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Aileron Induced Unbalanced Torque Compensation Using Contra-rotating Dynamic Motor Control for an AUV CRP

İlkay Özyiğit[1], Emre Güngör[2]

[1]Roketsan Technology and Research Center (ROKETSAN-ROTAM), Istanbul, Turkey
[2]Roketsan Technology and Research Center (ROKETSAN-ROTAM), Istanbul, Turkey

ABSTRACT

Generally, propellers are designed for stable on-design cruise conditions. These conditions contain almost zero pitch angle and zero roll angle on hull and almost zero rudder angles for rudder configurations. According to these initial assumptions, propeller performance characteristics are obtained by using parametric design and analysis codes or some CFD software calculations. In an AUV CRP design and analysis case, traditional methods and initial conditions were used and performance estimation was completed. In second case, same AUV CRP performance investigated in variable aileron rudder angles in different sea trails. Investigation shows that CRP's thrust and torque behavior in dA=0 condition are considerable different than variable dA conditions. Especially, considerable CRP torque differences resulting from different dA angels induce AUV hull stability on roll, torque and distributed power on each shaft and thermal behavior of propulsion motor in AUV. To enhance these disturbances on hull stability and AUV propulsion, a generic motor dynamic control algorithm was performed. Algorithm calculates the shaft torques by using electrical motors phase currents and decides shaft revolutions to compensate induced unbalanced torques on propulsion system while AUV propels. Electrical motor shaft revolutions with respect to shaft torques look-up table is fed by AUV sea trials.

Keywords

Unbalanced, torque, electrical motor, control, CRP

1 INTRODUCTION

In early sea trails of a restricted AUV project, especially in stable on-design cruise conditions, based on different AUV cruise speeds, lots of unexpected variable dA angles were obtained to provide the AUV hull stability at zero ϕ roll angles on the yaw plane. These dA angles were not expected in the sea trails and these results were completely off-design points for this objective cruise conditions.

Lots of different parameters are collected from the sea trails and evaluated. To calculate the total torque of propulsion system, different current sensors were used and electrical motor phase currents (I) were measured and used to calculate the electrical motor shaft output torques. Shaft torques were calculated by K_T-specific motor torque coefficient and delivered torque values were obtained for each propeller of CRP assembly.

Additively, propulsion system (electrical motor, intermediate shafts, CRP) shaft revolutions (rpm) were measured by an encoder device which is mounted on electrical motor and these shaft revolutions were used to calculate the motor shaft break powers (P_B), intermediate shaft powers (P_S) and delivered powers (P_D) for each propeller of CRP assembly.

On the other hand, AUV hull roll angle ϕ measured by Inertia Measurement Unit (IMU), commanded aileron angles were calculated and generated by auto-pilot which is embedded in central computer and actual aileron angles (dA) were measured by potentiometers which are located on rudder control system.

Off-design results which belong to sea trails were investigated and analyzed with the abovementioned parameters and thus some technical evaluations were obtained.

At the final evaluation, if dA angles occur in stable cruise conditions and in different stationary fixed shaft revolutions, CRP performances, generated torques and thrusts change. Aileron angels induce swirl-dominated flow pattern in the inlet wake field of fore propeller and affects the ideal/theoretical design wake field of CRP set. Thus, the characteristics of flow's tangential speed vector component, axial speed vector component and angle of attack change. In this case, fore and aft propeller generates different torque and thrust values which are different from each other.

This adverse difference causes unbalanced propeller torques, AUV speed variations and total residual torque on AUV hull. All of these factors force to be a roll movement on the hull and the roll movement causes to be generated different aileron angles to prevent the roll on the body. Hereby, zero ϕ roll angle is obtained.

As a solution, to make unbalanced torque compensation, contra-rotating dynamic motor control is performed for AUV CRP and an algorithm created for this goal.

2 AUV’s MAIN SPECIFICATIONS

Because of the restricted AUV project, all main specifications of AUV generated and redefined as a scaled-down version.

