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Design Load Propulsion Simulation (DLPS)

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16. Abstract

The primary objective of this project was the incorporation of an enhanced propeller/ice interaction model in Modular Ship Modelling (MSM) to assess the effect of propeller ice loads on the overall propulsion system and control system design of Arctic Class and Type ships. The enhanced propeller/ice interaction model was derived from the Joint Research Project Agreement #6 (JRPA #6) work to quantify the ice loads imposed on marine propellers and define an overall model of propeller and ice interaction loads known as the Design Load Model (DLM). Simulated results were shown to correlate reasonably well with the available full-scale measurements for the CCGS Louis St. Laurent and the USCGC Polar Star icebreakers.

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16. Résumé

Ce projet avait pour objet principal l'incorporation d'un modèle perfectionné des interactions hélices-glaces au logiciel MSM (*Modular Ship Modelling*) de modélisation en conception de la machinerie d'un navire, de façon à prendre en compte les charges glacielles sollicitant les hélices dans le calcul de l'ensemble du système de propulsion et de commande de navires de cote arctique et à homologation de type. Ce modèle perfectionné a été mis au point dans le cadre du projet de recherche mixte JRPA (*Joint Research Project Arrangement*) n° 6, lequel visait à déterminer les charges glacielles sollicitant les hélices marines et à définir un modèle global des interactions hélices-glaces. Les résultats des études de simulation se sont révélés raisonnablement corrélés avec les mesures en vraie grandeur effectuées à bord des brise-glace Louis-Saint-Laurent, de la Garde côtière canadienne, et Polar Star, de la U.S. Coast Guard.

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SUMMARY

An enhanced propeller/ice interaction model was developed and implemented as a new Modular Ship Modelling (MSM) component. This Design Load Model (DLM) was derived from the Joint Research Project Agreement #6 (JRPA #6) work targeted at developing design standards for the propellers and propulsion system for the construction of Arctic Class and Type ships. The model is useful in that it relates dynamic propulsion system performance to time varying propeller/ice load conditions. The modelling environment is also well suited to vary key parameters and observe their sensitivity on propulsion system performance. For propeller/ice interactions, propulsion drivetrain shafting inertia and ice load conditions such as thickness and duration of an ice milling event are parameters of key interest. The enhanced MSM propeller/ice interaction model was shown to correlate reasonably well with available full-scale measurements for the CCGS Louis St. Laurent and USCGC Polar Star.

Shaft speed was found to be a very good parameter to characterize the behaviour and performance of the propulsion system as a whole and to provide a means of calibrating a propeller/ice interaction model. More specifically, the maximum drop in shaft speed and the time to reach that point during a propeller/ice interaction event are key characteristics to note.

It is recommended that shaft speed be monitored as a useful condition indicator of propulsion system performance during propeller/ice interaction events for both Arctic Class and Type ships. Having this kind of information in a historical data base can yield important information on the number of occurrences and severity of shaft speed deviations during propeller/ice interaction events. This would contribute to the progressive evolution of suitable design standards for Arctic Class and Type ships.

SOMMAIRE

Un modèle perfectionné pour l'étude des interactions hélices-glaces a été développé et mis en oeuvre à titre de nouveau modèle composant du logiciel de modélisation en conception de la machinerie d'un navire (MSM, de l'anglais *Modular Ship Modelling*). Ce modèle a été mis au point dans le cadre du projet JRPA n° 6 qui portait sur l'élaboration de normes de calcul des hélices et des appareils propulsifs pour la construction de navires de cote arctique et à homologation de type. Ce modèle est particulièrement utile en ce qu'il permet d'étudier les performances dynamiques de l'appareil propulsif en fonction de charges glacielles variables dans le temps. De plus, la modélisation se fait dans un environnement favorable à la modification des paramètres de modélisation clés et à l'observation de leurs effets sur les performances de l'appareil propulsif. Parmi les paramètres représentant un intérêt tout particulier pour l'étude des interactions hélices-glaces, on peut mentionner l'inertie de la ligne d'arbres de l'appareil propulsif et certaines caractéristiques reliées aux charges glacielles, comme l'épaisseur de la glace et la durée des épisodes de broyage de glace. Les résultats obtenus au moyen du modèle perfectionné se sont révélés raisonnablement corrélés avec les mesures en vraie grandeur effectuées à bord des brise-glace Louis-Saint-Laurent, de la Garde côtière canadienne, et Polar Star, de la U.S. Coast Guard.

Le régime de rotation de l'arbre s'est avéré un paramètre très utile non seulement pour caractériser le comportement et les performances de l'appareil propulsif dans son ensemble, mais aussi en tant que repère pour le calage d'un modèle des interactions hélices-glaces. De façon plus précise, la chute maximale du régime de rotation de l'arbre, sous l'effet d'interactions hélices-glaces, et la durée de l'évolution à la baisse aboutissant à ce régime figurent parmi les principales variables à observer.

En conclusion, il est recommandé de mesurer le régime de rotation de l'arbre en tant qu'indicateur utile des performances de l'appareil propulsif des navires de cote arctique et à homologation de type, lors d'interactions hélices-glaces. Ces mesures pourraient servir à l'édification d'une base de données historiques fort utile sur le nombre et l'ampleur des fluctuations du régime de rotation de l'arbre lors d'interactions hélices-glaces. À son tour, cette information serait un apport précieux aux travaux devant mener à l'élaboration de nouvelles normes de conception pour la construction de navires de cote arctique et à homologation de type.

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List of Acronyms

ASPPR	Arctic Shipping Pollution Prevention Regulations
CAC	Canadian Arctic Class
CCG	Canadian Coast Guard
CCGS	Canadian Coast Guard Ship
CPP	Controllable Pitch Propeller
DCMT	David Clark Maritime Technologies
DLM	Design Load Model
DLPS	Design Load Propulsion Simulation
FPP	Fixed Pitch Propeller
GMI	German Marine Inc.
JRPA #6	Joint Research Project Agreement #6
KMD	Krupp Mak Diesel
MSM	Modular Ship Model
PCL	Power Control Lever
p.f.	Power Factor
TDC	Transportation Development Centre
USCGC	United States Coast Guard Cutter

1. INTRODUCTION

The development of propeller/ice interaction models which are capable of accurate prediction of transient loads on ship propulsion machinery will provide Marine, Prairie and Northern Region with a tool to assess ship machinery performance design criteria and protection regulations for ships navigating in ice-covered waters.

This project addresses the needs and requirements of Transport Canada to incorporate a suitable propeller/ice interaction model to evaluate the impact of ice loads on propulsion machinery and propulsion control system design of both Arctic Class and Type ships. Whereas Arctic Class ships will usually be designed to operate unassisted, Type ships will be designed to rely on icebreaker assistance in certain ice conditions.

1.1 Background

The scope of the Machinery Protection regulations for ships navigating in Canadian Arctic waters is to ensure safety of personnel, adequacy of ship design to operate in this region, and protection of the environment. The Arctic Shipping Pollution Prevention Regulations (ASPPR) have been reviewed and continue to evolve as more knowledge and experience are gained from ships operating in ice-covered waters [1 - 8]. In recent years research and development have provided more knowledge about the icebreaking capabilities of ships and how they vary with hull form, propulsion system characteristics, and the ice environment.

For ships navigating ice-covered waters, the suitability of a propulsion system can depend on some (for Type ships) or all (for Arctic Class ships) of the following power requirements:

(1) Power required to obtain a desired open water speed.

