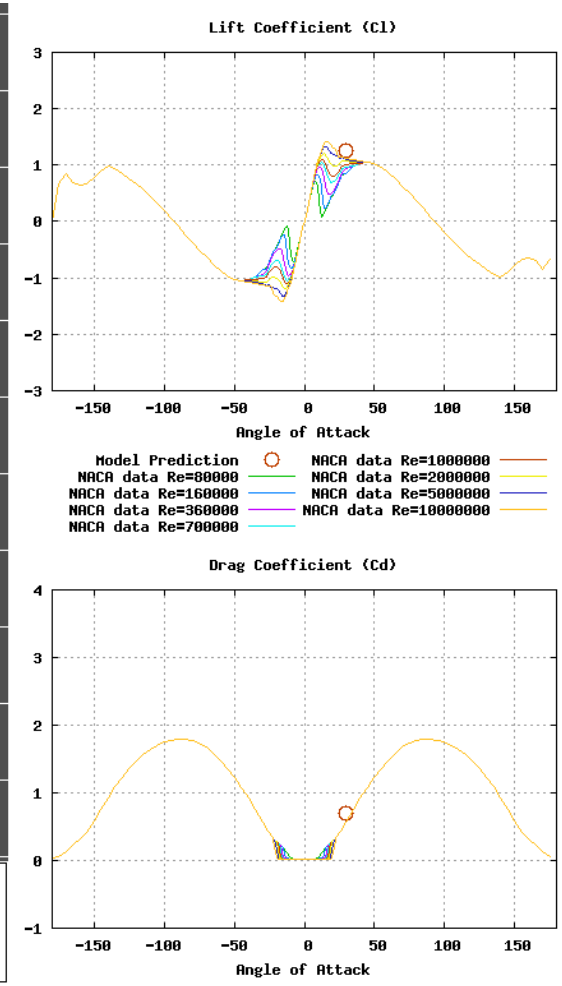


Figure 3

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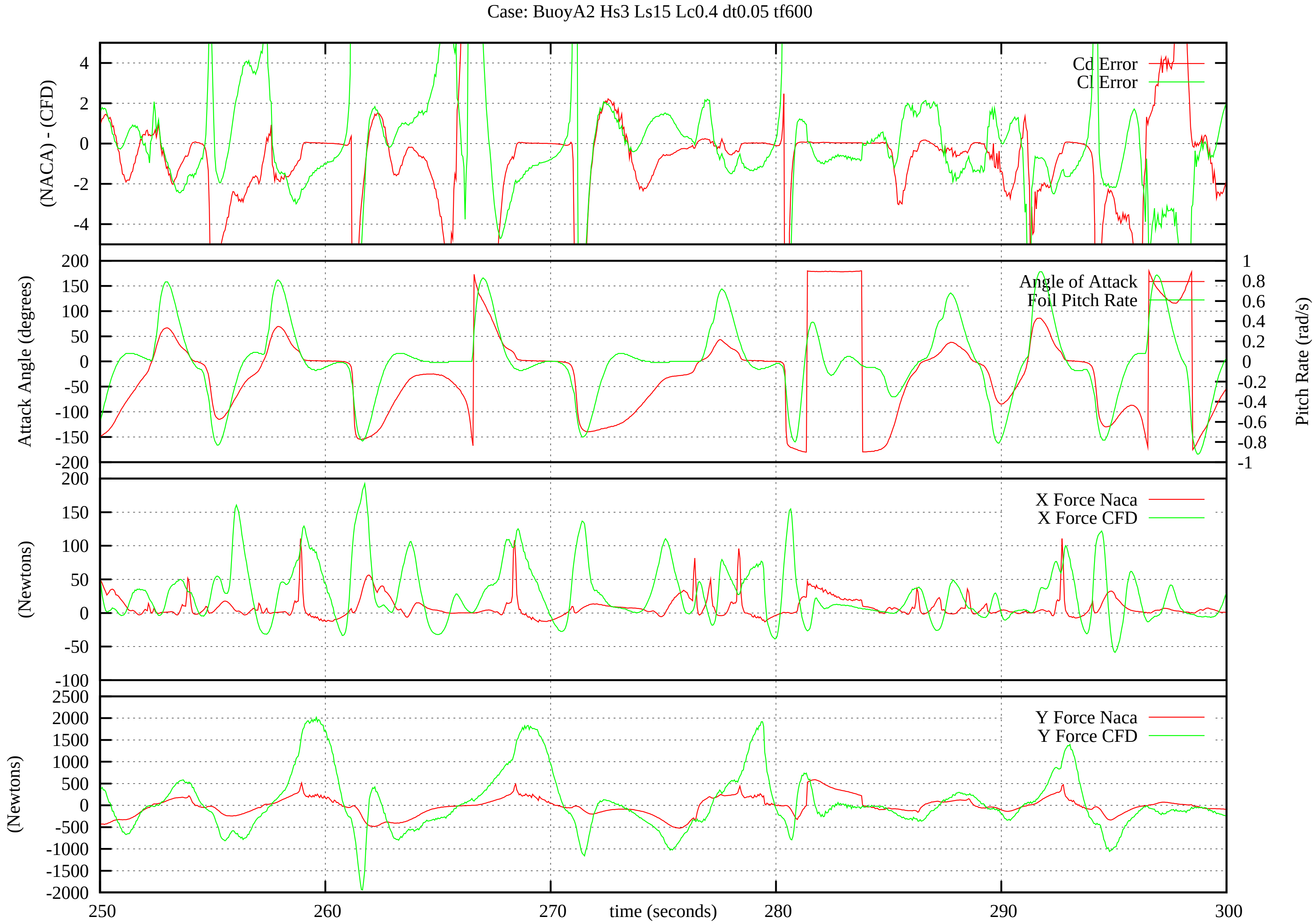
Case: BuoyA2 Hs3 Ls15 Lc0.4 dt0.05 tf600
(NACA) - (CFD)
Cd Error
Cl Error
Attack Angle (degrees)
Angle of Attack
Foil Pitch Rate
Pitch Rate (rad/s)
(Newtons)
X Force Naca
X Force CFD
(Newtons)
Y Force Naca
Y Force CFD
250
260
270
280
290
300
time (seconds)

