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TITLE

A Fully Interactive Dynamic Simulation of a Semi-Submersible Towing a Large Towfish

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A FULLY INTERACTIVE DYNAMIC SIMULATION OF A SEMI-SUBMERSIBLE TOWING A LARGE TOWFISH

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ABSTRACT

ISER and DREA are collaborating on the development of SIMRMS, a fully interactive nonlinear submersible /cable /towfish six degree-of-freedom (DOF) time domain simulation. This capability is not found in standard tow system codes. SIMRMS is a meshing of the DREA Submersible Simulation Program (DSSP) and the DYNTOCABS tow cable/towfish simulator. DSSP is a nonlinear 6 DOF vehicle simulator that models control, propulsion, and ballasting. DYNTOCABS provides a three-dimensional, nonlinear, 3 DOF, finite segment simulation of the cable and includes a nonlinear 6 DOF model of an active towfish. The two programs have been merged so that the equations of motion for all system components are simultaneously integrated in time. New features and capabilities have also been developed.

SIMRMS is used as a test bed to minimize technical risk for further development of a remote minehunting system. This paper discusses, and presents full scale sea trials data validating the program's capabilities.

ACRONYMS

BG	Distance from center of buoyancy to center of gravity
CG	Center of gravity
DSSP	DREA Submarine Simulation Program
DYNTOCABS	Dynamics of Towed Cable Systems
RMS	Remote Minehunting System
RMV	Remote Minehunting Vehicle
SIMRMS	Simulating Remote Minehunting System
VDT	Variable Depth Towbody

1. INTRODUCTION

ISE Research Ltd. (ISER) and Defence Research Establishment Atlantic (DREA) are supporting development of a Remote Minehunting System (RMS) for the Canadian Navy. The RMS includes a Remote Minehunting Vehicle (RMV) towing a deployable, active, Variable Depth Towbody (VDT) housing a side scan sonar for route surveying and mine location (see, for example, Fig. 1). In route surveying, sonar images are obtained for an area where minehunting is anticipated, in order to provide a reference against which future minehunting images are compared. A high degree of VDT stability is required to get good images, and its absolute location is needed for differencing images with those from subsequent minehunting surveys. RMV motions, whether from waves or necessary maneuvers, cause VDT (sonar) disturbances. These disturbances degrade the sonar image and make mine detection difficult.

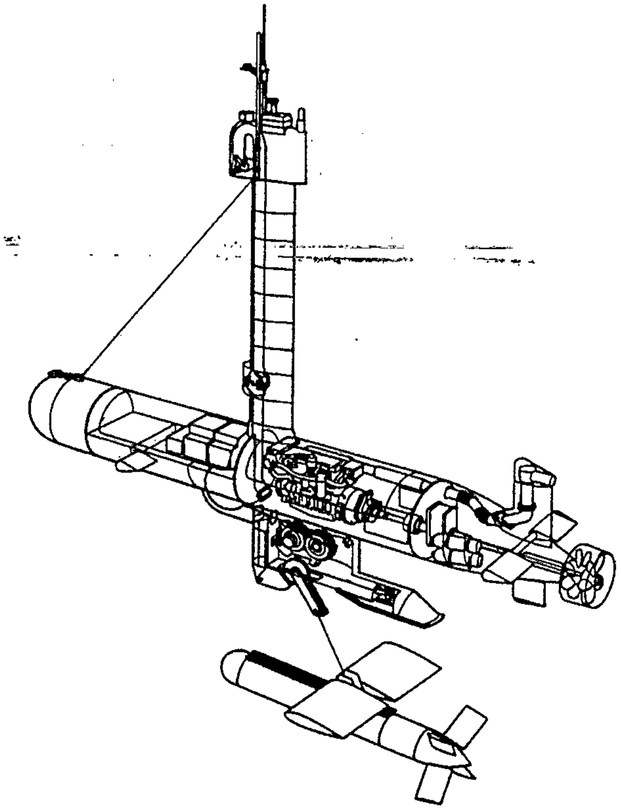


Fig. 1 DOLPHIN Mk 2 and Aurora VDT

Using a semi-submersible RMV has personnel safety and cost advantages over a minehunting surface ship. A semi-submersible retains the larger surface ship's stability in waves, its air breathing endurance, high data rate real time communications link, and accurate global positioning. However, a semi-submersible is still subject to surge motions in high sea states which cause cyclic tow cable tensions and, potentially, towfish positioning variations. Also, the lower inertia of the smaller semi-submersible results in increased interactions with the VDT.

The semi-submersible DOLPHIN vehicles, developed by ISER, are stable, proven, remote platforms capable of operations in up to sea state 5 [1]. They have been used for hydrographic surveys and have towed large towfish at 10 knot speeds down to depths of 120 m. DOLPHIN Mk 2 is 8.5 m long with a 1 m hull diameter, has a dry mass of 4500 kg, and is propelled by a 350 HP engine driving contra-rotating propellers. The Aurora VDT, also developed by ISER, is 3.2 m long with a 0.5 m diameter hull and incorporates an active depressor with a 2.4 m long span and four, symmetrical, independently actuated tail fins. Aurora has a dry weight of 400 kg.