(2) Power to continuously break ice of a nominal thickness and type at a specified speed.

(3) Power to allow a ship to ram ice ridges from reasonable distances at specified speeds.

(4) Power to cope with propeller/ice interaction loads.

Modular Ship Model (MSM) is a Graphical User Interface ship modelling tool that can be used to configure propulsion system models and simulate the performance of ship propulsion machinery systems under both steady state and dynamic manoeuvring conditions. As a consequence of research and development, it has evolved as a rapid prototyping tool that permits a user to focus more effort on applying the model rather than building it. MSM has also been structured so that it can evolve further to add new component models as the need arises. For ships navigating in ice-covered waters, MSM can be used to examine the power requirements of ships under various conditions of loading.

1.2 Project Objective

The primary objective of this project is the incorporation of an enhanced propeller/ice interaction model in MSM to assess the effect of propeller/ice loads on the overall propulsion system and control system design of a ship. The enhanced propeller/ice interaction model will be derived from the JRPA#6 work to quantify more accurately the ice loads imposed on marine propellers and define an overall model of propeller and ice interaction loads known as the Design Load Model (DLM). Simulated propeller/ice interaction performance will be verified against available full-scale performance measurements for the Canadian Coast Guard Ship (CCGS) Louis St. Laurent and the United States Coast Guard Cutter (USCGC) Polar Star icebreakers.

1.3 Scope

This document summarizes the derivation of an enhanced MSM propeller/ice interaction model based on the JRPA #6 work, the derivation and verification of appropriate MSM icebreaker models in support of this, and the correlation of simulated propeller/ice interaction events with available full-scale performance measurements for the CCGS Louis St. Laurent and USCG Polar Star icebreakers.

Section 2 of this document summarizes the reports referenced or used in support of this document.

Section 3 presents an overview of the propulsion systems for the icebreakers, the modelling assumptions, the engineering block diagram representations for implementation using MSM, and an overview of the derivation of the enhanced propeller/ice interaction model based on the JRPA #6 work.

Section 4 presents a summary of the sources of information for modelling the icebreakers and the model data required in support of the ship models.

Section 5 presents steady state verification simulated results for the icebreaker models. Open water ahead and level ice ahead performance is summarized at 1/4, 1/2, 3/4, and full power.

Section 6 presents transient state or dynamic verification simulated results for the icebreaker models. Ice ramming (which combines both decelerations and accelerations of the propulsion system) and propeller/ice interaction events are summarized. The sensitivity of drivetrain inertia to minimize shaft speed reductions during propeller/ice interaction events is also included.

Section 7 summarizes the correlation of available full-scale performance measurements from the CCGS Louis St. Laurent with results generated by the enhanced MSM propeller/ice interaction model.

Section 8 summarizes the enhanced MSM propeller/ice interaction model to correlate simulated events with available ones for the USCGC Polar Star. The correlation is presented in terms of shaft speed drops and times to reach a maximum drop in shaft speed as a consequence of propeller/ice interaction events. These two parameters characterize the behaviour of the propulsion system as a whole and provide a means of calibrating the propeller/ice interaction model to reproduce them in a simulated environment.

Section 9 summarizes conclusions and recommendations concerning the usefulness of the enhanced MSM propeller/ice interaction model, how well the model correlates with available CCGS Louis St. Laurent and USCGC Polar Star results, and the benefits of tracking certain condition indicators to better assess the adequacy of design standards for ships navigating in ice-covered waters.

The process of setting up the MSM for the purpose of conducting primarily propeller/ice interaction investigations of Arctic Class and Type ship propulsion systems has also been summarized in Appendix 4. The overall process can be broken down into a simulation process and an analysis process. For the simulation process, MSM is used as a tool to set up a ship model to simulate performance which is represented by means of time history traces of key parameters. For the analysis process, a standard spreadsheet is used as a tool to illustrate and understand the interrelationships among key parameters affecting the propulsion system performance.

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2. APPLICABLE DOCUMENTS

The following documents have been referenced or used in support of this document.

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3. PROPULSION MACHINERY AND CONTROL SYSTEM MODEL OVERVIEW

3.1 USCGC Polar Star Propulsion System Overview

The USCGC Polar Star has a unique propulsion machinery configuration which incorporates both direct gas-turbine mechanical drive mode as well as a Ward-Leonard electric (ac/dc) drive mode driven by controllable pitch propellers (CPP). An overview of this system is illustrated in Figure 3.1.

The ship has three propellers each fitted with a hydraulic pitch controller operated from the bridge and engine control room console. Throttle controllers interface through a computer based control system to an electric-pneumatic pitch setting device which, in turn, operates the hydraulic mechanism used to change propeller pitch.

Each one of the three propellers may be driven either by a Westinghouse 6000 HP dc motor or by a Pratt & Whitney FT4 20,000 shp gas turbine. In the diesel electric mode, each dc motor can be supplied from one or two diesel driven ac electric generators. A total of six diesel generator units are available. Motor set up switches enable each motor to be powered from four of the six generators with a maximum of two generators being connected at any one time. Solid state rectifiers convert the generator alternating current to direct current for the propulsion motor.

Three modes of control are provided: Free Running, Diesel-Electric Icebreaking, and Gas Turbine Icebreaking. For each mode of operation, the computer controls the machinery to follow pre-programmed RPM-Pitch schedules. For each schedule, the pitch varies between maximum and minimum operating characteristics. Diesel electric or gas turbine mode is achieved by mechanically connecting or disconnecting the gas turbine from the propeller shaftline.

Under free running operation, the pitch increases linearly over the throttle operating range up to throttle position 7.25. Between throttle position 7.25 and 10, the pitch is kept constant at the full ahead position. The rpm is maintained constant at 105 rpm and increases at throttle position 7.25 to 110 rpm if one generator per shaft is used and to 130 rpm if two generators per shaft are used.

Under icebreaking operation, the pitch varies linearly over the complete throttle range but is limited to a maximum value dependent upon the prime movers connected to the system. A maximum value of 87% pitch is used under gas turbine operation. The pitch is limited to 66% with two generators per shaft in the diesel electric mode and 44% with one generator per shaft. In the gas turbine mode the shaft rpm is regulated to 177 rpm on the centreline and 160 rpm on the port and starboard shafts. Under diesel electric mode, the shaft is regulated to 130 rpm.