Figure 4

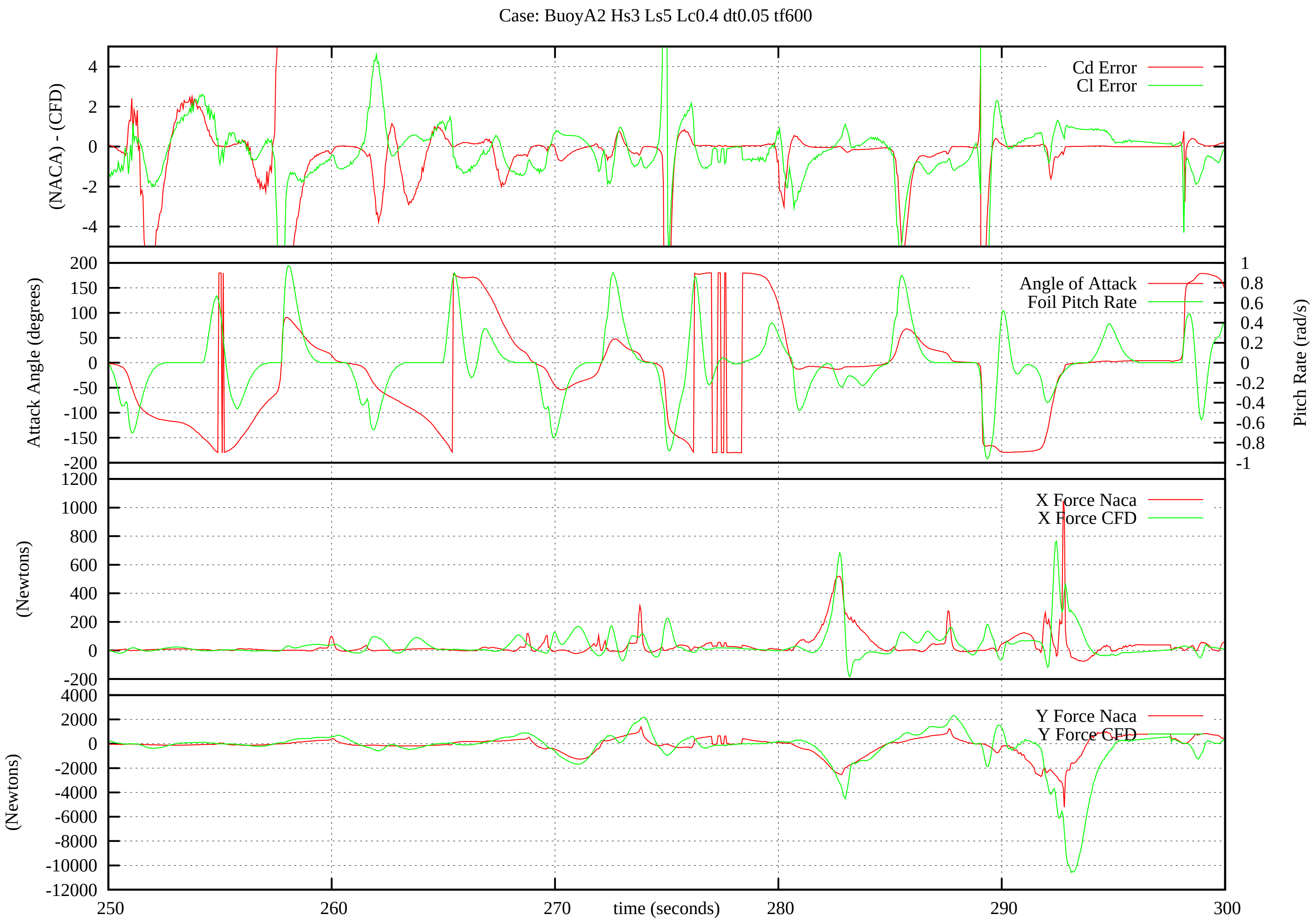
Case: BuoyA2 Hs3 Ls5 Lc0.4 dt0.05 tf600
(NACA) - (CFD)
4
2
0
-2
-4
Cd Error
Cl Error
Attack Angle (degrees)
200
150
100
50
0
-50
-100
-150
-200
Angle of Attack
Foil Pitch Rate
Pitch Rate (rad/s)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
(Newtons)
1200
1000
800
600
400
200
0
-200
X Force Naca
X Force CFD
(Newtons)
4000
2000
0
-2000
-4000
-6000
-8000
-10000
-12000
Y Force Naca
Y Force CFD
250
260
270
time (seconds)
280
290
300