Preliminary simulation work [2], confirmed by subsequent sea trials, has shown that interactions between the DOLPHIN Mk 2 RMV and its VDT are significant. Tow cable tension, for example, with the VDT at 130 m depth and 300 m scope can be a sizeable fraction of the available RMV thrust and buoyancy. It is necessary to assess the impact of RMV motions on the tow system and tow system effects on RMV maneuverability in order to understand, predict, and operate with these interactions.

This motivated the development of SIMRMS (SIMulating Remote Minehunting System), a fully interactive RMV/cable/VDT simulation program. Standard tow cable analysis codes like BCABLE [3] and DYNTOCABS [4,5,6] are intended to model cable systems towed by large ships. They model the tow system only, requiring the tow vehicle tow point kinematics as a boundary condition. This approach is satisfactory only if the tow vehicle is large enough that it does not interact with the tow.

Some work had been done previously on tow vehicle/towfish interactions, but at low speeds [7]. ISER and DREA chose to tackle the problem by integrating two programs which were both proven and familiar: the DREA Submarine Simulation Program (DSSP) and the Coastal Systems Station (Panama City) DYNamics of TOwed CABle Systems (DYNTOCABS) program. DSSP is a nonlinear 6 DOF vehicle simulator that also models control, propulsion, and ballasting. DYNTOCABS provides a three-dimensional, nonlinear, 3 DOF, finite segment simulation of the cable, and includes a nonlinear 6 DOF model of a towfish with active control.
Initially, the merging of DSSP and DYNTOCABS was iterative [2]. That is, the programs were repeatedly run alternately, with results from one becoming the boundary conditions for the other, and vice versa. These results showed both that interactions were substantial and that the programs could predict them well.

DSSP and DYNTOCABS were then fully merged, eliminating any iteration in the simulation. The fully interactive SIMRMS program simultaneously integrates in time the equations of motion for all system components (the RMV, the VDT, and the cable segments).

RMV, cable, and VDT hydrodynamic characteristics are determined in SIMRMS through input files. For the current work, these characteristics describe the DOLPHIN Mk 2 RMV and the Aurora VDT, as shown in Fig. 1.

SIMRMS has become a valuable test bed for further development of the RMS. It provides RMV and VDT performance predictions for untried maneuvers and an environment for tuning RMV/VDT control systems. Presently, SIMRMS does not model sea state effects, altitude following, or cable winching. Work is underway to include these features.

This paper describes the current features of SIMRMS, validates its predictions against full scale sea trials data, and discusses on-going development.

II. SIMRMS RMV, VDT AND CABLE MODELS

The RMV and VDT dynamics are each modelled with six, second order, nonlinear ordinary differential equations of motion, one for each degree-of-freedom, in body fixed coordinate systems. Control surface deflection, propulsion, tow cable, variable ballast, and steady and unsteady hydrodynamic effects are all modelled in the applied force terms on the right hand sides of these equations. The hydrodynamic forces are described using derivatives based on in-house DREA empirical and theoretical methods [8, 9,10].

The tow cable is modelled as a series of rigid links connected by frictionless spherical joints. Cable hydrodynamics is modelled using normal and tangential drag, side force, and added mass loading functions. Mass and hydrodynamic loads are uniformly distributed over each link, halved, and then lumped at the connecting joints. The cable links do not stretch and do not support moments; they are two-force members supporting only longitudinal loads. Hence, cable dynamics are described by a set of three, second order, nonlinear, ordinary differential equations of translational motion for each joint.

Proportional, integral, differential, and feed forward controllers for the RMV and VDT roll, pitch, yaw, and depth are implemented to emulate RMV algorithms that determine control surface deflection set points. These set points are based on fedback vehicle attitudes and vehicle set points. The control surface time responses are modelled by linear, second order, ordinary differential equations. Control surface response damping, frequency, and maximum rate inputs, together with initial conditions, determine a unique response [11].

The distribution of RMV control authority is quite flexible. Input file information determines whether a pair of planes deflects differentially or as a locked set. Roll, pitch, and depth authority can similarly be switched between the bow and stern planes. Plane control law algorithms can also be changed via input files.

The RMV navigates by three possible modes, emulating DOLPHIN Mk 2 capabilities. In 'rudder' mode, rudder deflection commands are given to the RMV via an input file. SIMRMS integrates the equations of motion from one command implementation to the next. This is similar to flying the RMV from a console. In 'heading' mode, the RMV is given a heading angle set point to maintain. In 'waypoint' mode, the RMV follows a series of lines through inertial-reference-frame waypoint specifications that define its flight path.