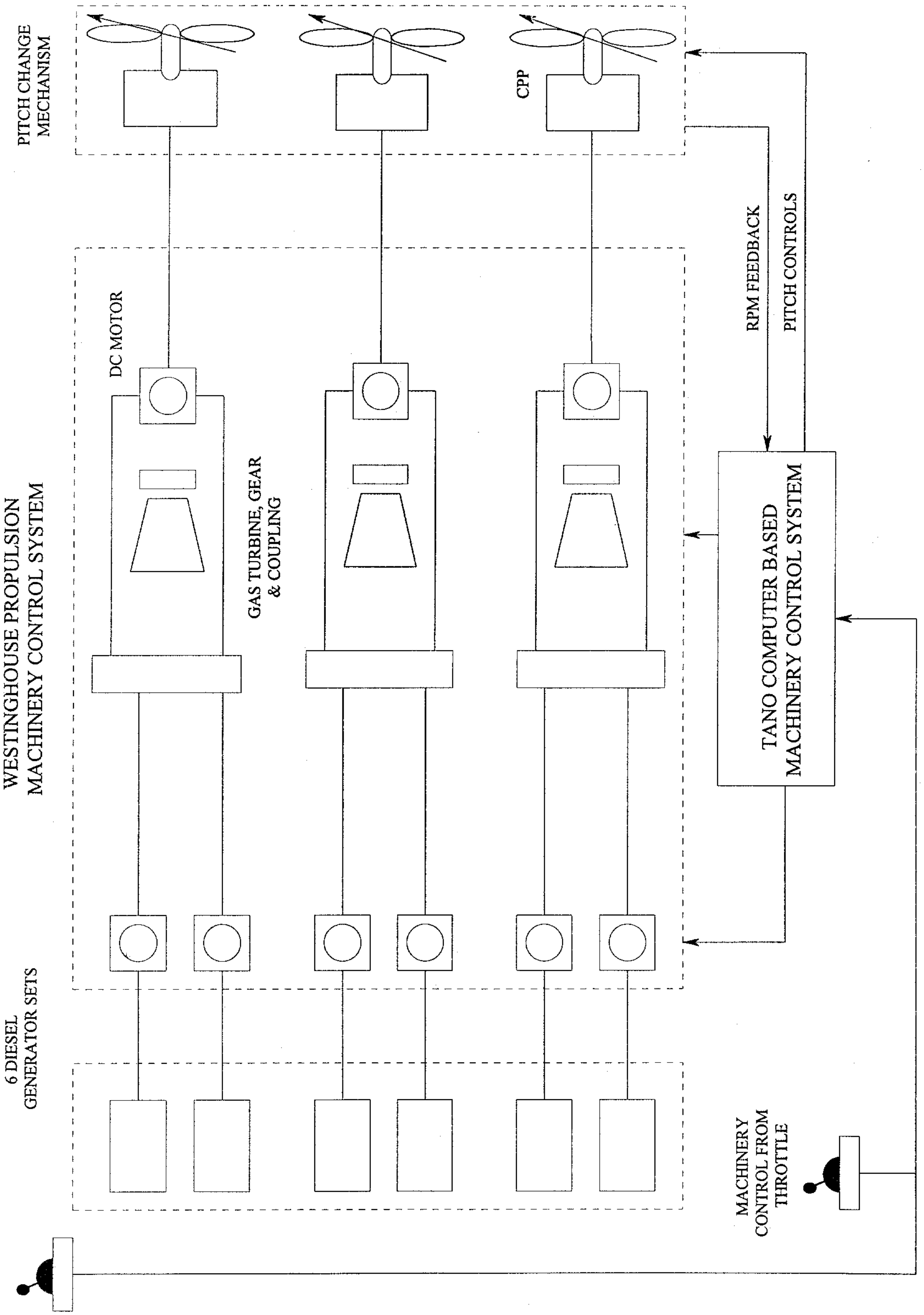


Figure 3.1 USCGC Polar Star Propulsion Machinery Overview

Under both gas turbine and diesel electric operating modes, the machinery is controlled to provide a fixed shaft rpm. A simple load control is provided by monitoring the shaft rpm for each throttle position. If the shaft rpm stays within -2 rpm of its scheduled value, the pitch is allowed to increase up to the maximum value permitted for the mode of operation. If the shaft rpm falls below -2 rpm, the pitch is prevented from increasing. If the shaft rpm falls below -5 rpm the pitch is held at its minimum pitch value for the throttle position. Between -5 and -10 rpm a visual and audible alarm is initiated but no automatic pitch reduction is implemented. The operator is required to remove pitch in order to remove the overload.

The propulsion system is monitored and controlled by an electronic computer based controller comprising a central computer which transmits data to the machinery over a Local Area Network and interfaces through local mounted Remote Data Units. The computer regulates the shaft rpm by providing reference signals to the gas turbine governor and to the diesel generator field exciter. The computer controls pitch through an electronic/pneumatic interface unit which operates a hydraulic pitch setting unit for the propeller.

3.2 USCGC Polar Star Model Requirements

Although the original objectives of this project included the evaluation of the USCGC Polar Star during propeller/ice interactions in both direct gas turbine mode and diesel electric mode, a lack of available data will limit the study for the direct gas turbine mode.

For ice manoeuvring investigations, the following modelling requirements have been assumed:

a) the icebreaker will be modelled as a rigid body with a single degree of freedom and is thus capable of simulating only ahead/astern motions for all manoeuvres;

b) only one shaft line will be modelled for several reasons:

  - simulation of non-symmetric ice milling loads is not necessary; and,
  - the three shaft lines operate independently;

c) the effect of cavitation on the propeller will not be modelled. This is a reasonable assumption as no data are available. The controllable pitch propeller model will provide performance prediction in four quadrants of operation;

d) sequenced logic for startup and shutdown of propulsion machinery components will not be modelled since it is not required for this investigation;

e) propulsion shaft lines will be modelled as flexible shafts having inertia, stiffness, and damping;

f) ship services and auxiliary loads will be modelled as lumped real and reactive loads which can be adjusted for different manoeuvres;

g) propeller/ice interactions will be modelled based on the JRPA #6 work for the DLM.

3.3 USCGC Polar Star Model Overview

An overview of the USCGC Polar Star propulsion machinery and control system model as an engineering block diagram representation is presented in Figure 3.2 with nomenclature defined in Appendix 1.

The USCGC Polar Star model was implemented using the MSM [9, 10, 11] tool.

3.4 CCGS Louis St. Laurent Propulsion System Overview

The CCGS Louis St. Laurent has an ac/dc electric propulsion machinery system. An overview of this system is illustrated in Figure 3.3.

The CCGS Louis St. Laurent design is a three screw arrangement with a 6.714 MW dc propulsion motor driving each shaft. The three propellers are identical fixed pitch propellers (FPP).

The dc propulsion motors are connected to the 6.6 KV ships electrical bus via a pair of parallel connected three phase bridge rectifiers. Speed regulation of the motor is achieved through a combination of armature current control and field current control.

Three phase electrical power is supplied to the ship’s electrical bus by five 6.4 MVA diesel generator sets. These diesel generator sets can be employed in various combinations depending on the load imposed on the system. The diesel generator power plant supplies power to the three propulsion motors as well as a pair of motor generator sets which supply the ships services load and a pair of 600 KW bubbler motors. The generators are ac synchronous machines. Dedicated fuel governors and voltage regulators provide frequency and voltage regulation for the diesel generator sets. The motor generator sets, which supply power for ship services, isolate the ship service loads from the distortion of the line current caused by the rectifier converter circuits.

Ship speed is controlled indirectly by selecting the desired propeller shaft speed. The three propulsion shafts are controlled independently using separate power lever controls.

In addition, an overall supervisory power management control has been provided to integrate the operation of the entire electrical propulsion system.