2.1 Main Characteristics

AUV’s main characteristics are as below.

Table 1 Main Characteristics of AUV

Parameter	Value	Unit
D-diameter	0,158	m
L-length	1,7	m
Propeller blade numbers	Fore: 7 Aft: 5	-
+ shape rudder and control surface configuration	4	piece

AUV’s different draft 3D model views are given below.

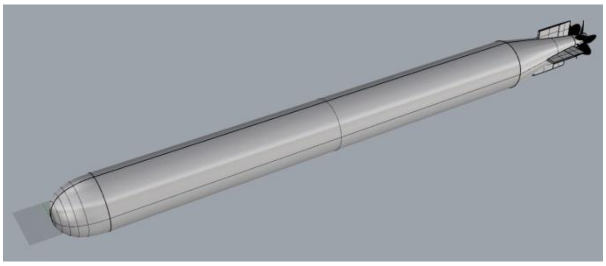

Figure 1 AUV’s Isometric Draft View from Bow

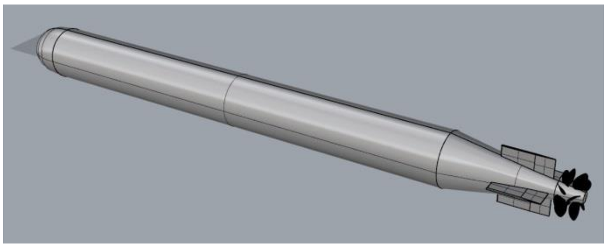

Figure 2 AUV’s Isometric Draft View from Rear

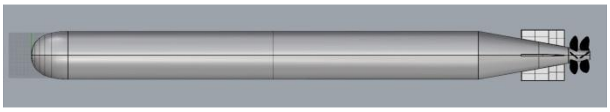

Figure 3 AUV’s Isometric Draft View in Profile

2.2 Theoretical Power and Torque Calculations

Electrical motor shaft break powers, delivered powers and delivered torques for each propeller of CRP set are calculated for stable on-design cruise condition at 20 kts.

These calculated parameters are as below.

Table 2 Main Propulsion Characteristics of AUV

Parameter	Value	Unit
V-advanced/service speed	20	knot
dA (aileron angles) dr (rudder angles) de (elevator angles)	0	degree
N-fore and aft propeller’s ***equal design revolutions*** @20kts service speed	**503**	Rpm
ηtr-transmission efficiency	%97,5	-
P_B-electrical motor shaft break power (total)	1770	W
P_D-delivered power to CRP’s (total)	1725,75	W
P_{D1}-delivered power to fore propeller	862,88	W
P_{D2}-delivered power to aft propeller	862,88	W
Q_{D1}-delivered torque to fore propeller	**16,38**	Nm
Q_{D2}-delivered torque to aft propeller	**16,38**	Nm

2.3 Pitch (α), Roll (ϕ) Aileron (dA), Rudder (dr) and Elevator Angles (de) of Rudder Control System of AUV

Given results under heading 2.2 are calculated in zero α, ϕ, dA, dr and de at 20kts service speed of AUV. These are theoretical calculations.

2.4 Electrical Motor Properties of AUV

Used electrical motor properties presented generally below.

- Direct drive type, no gear box
- Tandem type (2 pieces packaged in 1 case -fore and aft electrical motors with in same performance)
- Hollow type rotors and hollow type shafts
- Have phase current sensors for current measurements
- Have encoders for shaft RPM measurements
- Attachable with inner and outer hollow shafts directly
- Torque coefficients (K_T) are same for these 2 electrical motors and K_T is approximately 1,5.

3 SEA TRIAL TEST RESULTS AND EVALUATION

After theoretical calculations mentioned under heading 2.2 and 2.3, AUV’s sea trial tests were performed and following results were measured and obtained by analyses. These values presented below.