Figure 5

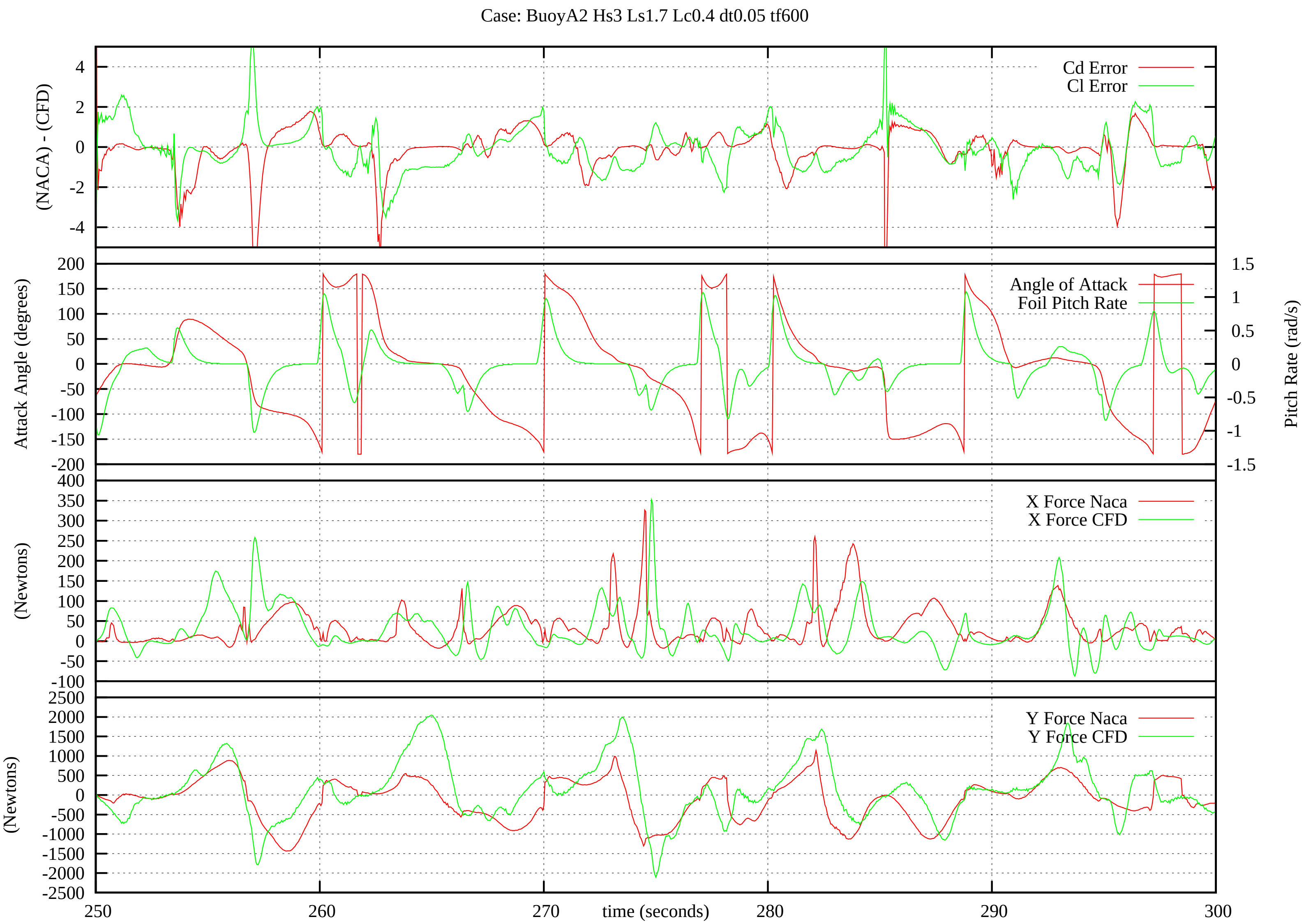

Figure 6

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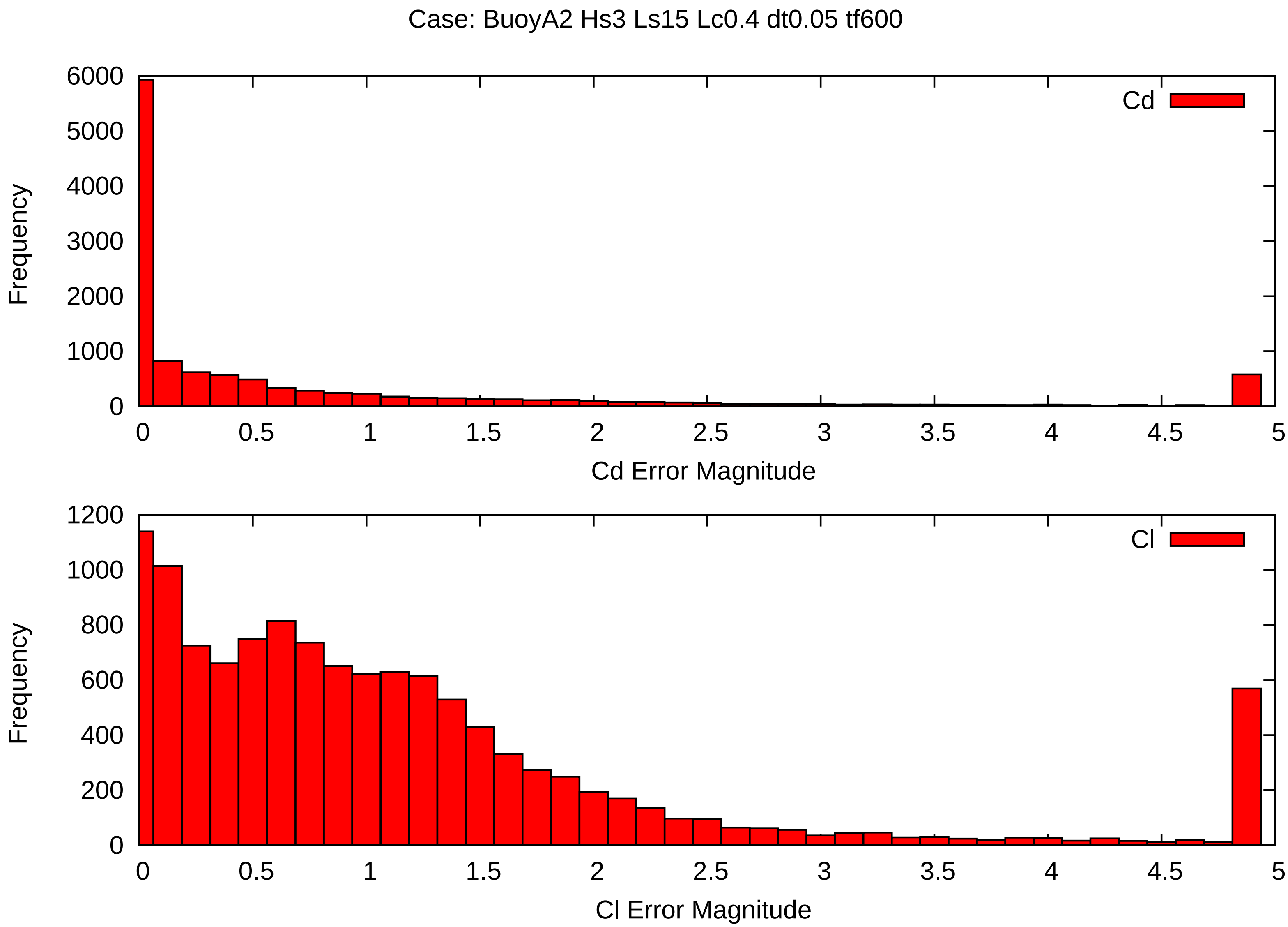
Case: BuoyA2 Hs3 Ls15 Lc0.4 dt0.05 tf600
Frequency
6000
5000
4000
3000
2000
1000
0
Cd
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Cd Error Magnitude
Frequency
1200
1000
800
600
400
200
0
Cl
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Cl Error Magnitude