The waypoints can be chosen from a list of existing maneuvers or they can be generated by 'preview' mode. Here, waypoints defining a standard minehunting maneuver (Fig. 2) are automatically generated as a function of user specified lane spacing, minimum turn diameter, swath length, nominal RMV speed, waypoint spacing, and number of sweeps.

The RMV propulsion model simulates the power delivered to the contra-rotating propellers as a function ,of RMV speed, cross flow angle, tow load, and the engine set point and achieved (feedback) rpms. Thrust and power levels are obtained from propeller open water thrust and torque characteristics, wake fraction, thrust deduction, and shaft and transmission loss parameters. Cross-flow effects on propulsion are estimated from wind tunnel experiments with a powered submarine model [12]. The maximum engine power is modelled as a function of rpm using the manufacturers performance specifications.

The RMV has variable ballast tanks at its bow and stern. These tanks vent or flood at a given rate for a controlled duration, all of which can be modelled in SIMRMS and controlled via an input file.

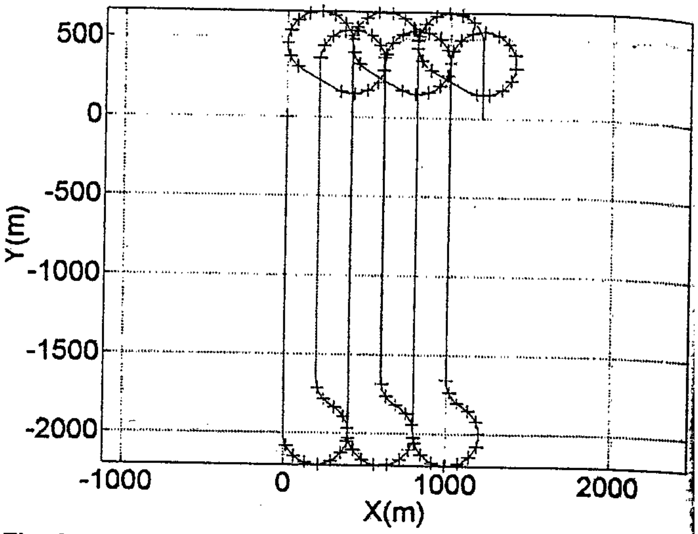


Fig. 2: A minehunting maneuver defined by waypoints (+) generated in preview mode.

III. VALIDATION

The SIMRMS validation began by ensuring that the program reproduced the already validated behaviors of DSSP and DYNTOCABS at the limiting extremes where cable scope is zero (the VDT is docked: the DSSP limit) and the RMV is infinitely large and powerful (the DYNTOCABS limit). This was done satisfactorily.

The validation of primary interest compares the SIMRMS predictions of RMV/tow interactions with sea trials data, and this is presented here. The data is from 1998 trials of the DOLPHIN Mk 2 towing the Aurora VDT through figure 8 turns in which turn diameter, cable scope, and VDT depth varied. Tables 1a through 1c summarize results from 12 of the runs in which the turns were tightest and the interactions strongest. Fig. 3 plots several quantities of interest as a function of time for case 8.

Table 1 compares trials data and SIMRMS predictions of both level flight and critical turn values. Engine speed, cable tension at the RMV towpoint, RMV depth, pitch and roll, and VDT speed through the water are examined. The absolute trials measurements are listed and the SIMRMS prediction is presented as either a ratio or an absolute measurement. Table 1 style comparisons were made for all quantities shown in Fig. 3 for all cases. This analysis for the case in Fig. 3 is shown in Table 2.

Table 1a: Comparison of SIMRMS predictions and trials data RMV engine speed and cable tension (RMV ~ 10 knots)

case	inputs				achieved RMV engine speed (set point as shown in inputs)				RMV cable tension			
	depth (m)	scope (m)	turn dia (m)	rpm set point	level flight		turn max		level flight		turn min	
					trials (rpm)	SIMRMS/ trials	trials (rpm)	SIMRMS/ trials	trials (lb)	SIMRMS/ trials	trials (lb)	SIMRMS/ trials
1	20	50	250	1895	1890	1.003	1934	0.980	597	0.873	547	0.945
2	40	100	250	1837	1855	0.990	1858	0.989	787	1.107	709	1.081
3	60	120	250	2102	2119	0.992	2148	0.979	1758	0.948	1313	1.017
4	80	160	250	2215	2200	1.007	2222	1.007	2145	1.038	1383	1.159
5	80	240	250	2290	2314	0.990	2352	0.974	2019	1.022	960	1.049
6	100	200	250	2335	2342	1.006	2457	0.950	2848	0.99	2101	1.302
7	100	200	300	2437	2428	1.004	2484	0.981	3069	1.001	1932	1.055
8	100	250	250	2437	2427	1.004	2495	0.977	2785	1.008	1137	1.131
9	100	250	300	2437	2417	1.008	2458	0.991	2726	1.030	1722	0.906
10	120	260	250	2637	2487	1.015	2606	1.009	3289	1.068	2060	0.814
11	120	300	300	2582	2487	1.018	2612	0.987	3210	1.040	2008	0.789
12	120	300	400	2475	2484	0.996	2504	0.996	3149	1.010	1701	1.120