Table 3 Fore Electrical Motor Measured Instant Phase Currents in Different dA Angles

FORE ELECTRICAL MOTOR instant phase current-A				
ϕ-AUV	**dA/rpm⇨**	**505**	**526**	**548**
0	⇩ **-3,87**	13,37	14,60	15,94
0	**0**	14,30	**15,60 (@20kts)**	16,90
0	**3,23**	15,36	16,59	17,93

Table 4 Aft Electrical Motor Measured Instant Phase Currents in Different dA Angles

AFT ELECTRICAL MOTOR instant phase current-A				
ϕ-AUV	dA/rpm ⇨ ⇩	460	480	500
0	-3,87	15,16	16,41	17,72
0	0	14,30	**15,60 (@20kts)**	16,90
0	3,23	13,17	14,42	15,72

AUV's service speed (20 kts) is measured by a stationary hydrophone system. ϕ is measured by internal Inertia Measurement System (IMU). dA aileron angles are measured by rudder control system. Inner and outer shaft revolutions (rpm) are measured by fore electrical motor encoder device. Fore electrical motor and inner shaft which is together with aft propeller are coupled directly, aft electrical motor and outer shaft which is together with fore propeller are coupled directly. And fore and aft electrical motor instant phase currents are measured by current sensors.

Thus, fore and aft propellers' delivered nominal torque values are calculated with using Table 3 and Table 4. These are as noted below.

Table 5 Aft Propeller's Calculated Nominal Torque Values in Different dA Angles

AFT PROPELLER nominal torque-Nm				
ϕ-AUV	dA/rpm ⇨ ⇩	505	526	548
0	-3,87	14,29	15,60	17,03
0	0	15,30	**16,70 (@20 kts)**	18,10
0	3,23	16,42	17,73	19,16

Table 6 Fore Propeller's Calculated Nominal Torque Values in Different dA Angles

FORE PROPELLER nominal torque-Nm				
ϕ-AUV	dA/rpm ⇨ ⇩	460	480	500
0	-3,87	16,21	17,54	18,94
0	0	15,30	**16,70 (@20 kts)**	18,10
0	3,23	14,08	15,41	16,81

4 FINDINGS AND DETERMINATIONS AFTER SEA TRIAL TEST RESULTS

From this point of view, the detected differences, findings and determinations between theoretical calculations (Table 2) and practical sea trial results (Table 5, Table 6) are summarized below.

- Fore and aft propeller's design rotational speeds @20kts are 503 rpm (equal for each propeller) for ϕ=0 and dA=0 conditions (Table 2).
- After first sea trial tests, too residual torque was determined on the AUV hull @20kts, 503rpm equal revolution for each propeller. And rudder control system generated dA≠0 to provide the ϕ=0.
- dA≠0 condition induced inlet wake distribution of fore propeller and generated swirl-dominated flow pattern on the fore propeller inlet plane. Thus, fore and aft propeller's torque and thrust characteristics were changed @503rpm for each propeller.
- Hereafter, fore and aft propeller's design rotational speeds changed and generated a speed envelope to obtain residual torque=0, ϕ=0 and dA=0 conditions. These rotational speeds were tested in sea trial tests
- In second sea trial tests, fore and aft propeller's design rotational speeds @20kts are measured as 526 rpm and 480 rpm (for aft) for ϕ=0 and dA=0 conditions (Table 5, Table 6). In other words, 503 rpm (equal for each propeller) theoretical design point shifted to 480 rpm for fore and 526 rpm aft propeller. But nominal torque values are almost the same (theoretical result is 16,38 Nm and sea trial result is 16,70 Nm).
- This means that,
  - dA≠0 induces propeller performances.
  - To not induce propeller performances, dA should not be used for residual torque compensation in this case.
  - For residual torque compensation only shaft rotational speeds should be adjusted.
  - Under this residual torque compensation case, ϕ and dA will be zero.