Figure 7

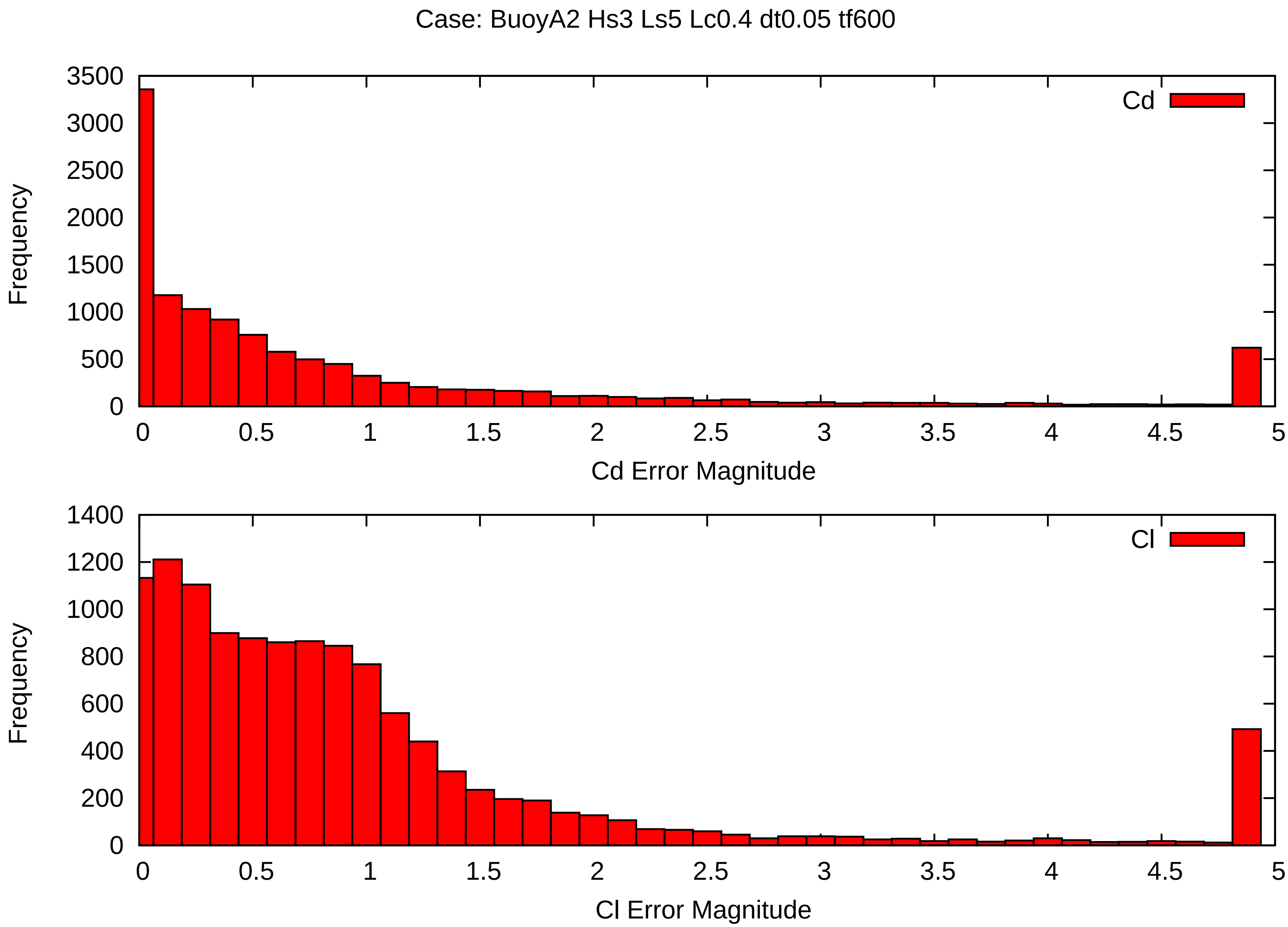
Case: BuoyA2 Hs3 Ls5 Lc0.4 dt0.05 tf600
Frequency
3500
3000
2500
2000
1500
1000
500
0
Cd
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Cd Error Magnitude
Frequency
1400
1200
1000
800
600
400
200
0
Cl
Cl Error Magnitude