Table 1b: Comparison of SIMRMS predictions and trials data RMV depth and pitch (RMV ~ 10 knots)

case	inputs				RMV depth (set point = 3.0 m)				RMV pitch (+ve nose-up) (set point = 0.0 deg)			
	depth (m)	scope (m)	turn dia (m)	rpm set point	level flight		turn min		level flight		turn max	
					trials (m)	SIMRMS/ trials	trials (m)	SIMRMS/ trials	trials (deg)	SIMRMS (deg)	trials (deg)	SIMRMS (deg)
1	20	50	250	1895	3.100	0.957	3.096	0.958	-0.62	1.43	-0.70	1.47
2	40	100	250	1837	3.100	0.976	3.086	0.971	-0.56	-0.26	-0.60	0.69
3	60	120	250	2102	3.300	0.948	3.292	0.929	-1.29	-4.10	-1.09	-1.79
4	80	160	250	2215	3.400	0.934	2.925	1.043	-1.23	-5.96	1.10	-1.72
5	80	240	250	2290	3.357	0.911	3.184	0.927	-1.52	-1.92	-0.68	1.70
6	100	200	250	2335	3.300	0.976	3.108	0.973	-1.43	-7.60	-0.82	-0.75
7	100	200	300	2437	3.506	0.917	3.284	0.928	-0.68	-7.60	-0.49	-1.73
8	100	250	250	2437	3.490	0.899	3.178	0.925	-1.25	-4.89	0.26	1.12
9	100	250	300	2437	3.498	0.897	3.202	0.925	-1.26	-4.89	0.53	1.12
10	120	260	250	2637	3.590	0.897	3.413	0.902	-3.06	-7.98	-2.36	-2.85
11	120	300	300	2582	3.602	0.880	3.278	0.903	-1.49	-6.25	0.96	1.07
12	120	300	400	2475	3.645	0.872	3.388	0.872	-1.50	-6.40	0.08	1.33

Table 1c: Comparison of SIMRMS predictions and trials data VDT *speed and RMV roll* (RMV ~ 10 knots)

case	inputs				RMV roll (+ve out of turn) (set point = 0.0 deg)				VDT speed through water			
					level flight		turn extrema		level flight		turn min	
	depth (m)	scope (m)	turn dia (m)	rpm set point	trials (deg)	SIMRMS (deg)	trials (deg)	SIMRMS (deg)	trials (m/s)	SIMRMS/ trials	trials (m/s)	SIMRMS/ trials
1	20	50	250	1895	-0.45	0.00	2.04	-0.15	5.21	1.035	5.04	1.052
2	40	100	250	1837	1.62	-0.10	2.83	0.62	4.69	1.021	4.24	1.038
3	60	120	250	2102	1.46	0.00	1.87	1.59	5.08	0.988	4.45	0.982
4	80	160	250	2215	0.74	0.01	14.44	2.23	5.09	0.974	3.37	1.187
5	80	240	250	2290	0.71	-0.02	4.30	1.25	5.67	0.935	3.26	1.012
6	100	200	250	2335	-0.03	-0.03	10.61	2.64	4.81	1.035	4.11	0.844
7	100	200	300	2437	-0.82	0.08	6.17	3.46	5.00	1.040	3.42	1.149
8	100	250	250	2437	-0.26	-0.04	18.87	2.11	5.35	0.989	2.82	1.128
9	100	250	300	2437	-0.74	-0.04	22.00	2.26	5.18	1.021	3.62	0.967
10	120	260	250	2637	-0.74	-0.06	20.87	3.75	4.79	1.081	3.28	0.976
11	120	300	300	2582	-0.41	-0.15	26.80	2.78	4.89	1.080	3.55	0.885
12	120	300	400	2475	0.11	-0.15	24.60	3.63	4.99	1.038	3.21	1.112

Table 2: SIMRMS and trials data comparison for case 8 (Figure 3 - 250 m scope, 100 m depth, 250 m turn diameter)

	quantity	*level flight*	*turn*
SIMRMS / trials	RMV tension	1.008	1.131
	VDT depth	1.000	1.003
	RMV speed	1.025	0.987
	VDT speed	0.986	1.128
	engine rpm	1.004	0.977
	RMV depth	0.899	0.925
diff (deg)	VDT roll	0.67	-3.33
	VDT pitch	0.32	0.51
	RMV roll	-0.22	-16.75
	RMV pitch	3.64	-0.86