5 MOTIVATION

To obtain ϕ=0, dA=0 and residual torque=0 conditions, fore and aft propeller shaft's rotational speeds should be managed by a Contra-Rotating Dynamic Motor Control Algorithm.

The algorithm's main logic could be explained with three steps:

1. Input fore propeller rpm
2. Run the algorithm
3. Get estimated aft propeller rpm when equal torque values occur at fore and aft propeller

For this reason, to overcome the residual torque and changed propeller performance problems @20kts design service speed and to gain the dynamic propulsion stability in the sea trial tests, a Contra-Rotating Dynamic Motor Control Algorithm is needed to be improved and used in the development phase of AUV project.

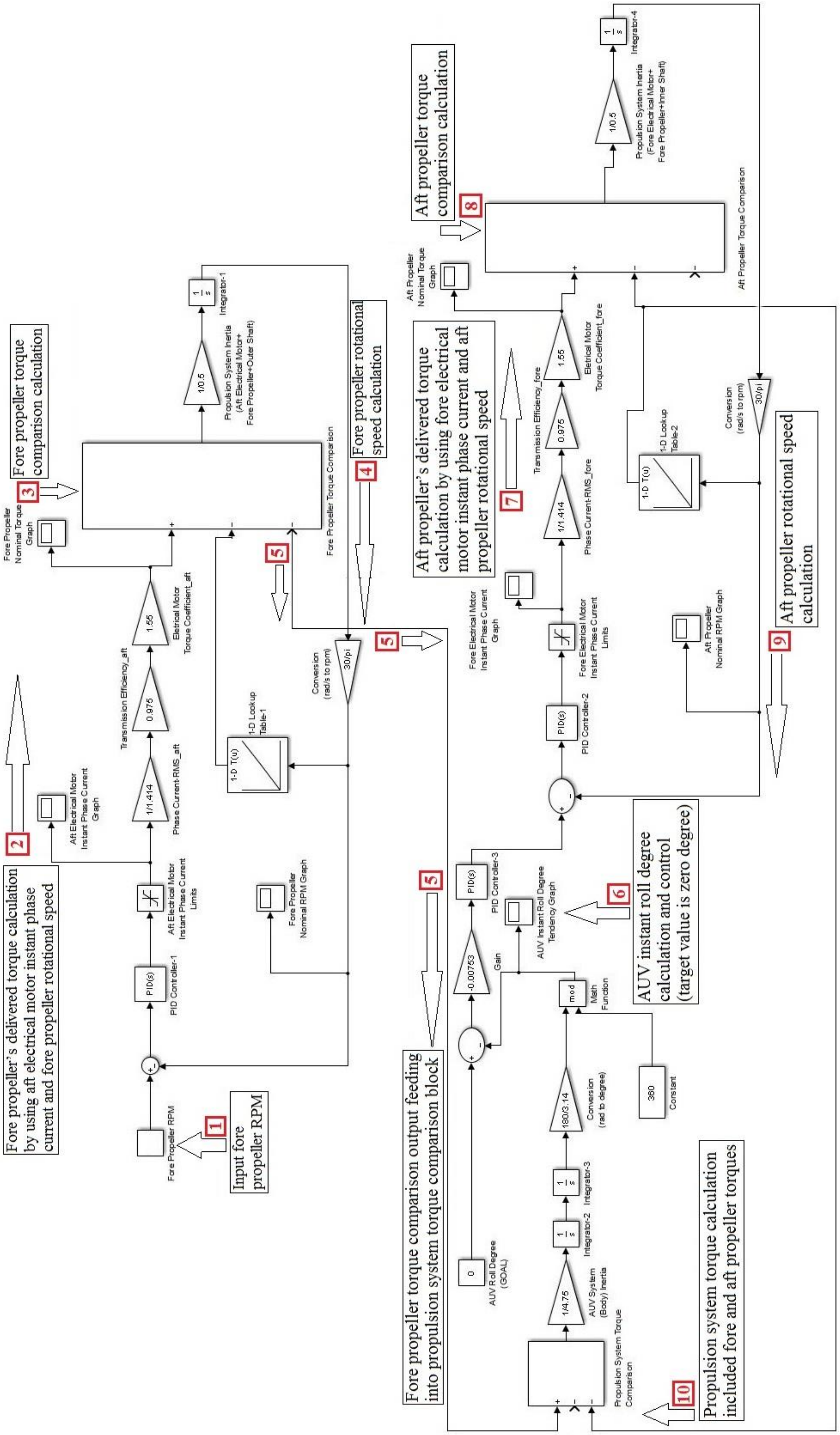

Figure 4 Contra-Rotating Dynamic Motor Control Algorithm's Logic Schema/Flow Chart in MATLAB Simulink

6 MATHEMATICAL FORMULATIONS AND DESCRIPTIONS USED IN ALGORITHM

Proportional-Integral-Derivative (PID) control is the most common algorithm used in industry and has been widely accepted for a wide range of applications. Due to its robust performance and its simplicity, it can be operated in a straightforward manner. The basic formulation suggests that it consists three coefficients; proportional, integral and derivative which are varied to get best desired response. Tuning the parameters in a close loop control results in robust output. The basic formulations can be illustrated as,

$$u = K_p \times e(t) + K_I \times \int e(t)dt + K_d \times \frac{d}{dt}e(t) \quad (1)$$

in which u is the output, K_P, K_I and Kd are tuned parameters and e represents error. The relation between set-point r and input y can be written as,

$$e = r - y \quad (2)$$

In this paper PID controller is implemented while some parameters are ignored in some close loops during the simulation process, so that robustness is able to be sustained for most of the time. The discrete form of this formulation is attained as a MATLAB Simulink block function using simulation time and the parameters are tuned in a way that minimum residual torque on AUV hull and CR Propellers can be easily managed. RPM controllers are used in the closed loops to obtain torque in each shaft by both PID error parameters and the loop outputs fed into the AUV sea trial test results as a look-up table. In the loop, torque can be attained using error and PID parameters as,