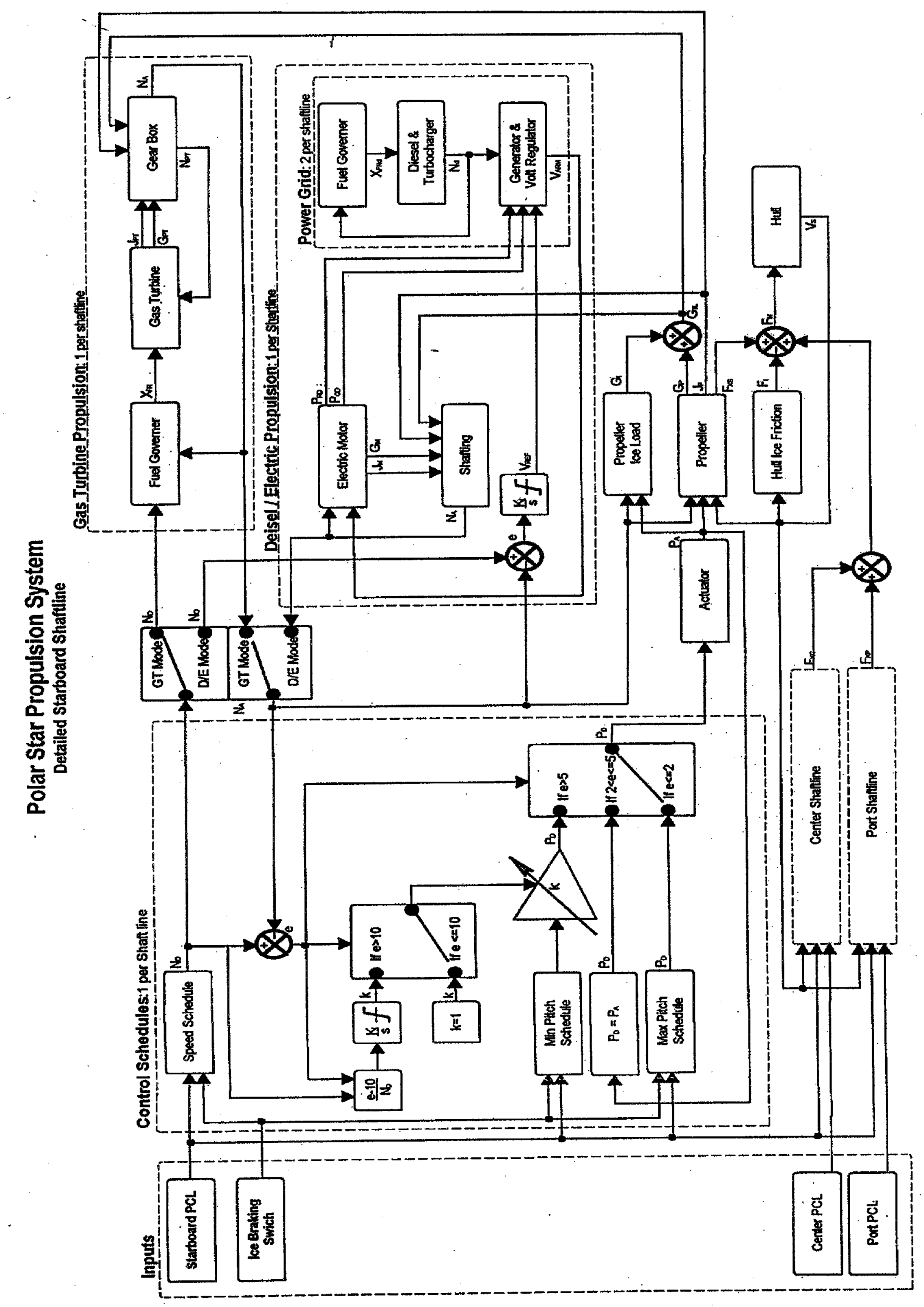


Figure 3.2 USCGC Polar Star Propulsion System Block Diagram

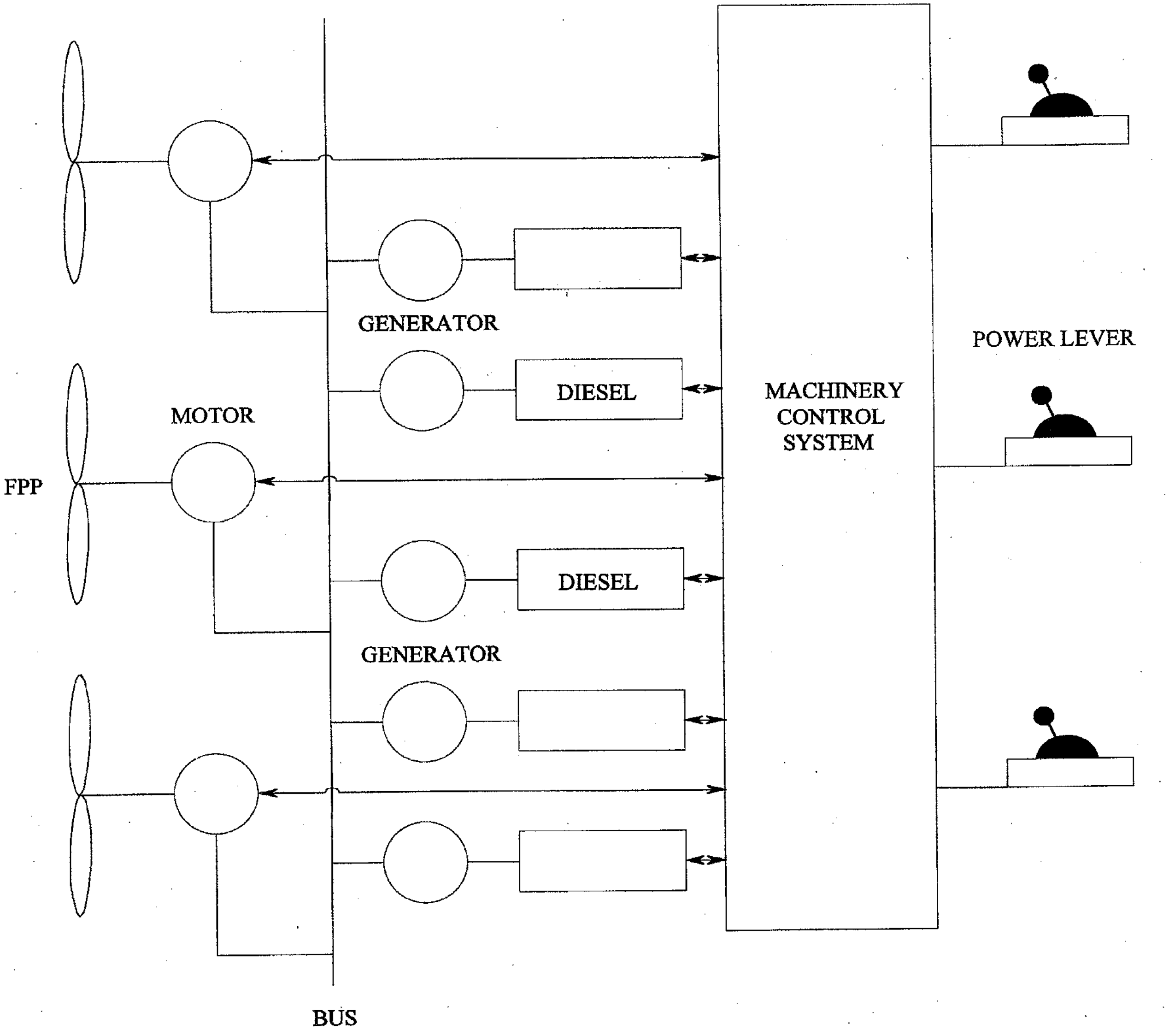


Figure 3.3 CCGS Louis St. Laurent Icebreaker Propulsion System Overview

3.5 CCGS Louis St. Laurent Model Requirements

For ice manoeuvring investigations, the following modelling requirements have been assumed:

a) the icebreaker hull will be modelled as a rigid body with a single degree of freedom and is thus capable of simulating only ahead and astern motions for all manoeuvres;

b) a single shaft line will be modelled for several reasons:

- simulation of non-symmetric ice milling loads is not required; and,
- balanced three shaft operation will be assumed;

c) the effect of cavitation on propeller performance will not be modelled. This is a reasonable assumption given that no data are available. The fixed pitch propeller model will provide performance prediction in four quadrants of operation;

d) all dc propulsion motors will be modelled as identical machines;

e) propulsion shaft lines will be modelled as flexible shafts having inertia, stiffness, and damping;

f) the ac/dc converter and dc motor speed control will be modelled in terms of the control strategy and will describe the dc motor speed control concept;

g) ship service and auxiliary loads will be modelled as lumped real power and reactive loads which can be adjusted for different manoeuvres;

h) transformers will be modelled as ideal devices. This is a reasonable assumption for the proposed investigation. Moreover, for this type of model the data are readily available;

i) all diesel generator sets will be modelled as identical units;

j) for a particular diesel generator set, the masses and inertias of the rotor will be lumped. This is a reasonable assumption since the coupling between the machines is stiff;

k) when two or more diesel generator sets are operational, each unit will be assumed to share the total load equally. Hence, several diesel generator sets that are on-line at any given time will be represented as a single diesel generator set with equivalent lumped mechanical and electrical parameters. This assumption implies that the tie lines between the various electrical generators are very stiff;

l) sequenced logic for startup and shutdown of propulsion machinery components will not be modelled since it is not required for this investigation; and,

m) propeller/ice interactions will be modelled based on the JRPA #6 work for the DLM.

3.6 CCGS Louis St. Laurent Model Overview

An overview of the CCGS Louis St. Laurent propulsion machinery and control system as an engineering block diagram representation is presented in Figures 3.4a and 3.4b with nomenclature defined in Appendix 2.

The CCGS Louis St. Laurent model was implemented using the MSM [9, 10, 11] tool.

3.7 Enhanced MSM Propeller/Ice Interaction Models

Since the primary objective of this project was to incorporate an enhanced propeller/ice interaction model into MSM, a considerable amount of effort was spent formulating an adequate model for use in MSM to represent various types of propeller/ice interaction events as suitable time history traces.

The JRPA #6 have proposed a DLM to determine loads applied to the propeller in order to set some minimum standards for the design of the propeller and the propulsion system. The DLM in its current form could not be imported directly into MSM. However, with the guidance of R. Browne, who had been involved in full-scale ship performance tests [12] and the development of the DLM, the DLM was enhanced further to evolve a propeller/ice interaction model suitable as a component model in MSM [9, 10, 11].

B. Veitch at NRC/IMD was also attempting to develop a suitable Design Load Model [13]; unfortunately the Veitch model was available in a different form than the JRPA #6 model. It consisted of predicted time history traces of propeller/ice torque loads rather than a model formulation capable of generating such traces. Furthermore, for these time history traces, there was no explicit correlation with ice block thickness and ship operating conditions. As a consequence, the emphasis was placed on the development of an enhanced MSM propeller/ice interaction model based on the JRPA#6 work. Having now successfully implemented an enhanced propeller/ice interaction model in MSM based on the JRPA #6 work, it can now provide guidance on how to formulate the Veitch model at some later date if so desired.