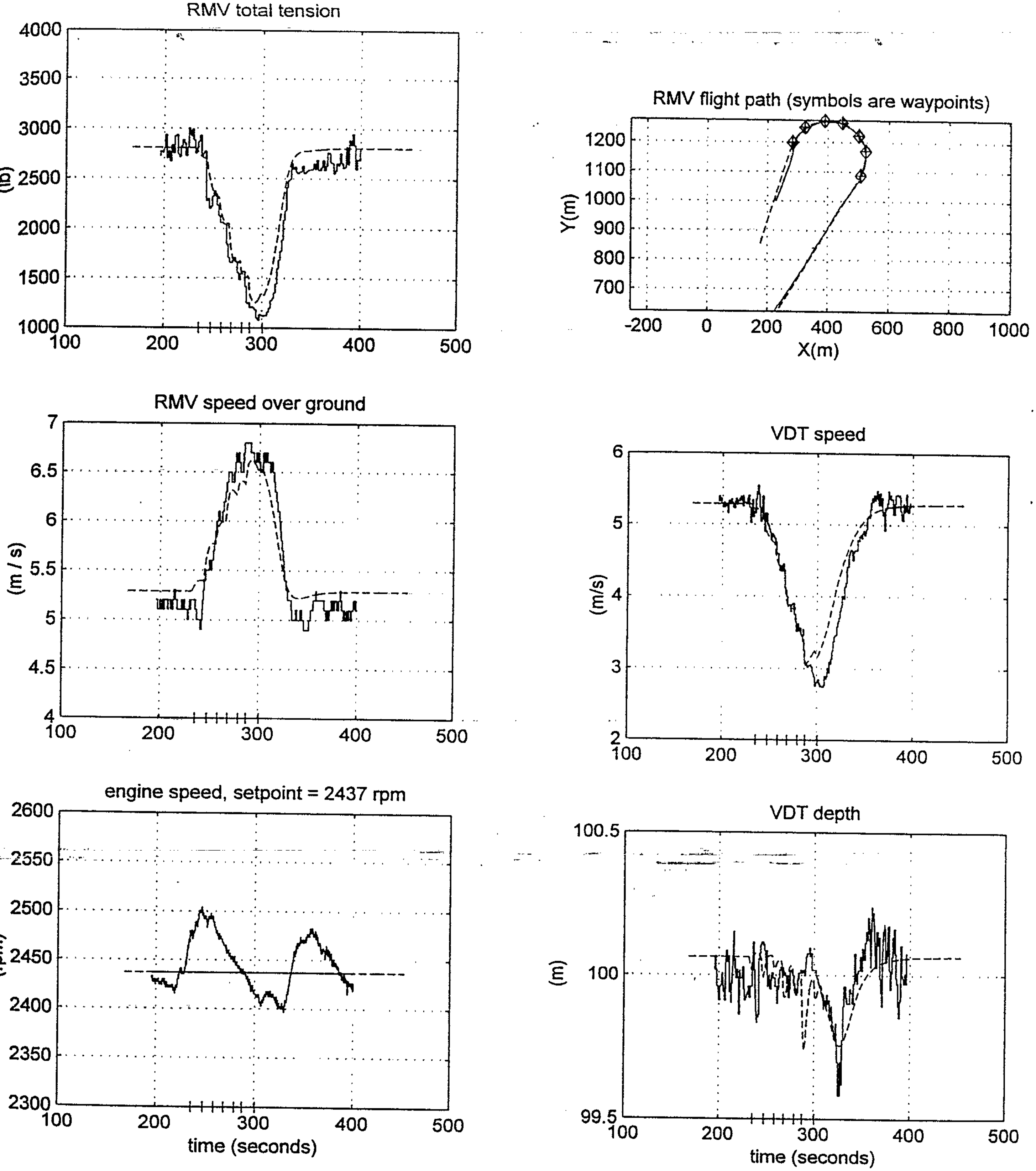


Fig. 3a: SIMRMS predictions (dashed line) superimposed on trials data (solid line) for cable scope = 251 , VDT depth = 100 m, and RMV turn diameter = 250m (figure 1 / 3). RMV waypoint crossings are '+' on time axes. Waypoints are shown in 'RMV flight path'.