$$Q_{computed} = \left[K_p \; x \; e(t) + K_I \; x \int e(t)dt + K_d \; x \; \frac{d}{dt}e(t)\right]_{rms} \times \mu_{trans} \times K_T \quad (3)$$

In this relation $\mu trans$ represents transmission efficiency and K_T is the motor torque coefficient obtained by factory test conditions. RPM can be easily related to the torque compensation, in which torque computed in the loop and found in look-up table stated as below,

$$Q_{measured} = f(AUV \; velocity, RPM) \quad (4)$$

$$RPM = \int (Q_{computed} - Q_{measured})/J_{PS} \quad (5)$$

In this equation J_{PS} is the propulsion system (motors, shafts, CRPs) total inertia while function of AUV velocity and RPM are fed into the look-up table to find motor's overall balanced torque.

$$\Phi_{hull} = \iint (Q_{measured1} - Q_{measured2}) / J_{hull} \quad (6)$$

In this equation J_{hull} is the AUV's hull total inertia while $Q_{measured1}$ and $Q_{measured2}$ are fed into the look-up table to find AUV's overall balanced torque.

7 CONTRA-ROTATING DYNAMIC MOTOR CONTROL ALGORITHM IDENTIFICATION

Algorithm's operating logic flow will be monitored as in presented sequence and simulation schema above in Figure 4 and algorithm's operating logic presented fragmentally as items below.

1. Input fore propeller RPM
2. Fore propeller's delivered torque calculation by using aft electrical motor instant phase current and fore propeller rotational speed
3. Fore propeller torque comparison calculation
4. Fore propeller rotational speed calculation
5. Fore propeller torque comparison output feeding into propulsion system torque comparison block
6. AUV instant roll degree calculation and control (target value is zero degree)
7. Aft propeller's delivered torque calculation by using fore electrical motor instant phase current and aft propeller rotational speed
8. Aft propeller torque comparison calculation
9. Aft propeller rotational speed calculation
10. Propulsion system torque calculation included fore and aft propeller torques

These steps run until the close loops attain the converged torque values.