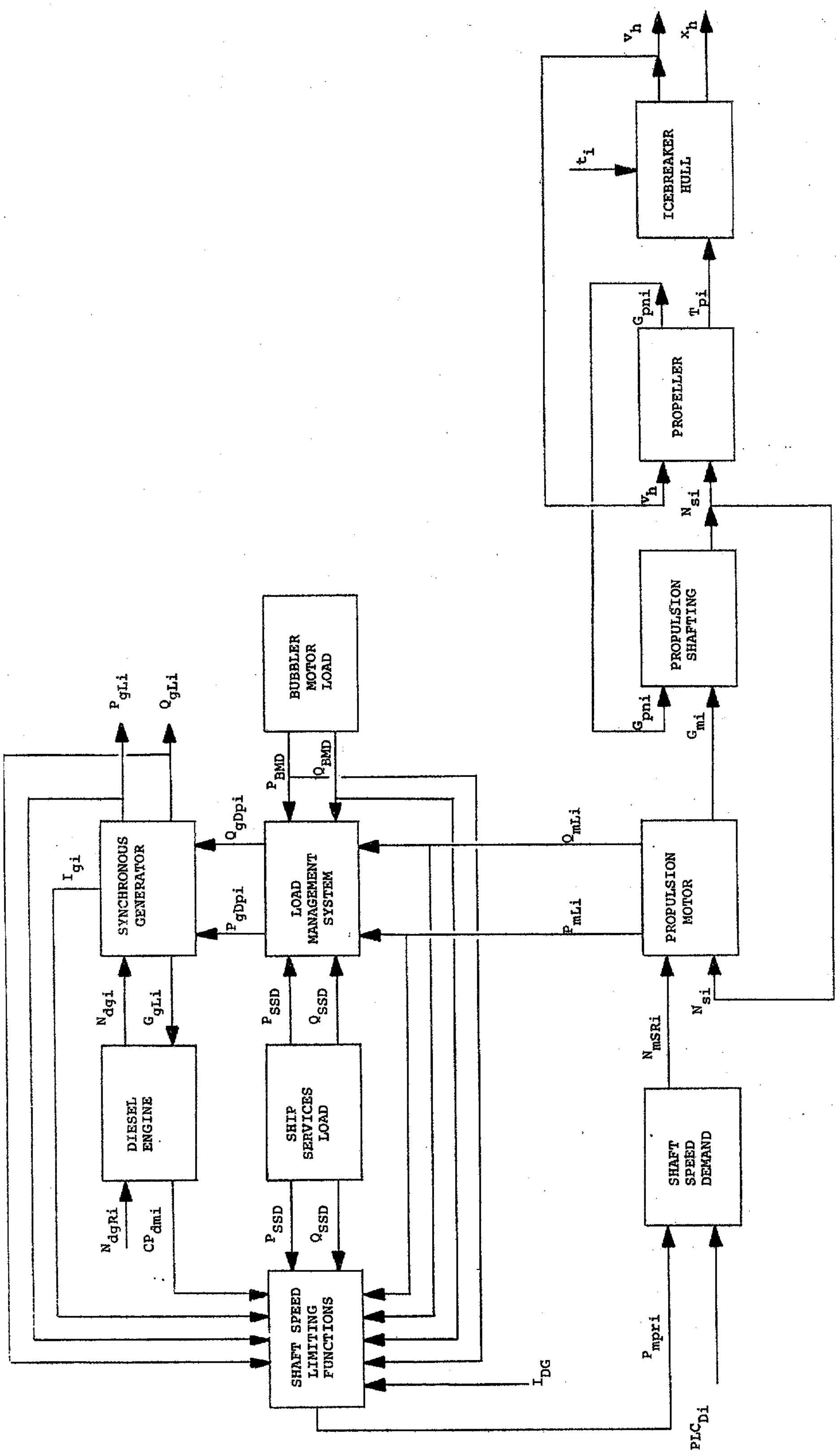


Figure 3.4a CCGS Louis St. Laurent Propulsion System Block Diagram

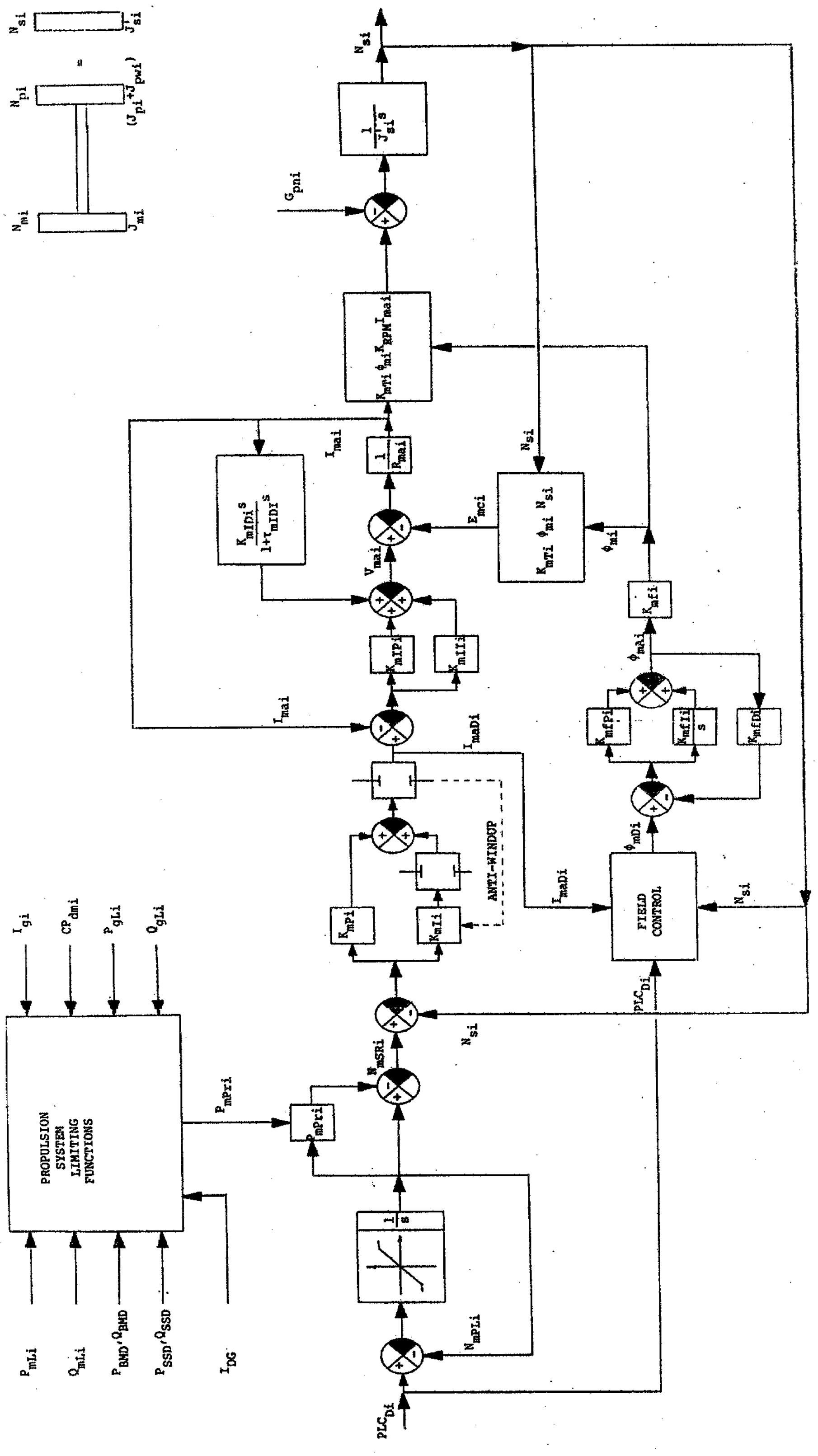


Figure 3.4b CCGS Louis St. Laurent Propulsion Motor Control Block Diagram

3.7.1 Enhanced MSM Propeller/Ice Interaction Model Derivation

The complete derivation of the enhanced MSM propeller/ice interaction model based on the JRPA#6 work is given in [10]. This model was formulated to represent the transient forces and torques which act upon a propeller and the propeller shaft as a propeller encounters blocks of ice and mills them to a certain extent. The transient responses as time history traces are computed from the maximum and average force and torque values based on known or assumed behaviour of the propeller during propeller/ice interactions [12].

The maximum and average ice torque values are calculated using equations derived from a regression analysis of actual ship results during propeller/ice interaction events. The equations describing the maximum and average values of ice torque have the same form but the regression coefficients (c_i) are different depending on whether $Q_{maximum}$ or $Q_{average}$ is calculated. The form of the equation is as follows:

$$Q = c_1 \bullet (1 - d/D) \bullet \sigma^{c_2} \bullet (H/D)^{c_3} \bullet \left(c_4 \frac{V^2}{N^2 D^2} + \frac{V}{ND} + c_9\right) \bullet (P/D)^{c_5} \bullet$$
$$(t/D)^{c_6} \bullet (ND)^{c_7} \bullet D^{c_8}$$

where:

d	is hub diameter
t	is blade thickness at 70% blade radius
P	is propeller pitch
H	is ice block thickness
σ	is ice uni-axial compression strength
N	is shaft speed
V	is ship speed
c_1 to c_9	are empirically derived constants

The various propeller, ice, and operational parameters are also illustrated in Figures 3.5 and 3.6. Note that ice block size is essentially limited to a thickness which is approximately half of the propeller diameter.

In the equation above the ice torque is dependent on a number of key non-dimensional and dimensional parameters.

(1 - d/D) accounts for the hub to diameter ratio effect. If d = D then Q = 0 as expected.

σ accounts for ice strength.

H/D accounts for ice thickness and should be restricted to a maximum ratio of 0.5 to limit the ice block size to half of the propeller diameter.

P/D accounts for the contact geometry conditions and *V/ND* represents operational conditions that further bias these conditions.

t/D accounts for the blade width effects.

ND accounts for the influence of the propeller speed in terms of tip velocity during the ice milling process.

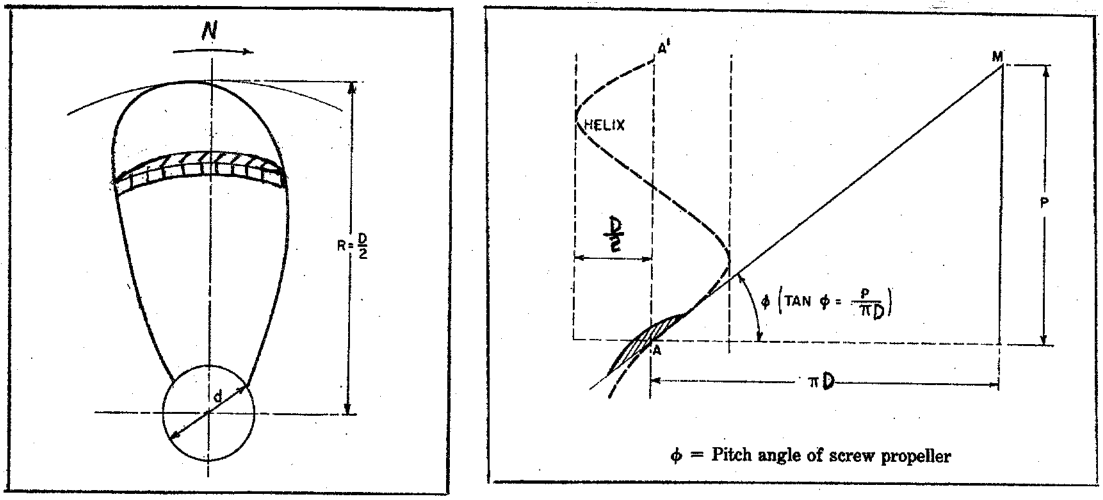
D accounts for the propeller size and represents the overall scaling factor for the non-dimensional expressions in the equation.