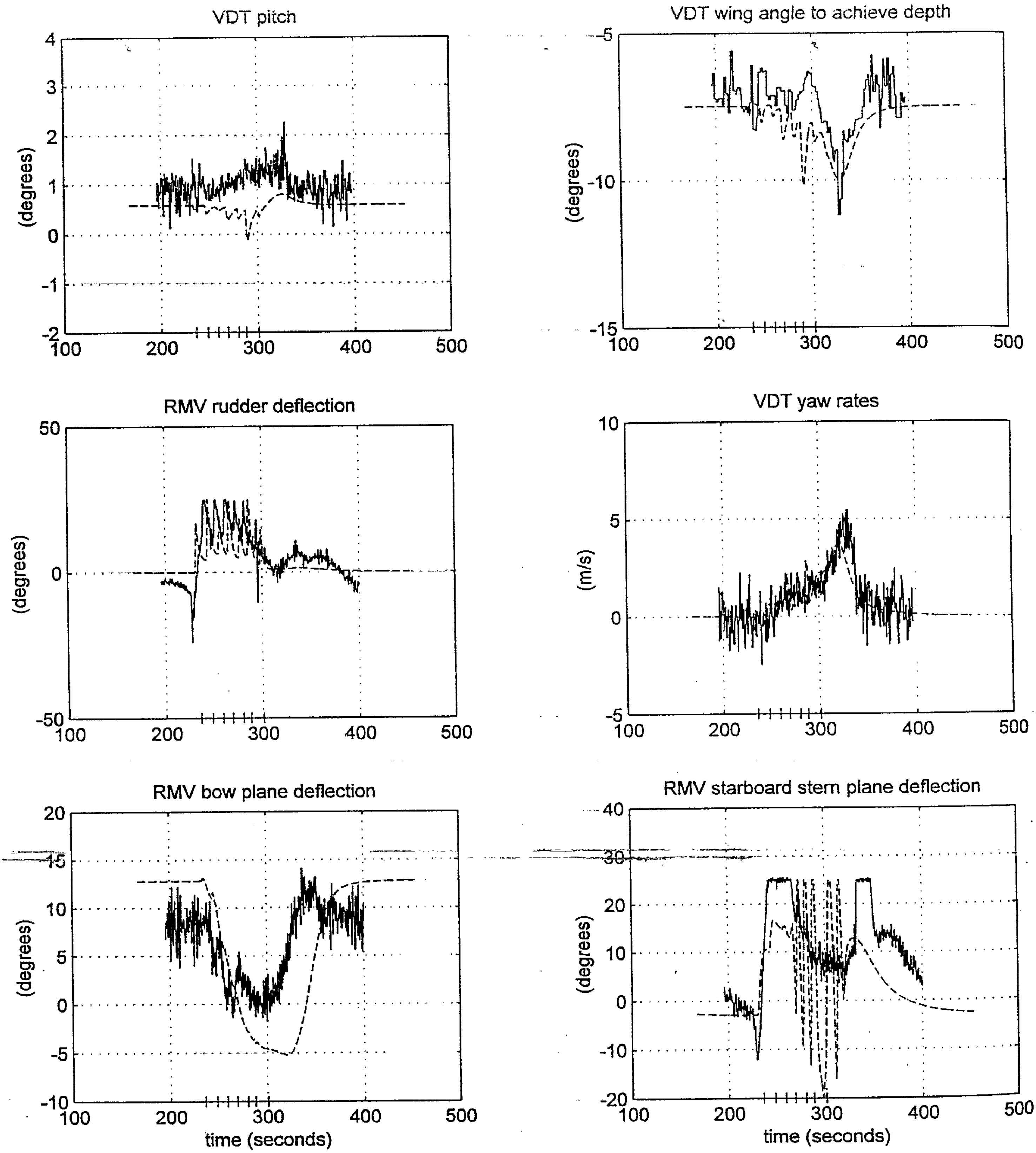
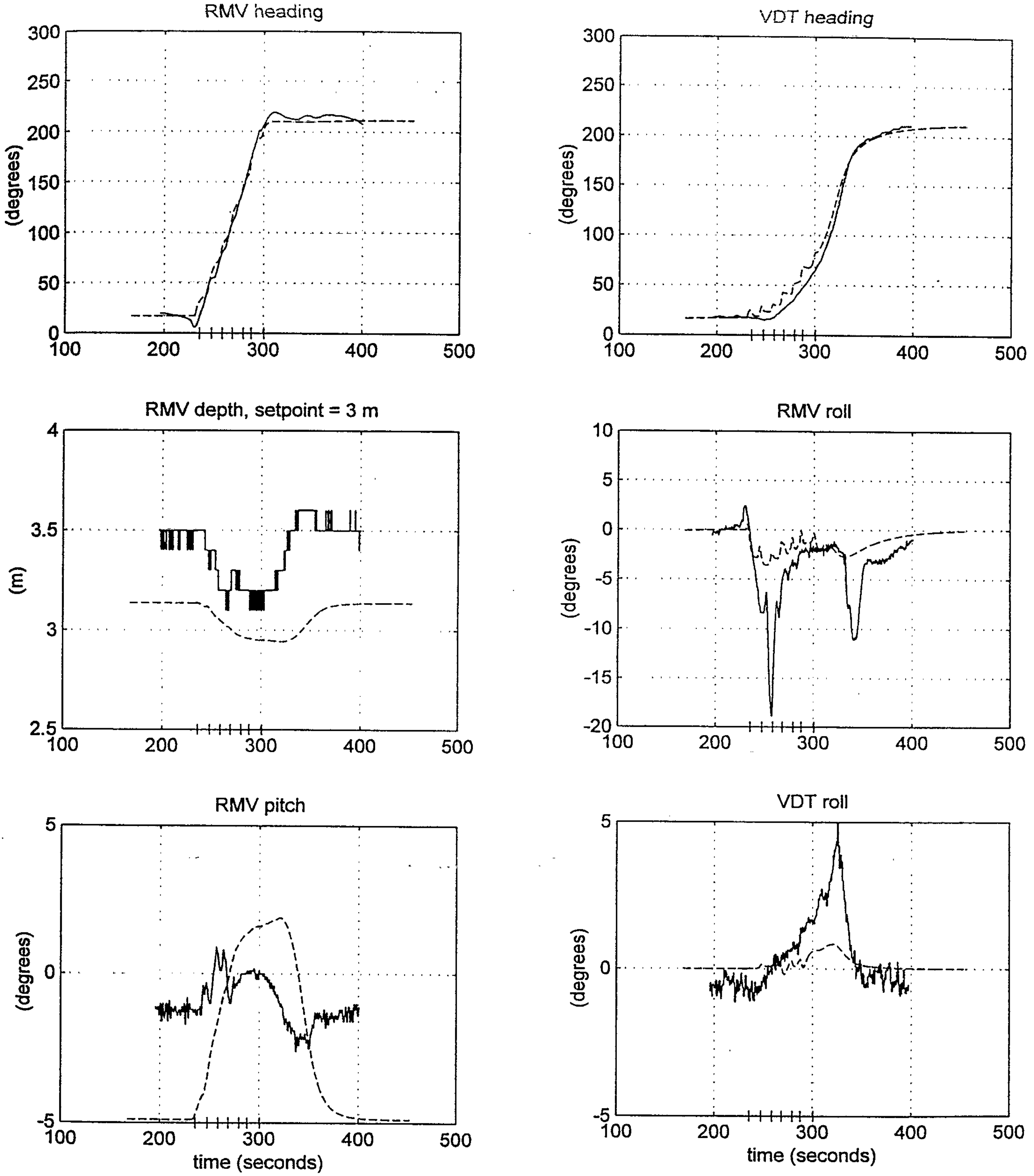