8 CONTRA-ROTATING DYNAMIC MOTOR CONTROL ALGORITHM RESULTS AND OUTPUTS

At first, Contra-Rotating Dynamic Motor Control Algorithm is run for near equilibrium field of theoretical CRP's rotational design speeds around 503 rpm.

Then, fore propeller's rotational speeds are determined/estimated by designer to input to the algorithm. These variable rotational speeds presented below.

Table 7 Fore Propeller's Determined/Estimated Rotational Speeds

FORE PROPELLER RPM		
1st step	2nd step	3rd step
460 rpm	480 rpm	500 rpm

2nd speed step shown in Table 7 is the closest equilibrium speed value to 503 rpm point. Then, 1st and 3rd speed values shown in Table 7 are scanned in algorithm. Thus, aft propeller's variable rotational speeds shown in Table 8 and equal torque values for each propeller shown in Table 9 are calculated for all these speeds by Dynamic Motor Control Algorithm.

Table 8 Aft Propeller's Obtained Rotational Speeds at dA=0

AFT PROPELLER RPM		
1st step	2nd step	3rd step
505 rpm	526 rpm	548 rpm

Table 9 Fore and Aft Propeller's Obtained Torque Values at dA=0

FORE PROPELLER nominal torque-Nm				
ϕ-AUV	**dA/rpm ⇨**	**460**	**480**	**500**
0	⇩ **0**	15,30	**16,70 (@20 kts)**	18,10
AFT PROPELLER nominal torque-Nm				
ϕ-AUV	**dA/rpm ⇨**	**505**	**526**	**548**
0	⇩ **0**	15,30	**16,70 (@20 kts)**	18,10

The equal torque values for different propeller speeds shown in Table 9 provide ϕ=0, dA=0 and residual torque=0 while AUV propels.

Simulation inputs and outputs for AUV propulsion presented below. Simulation is run for wide rpm range.

- Inputs: Fore propeller rotational speeds
- Outputs:
  - Aft propeller rotational speeds
  - Fore propeller torques
  - Aft propeller torques
  - Fore electrical motor instant phase currents
  - Aft electrical motor instant phase currents
  - ϕ=0, dA=0
  - residual torque=0

Table 10 Simulation Inputs and Outputs for AUV Propulsion (ϕ=0, dA=0)

Which propeller in CRP set?	**Propeller (rpm)**	**Delivered torque to propellers (Nm)**	**Electrical motor instant phase current (A)**
Fore	250	1,26	1,18
Aft	278	1,26	1,18
Fore	300	4,61	4,31
Aft	332	4,61	4,31
Fore	350	7,96	7,45
Aft	386	7,96	7,45
Fore	400	11,3	10,6
Aft	440	11,3	10,6
Fore	460	15,3	14,3
Aft	505	15,3	14,3
Fore	**480**	**16,7**	**15,6**
Aft	**526**	**16,7**	**15,6**
Fore	500	18,1	16,9
Aft	548	18,1	16,9
Fore	550	21,6	20,2
Aft	602	21,6	20,2
Fore	600	25,1	23,5
Aft	656	25,1	23,5
Fore	650	28,7	26,8
Aft	710	28,7	26,8
Fore	700	32,2	30,1
Aft	765	32,2	30,1
Fore	750	35,7	33,4
Aft	819	35,7	33,4
Fore	800	39,2	36,7
Aft	873	39,2	36,7
Fore	850	42,8	40
Aft	927	42,8	40
Fore	900	46,3	43,3
Aft	982	46,3	43,3
Fore	950	49,8	46,6
Aft	1040	49,8	46,6
Fore	1000	53,3	49,9
Aft	1090	53,3	49,9

Delivered torque and motor phase current vs rotational speed of fore and aft propeller correlation graphs presented below.