Figure 8

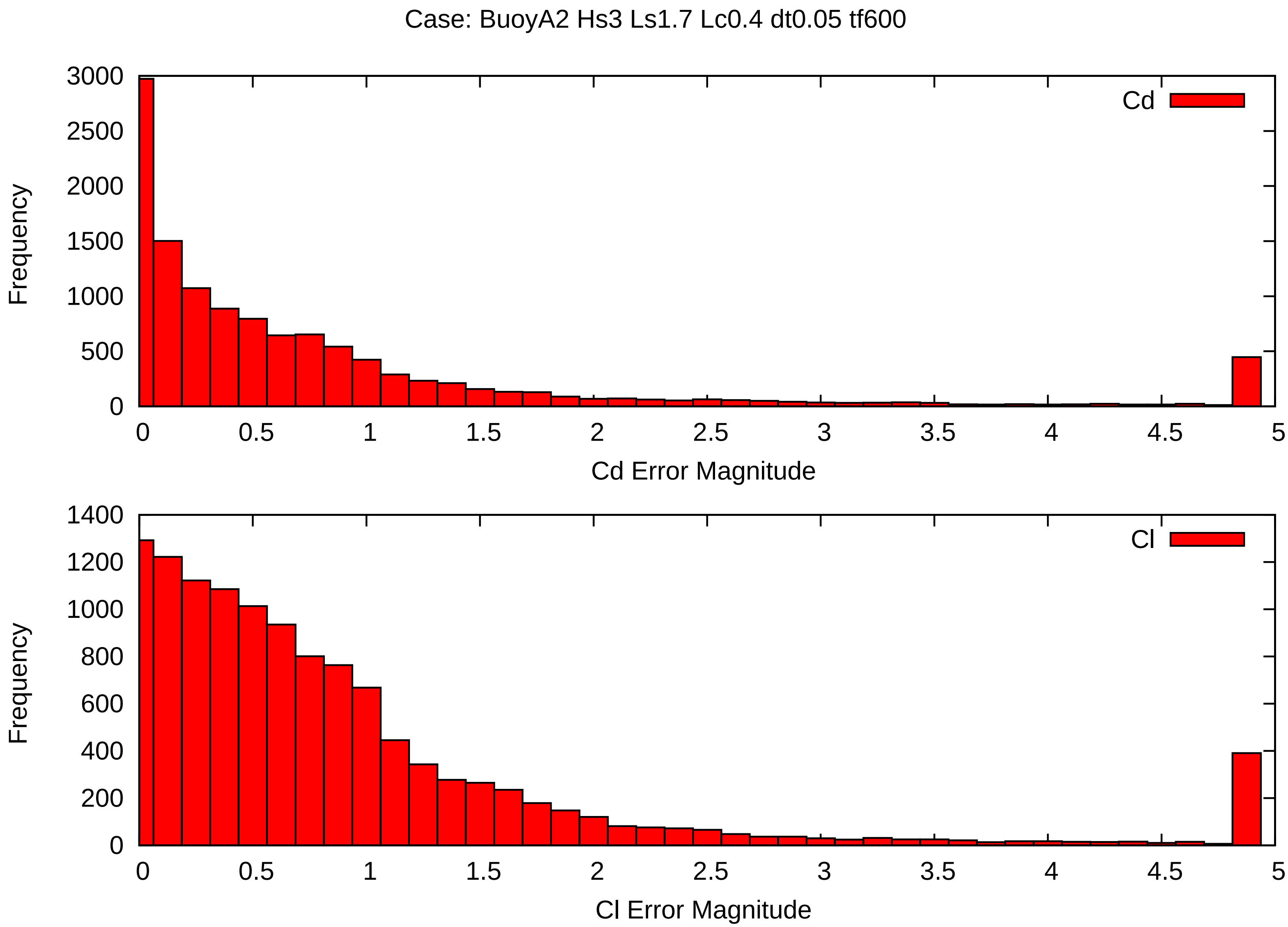
Case: BuoyA2 Hs3 Ls1.7 Lc0.4 dt0.05 tf600
Frequency
Cd
Cd Error Magnitude
Frequency
Cl
Cl Error Magnitude