Fig. 3b: SIMRMS predictions (dashed line) superimposed on trials data (solid line) for cable scope = 251 , VDT depth = 100 m, and RMV turn diameter = 250m (figure 2/ 3). RMV waypoint crossings are '+' on time axes. Waypoints are shown in 'RMV flight path'.


RMV heading

VDT heading

RMV depth, setpoint = 3 m

RMV roll

RMV pitch

VDT roll

Fig. 3c: SIMRMS predictions (dashed line) superimposed on trials data (solid line) for cable scope = 251 , VDT depth = 100 m, and RMV turn diameter = 250m (figure 3/3). RMV waypoint crossings are '+' on time axes. Waypoints are shown in 'RMV flight path'.

A. RMV Propulsion, Speed, and Cable Tension DOLPHIN speed control is effected through closed loop control on engine rpm. The rpm set point cannot be met if doing so requires more power than the engine can generate at that rpm (the engine is then 'power limited'). SIMRMS models these phenomena. Cases 10, 11, and 12 in Table 1 represent the deepest tows and, hence, the greatest power requirements. In cases 10 and 11 the RMV is power limited. Case 12 has the same level flight tow condition as case 11 but is not power limited since the rpm set point is achievable.

SIMRMS models the trends in the engine rpm well, with the worst discrepancy being less than 3%. SIMRMS correctly predicts that case 10 and 11 are power limited and that case 12 is not. For these power limited cases, it is interesting that SIMRMS achieved rpms are higher than those measured in trials. SIMRMS consistently over predicts available power by 2%.

An important measure of the validity of the propulsion model, as well as of the hydrodynamic models, is the accuracy of the SIMRMS RMV speed prediction. This prediction is compared with trials data (an average of 11 runs) in Table 3 for a 300 m scope tow with the VDT at a depth of 120 m, the most demanding set of conditions trialed. The SIMRMS prediction is within the speed variation of the measured data.

Table 3: Propulsion performance from SIMRMS predictions and trials data (300 m scope, 120 m VDT depth, rpm set point = 2582)

	SIMRMS	trials range (11 runs)	% diff from trials avg
achieved level flight engine rpm	2534	2461-2500	2.2
RMV tow tension (lb)	3327	3188-3350	1.8
RMV speed (m / s)	5.26	4.73-5.32	4.7

The tension logged in trials is the total RMV tow point tension, of which nominally 90% is in the axial direction directly affecting propulsion performance and speed. Tension predictions in level flight are generally good, usually being less than 5% but occasionally 10 to 15% in error. Minimum tension predictions in a turn can be in error by as much as 30%, particularly when the turn diameter/scope and scope/depth ratios are small. This latter, transient, quantity is probably less important than the ability of the code to predict the overall shape of the tension variation with time, as shown in Fig. 3a.

B. RMV Depth, Pitch, and Roll Discrepancies Unfortunately, RMV buoyancy was not precisely measured during the sea trials. The variable ballast, and other ballast, was manually adjusted for each run, and sometimes during the run, to achieve desired pitch and depth settings; these adjustments were not logged. In addition, the amount of onboard fuel (specific gravity 0.8) in the collapsible fuel bags was not logged; the vehicle BG can vary by 12% between the fully fueled and empty conditions. These unknowns affect RMV trim and vertical plane dynamics.