The ice torque loads on propeller blades are represented as triangular torque pulses, whose width and height are functions of the maximum and average torque loads as well as speed and number of blades of the propeller as shown in Figure 3.7. The overall ice torque load acting on the propeller is the summation of individual blade contributions over the course of an entire propeller/ice interaction event as shown in Figure 3.8. The ice torque profile essentially consists of a slowly varying offset component and a high frequency oscillatory component. The offset component arises from the phenomenon of blade “shadowing” where the geometry of the ice block and the propeller may result in a situation where two propeller blades are in contact with the ice simultaneously; this happens because of an overlap in the triangular torque pulses for the blades.

The duration of propeller/ice interaction event can also be varied by compressing or expanding the typical ice torque profile shown in Figure 3.8 as a functions of time.

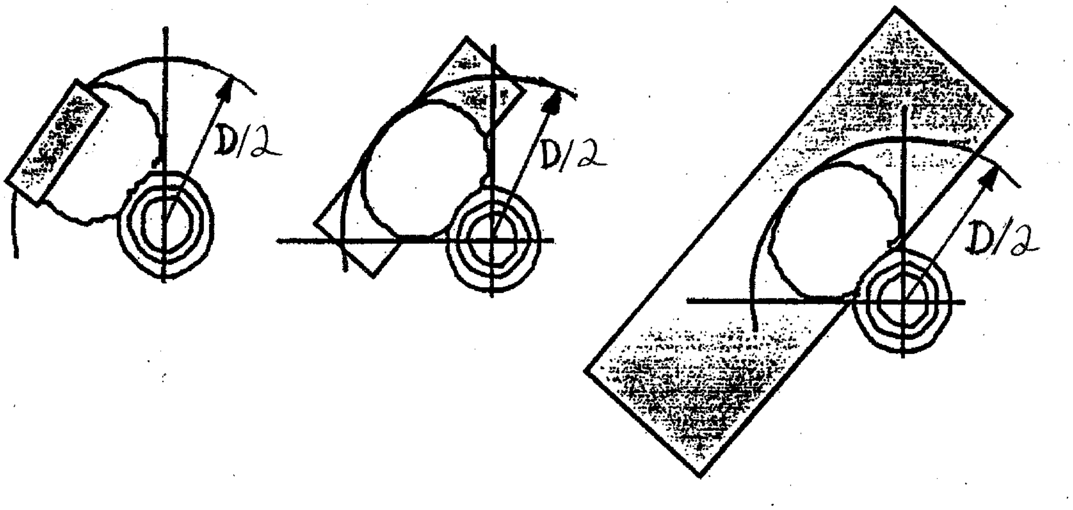
The process of generating the time history trace of an overall ice torque profile to be applied as an additional torque load on the propeller is outlined in Appendix 3 for the MSM enhanced propeller/ice interaction model.

Physical characteristics for the CCGS Louis St. Laurent and USCGC Polar Star propellers are summarized in Figure 3.9.



ϕ = Pitch angle of screw propeller

Figure 3.5 Definition of Propeller Parameters



H =D/8 H =D/4 H =D/2

Figure 3.6 Definition of Ice Block Thickness Ratio

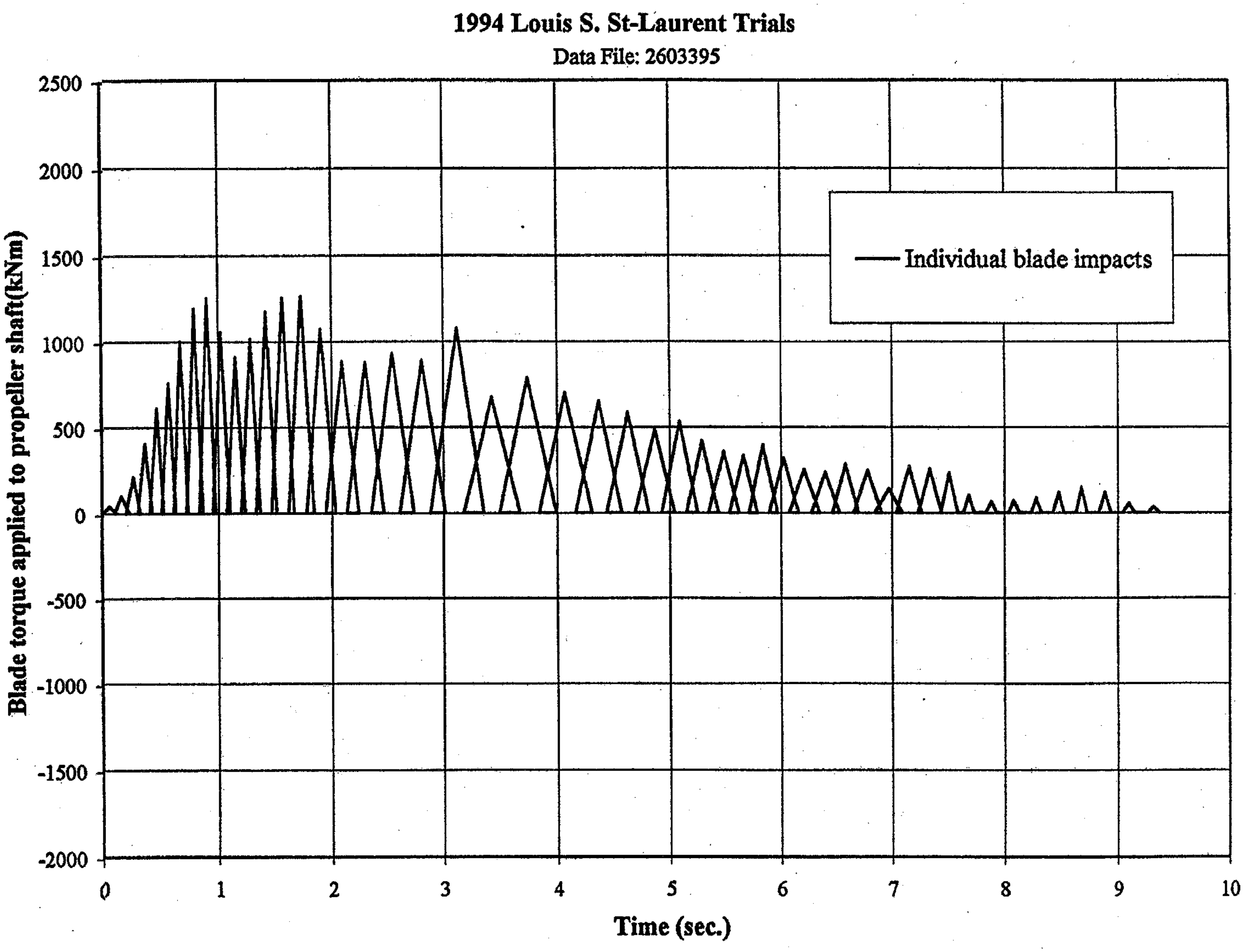


Figure 3.7 Ice Torque Applied to Shaft by Individual Blades [12]