Figure 9

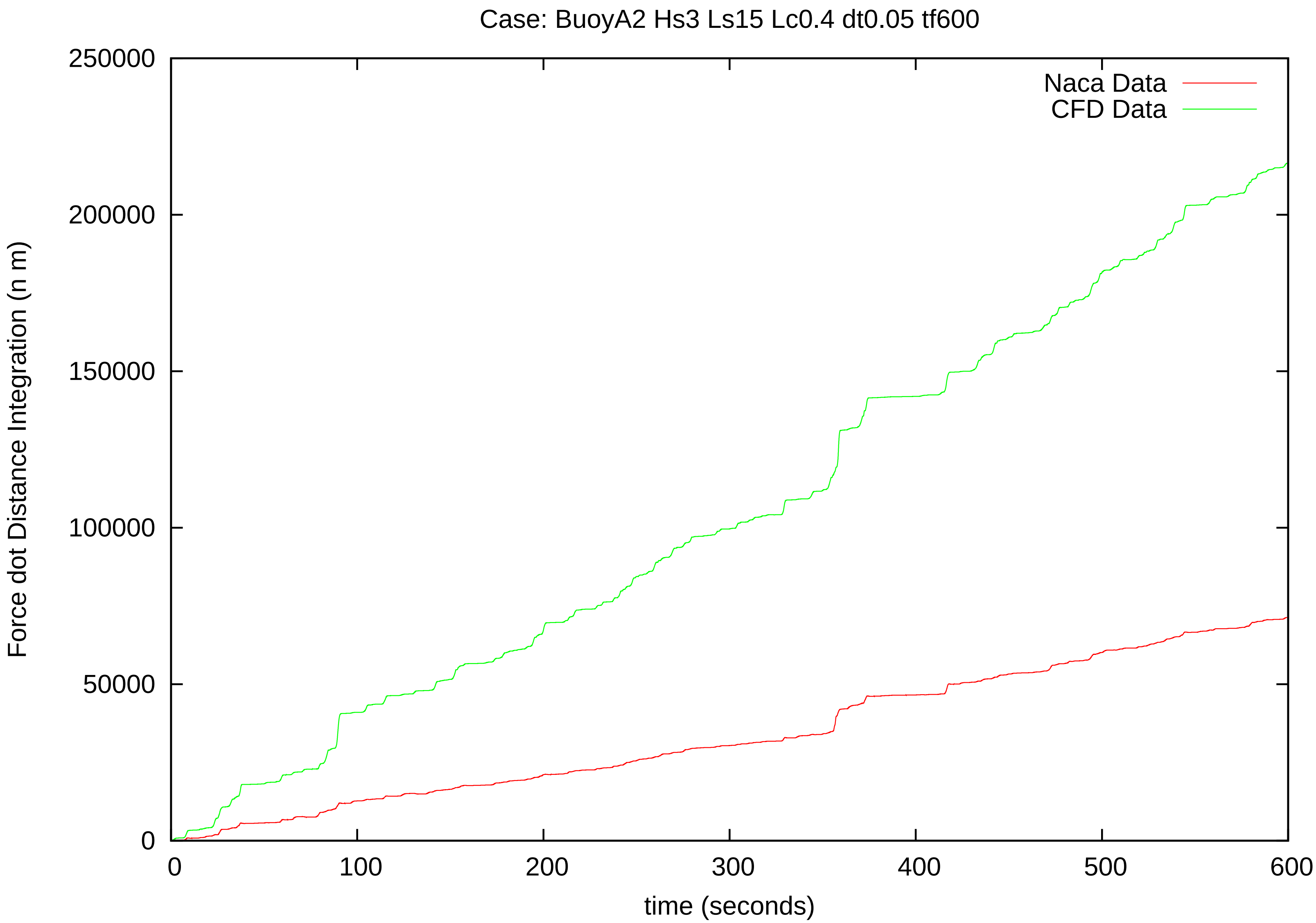

Figure 10

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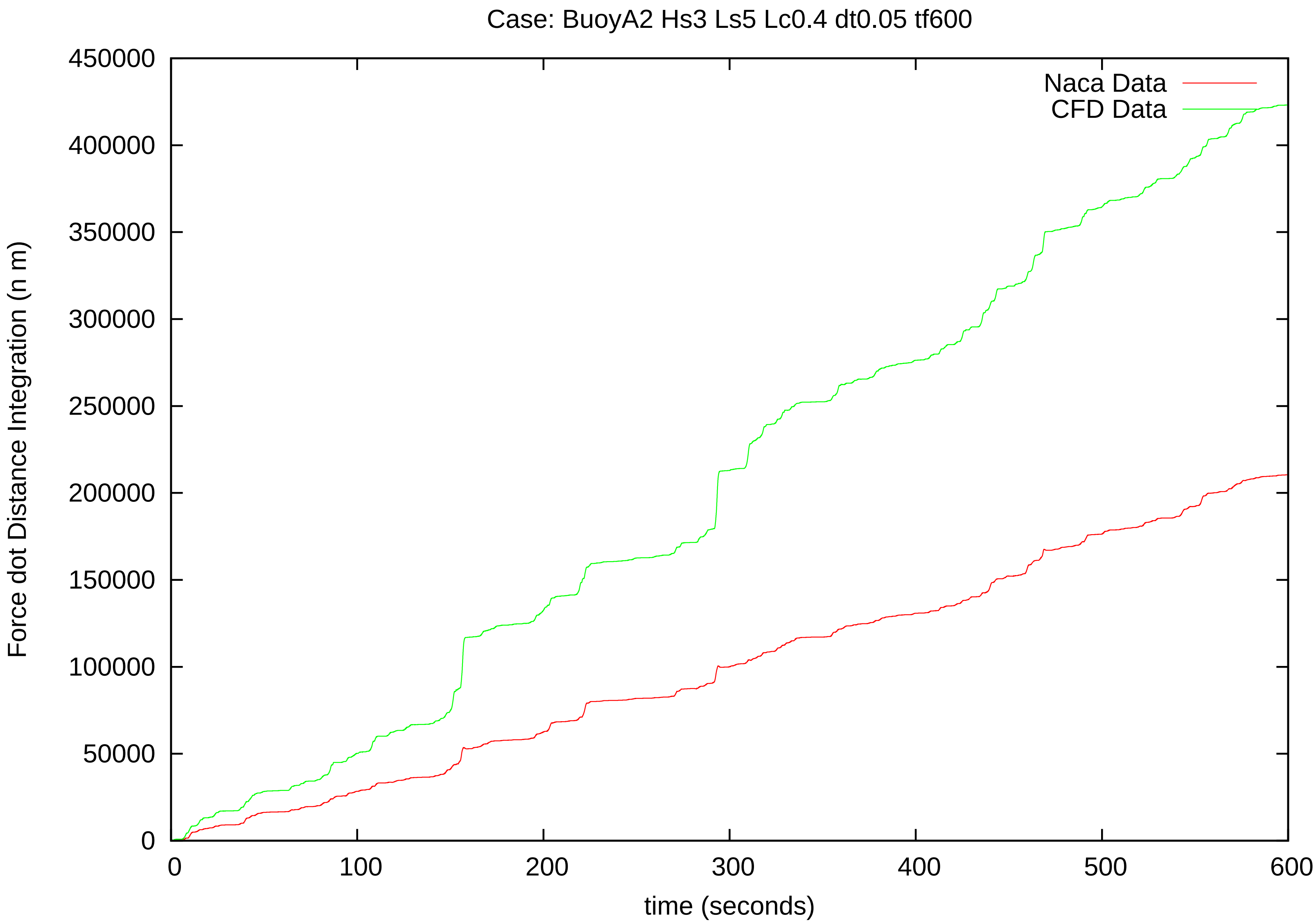