SIMRMS predictions assume the ballast tanks and fuel bags are always half full. This results in systematic differences between RMV depth and pitch predictions and measurements, as seen in Table 1.

The greatest discrepancies in the validation are for RMV roll angles in turns with deep tows. Roll angles of over 20 degrees are observed but SIMRMS does not predict anything higher than 4 degrees (Table 1c). The cases in Table 1 were rerun in SIMRMS with a smaller BG (assuming full fuel bags) but only a further 4 degrees of roll was obtained. A possible reason for the low roll angle predictions is a large trials BG reduction from systematic operator reduction of ballast in response to increasing tow depth (down force). A complicating factor is a predicted side force on the mast self-aligning fairings generated by curvature in the onset streamlines during turns [9], something not accounted for in the current RMV roll derivatives.

Although SIMRMS under predicts the critical RMV roll angles, it does predict well the time at which roll occurs and the roll 'cusps' from sudden turns as the RMV passes through a waypoint.

C. RMV Horizontal Plane Validation The SIMRMS RMV flight path is predicted using the same input waypoint file as used in the trials. A portion of the Figure 3 case 8 'RMV Flight Path' plot is reproduced below in Fig. 4.

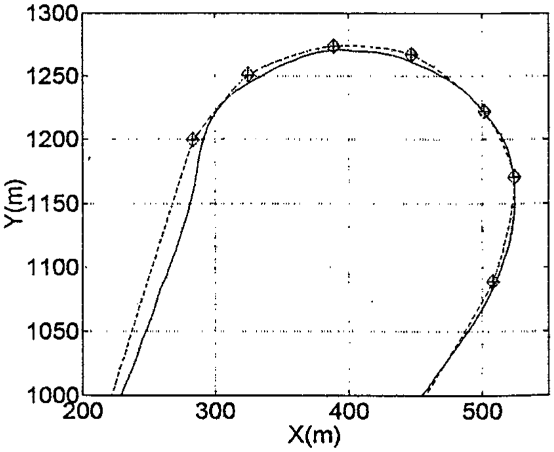


Fig. 4: RMV flight path for a tow of 250 m scope, 100 m VDT depth, and 250 m turn diameter (symbols indicate waypoints)

Generally, SIMRMS predictions of horizontal plane characteristics (yaw rates, heading, and flight path data) agree satisfactorily with sea trials data. The agreement deteriorates when the lateral RMV cable tension is maximum, when the RMV tends to turn outside the predicted trajectory. This happens when RMV heading changes occur and results in the largest errors in RMV heading predictions. The discrepancy grows with decreasing turn diameter/scope ratio to a maximum of 5 m in a 250 m diameter turn once in the turn.

D. VDT Comparisons

SIMRMS predictions and sea trials data for the VDT depth, pitch, roll, and speed are generally in good agreement. During level flight and in turns the depth agreement is within 2.3% for a range of 20 m to 120 m. Similarly, pitch is within 2 degrees and roll about 3 degrees. Discrepancies in the VDT speed are less than 10% in level flight while the transitory minimum speed prediction is within 20%, and usually much better.

IV. RMV/TOW INTERACTIONS

Evidence of strong interactions between the DOLPHIN Mk 2 RMV and Aurora VDT is apparent from:

- increased RMV speed in a turn as the tow load decreases,
- RMV depth and pitch variations (when variable ballast is inactive) due to tow load variations,
- RMV roll in response to increased lateral cable tension in a turn.

The first of these is well predicted by SIMRMS. The second interaction is predicted to be large by SIMRMS but validation could not take place because of unlogged ballast changes during the trials. The last interaction is not well modelled though the trials data show it to be large.

V. CONCLUDING REMARKS

SIMRMS simulates the 6 DOF dynamics of a fully coupled RMV/cable/VDT minehunting system, including [5]
dynamic interactions. Hydrodynamic loads and control algorithms can be customized through input files. SIMRMS has been validated against full scale sea trials data. With the exception of RMV roll and pitch, the agreement between SIMRMS and the trials data is acceptable. SIMRMS appears to capture RMV/tow interactions well, but requires better ballast and fuel data, and a better roll hydrodynamic model, to complete the validation.

VI. ON-GOING WORK

ISER and DREA are continuing to develop and improve SIMRMS. Work is divided into two types of activities, problems to solve and new features.

A new RMV hydrodynamic roll model will be implemented shortly. ISER is using SIMRMS to devise an active control strategy for managing RMV variable ballast to maintain optimal buoyancy and trim for various fuel and tow cable tension loads. When complete, new trials will be required to validate the SIMRMS pitch interaction.

New SIMRMS features currently under development include:

- a sea state simulation modelling the effects of sea state on the RMV and, hence, the VDT.
- a variable cable scope model, since it is desirable to incorporate active winching and deploying of the VDT into maneuvering strategies.
- VDT altitude keeping relative to three-dimensional sea floor profiles.

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