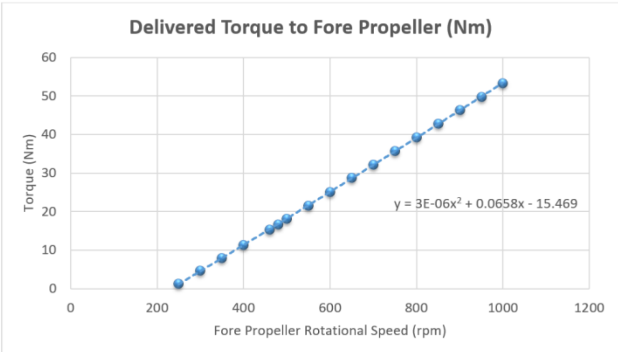

Figure 5 Delivered Torque to Fore Propeller vs Fore Propeller Rotational Speed

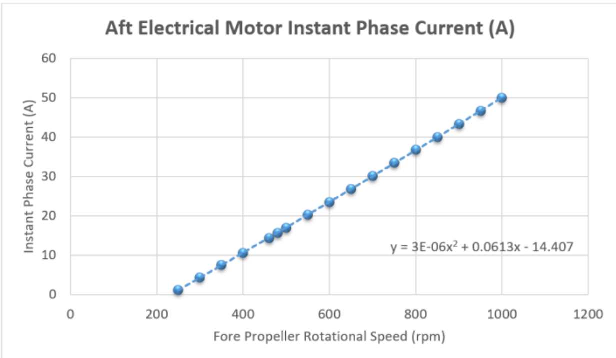

Figure 6 Aft Electrical Motor Instant Phase Current vs Fore Propeller Rotational Speed

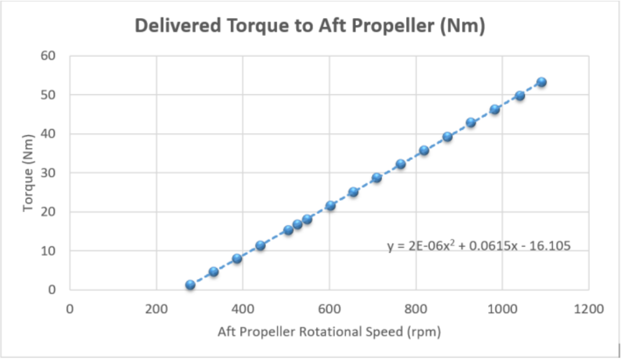

Figure 7 Delivered Torque to Aft Propeller vs Aft Propeller Rotational Speed

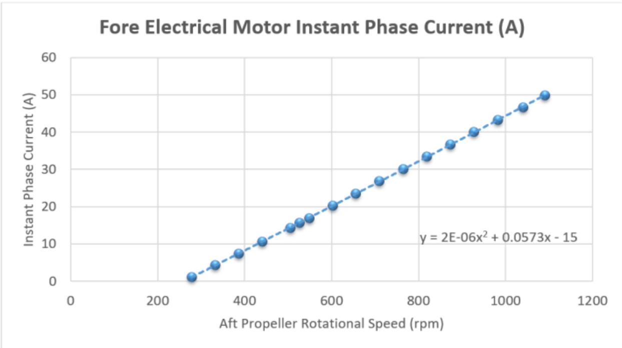

Figure 8 Fore Electrical Motor Instant Phase Current vs Aft Propeller Rotational Speed

9 CONCLUSION

In this paper, aileron induced unbalanced torque compensation using contra-rotating dynamic motor control for an AUV CRP subject was presented. The technical reasons of mentioned control algorithm in this paper were tried to be explained and the approach was tried to be presented.

The control algorithm's estimation performance will be improved and its skills will be developed later on.

In the future, improved version of the control algorithm will be aimed to be used in AUVs for aileron induced unbalanced torque compensation directly.

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