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Figure 11

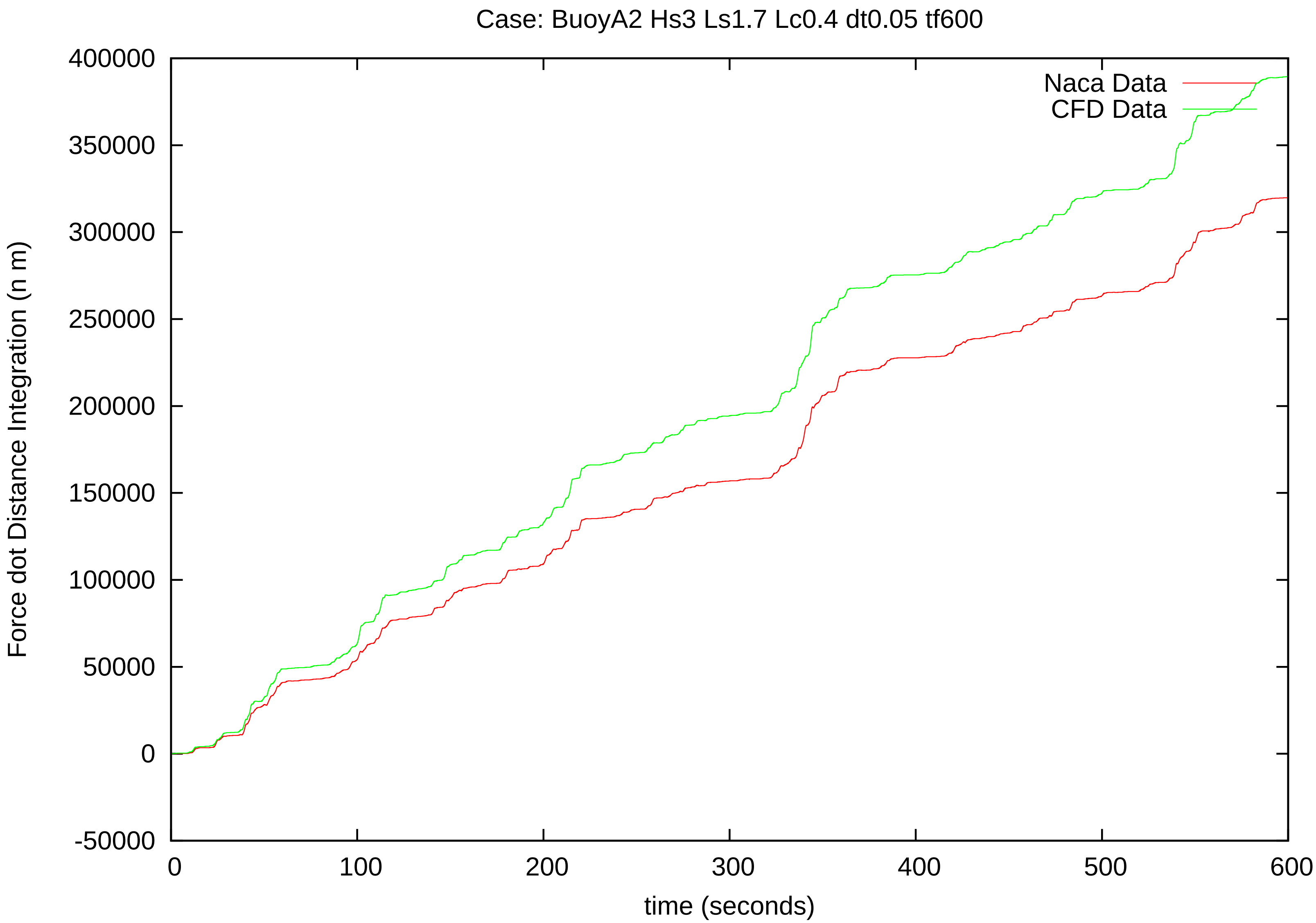
Case: BuoyA2 Hs3 Ls1.7 Lc0.4 dt0.05 tf600
Naca Data
CFD Data
Force dot Distance Integration (n m)
400000
350000
300000
250000
200000
150000
100000
50000
0
-50000
0
100
200
300
400
500
600
time (seconds)

Figure 12