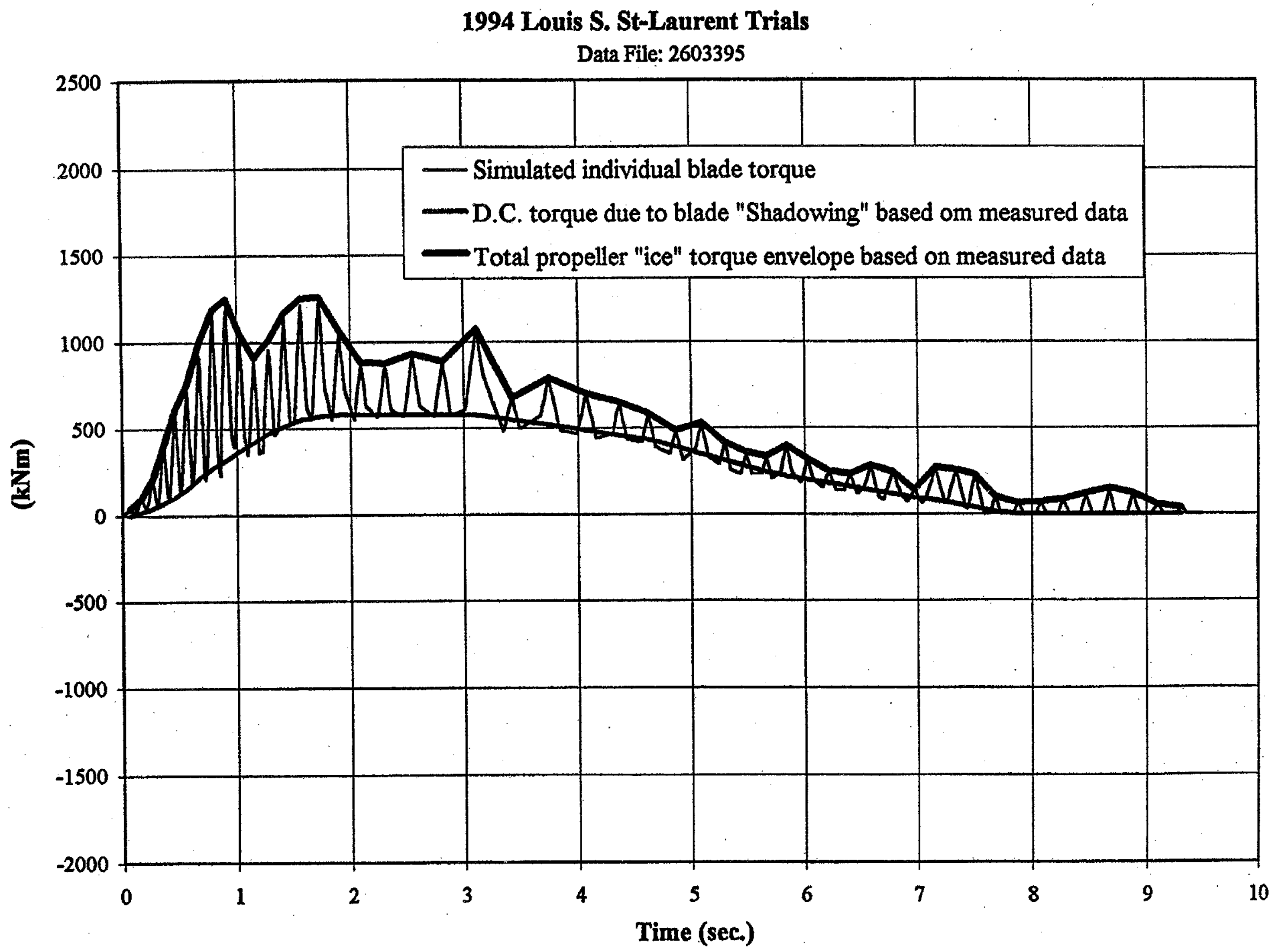
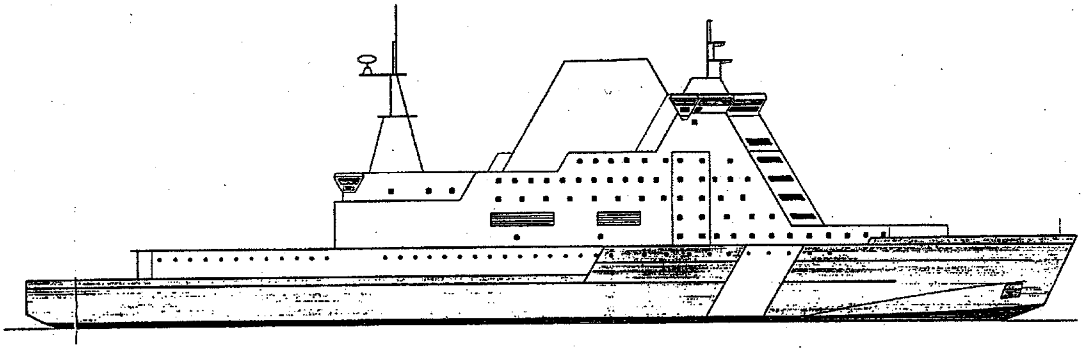


Figure 3.8 Overall Ice Torque Applied to Shaft [12]



Propeller Characteristics	CCGS Louis St. Laurent	USCGC Polar Star
Propeller	Fixed pitch	Controllable pitch
Propeller diameter	4.6 m	4.9 m
Propeller hub diameter	1.38 m	1.47 m
Number of Blades	4	4

Figure 3.9 Physical Propeller Characteristics

4. PROPULSION SYSTEM MODEL DATA

The USCGC Polar Star and CCGS Louis St. Laurent propulsion system models will be implemented using MSM. MSM uses a library of standard component models which are combined to represent the propulsion systems. Each component model is supported by data describing its physical and geometrical design parameters and component performance characteristics.

Model data in support of the icebreaker propulsion systems were obtained from various sources. The origin of the data and any assumptions made to synthesize data when not available are summarized in the following subsections.

4.1 USCGS Polar Star Component Model Data

4.1.1 Hull Data

The USCGC Polar Star hull data have been derived from minimal performance data available from the data collected during sea trials. The bulk of these data was available for operation in level-ice (due to the fact that data were only collected while ice breaking). For open water operation, the data were synthesized.

4.1.2 Pratt & Whitney FT-4A Gas Turbine

The Pratt & Whitney FT-4A gas turbine engines, rated at 20,000 shp, are used to power the three shafts in direct gas turbine drive mode. These same engines are used to power the Tribal Class destroyers currently operated by the Canadian Navy. Because of work done for the Canadian Navy, FT4 gas turbine data were available.

4.1.3 Gearboxes and Propeller Shafting

The gearbox is described by the gear reduction ratio and the shafting is described by its stiffness, damping, and inertia. These data were supplied by the Transportation Development Centre (TDC).

4.1.4 Controllable - Pitch Propellers

Controllable pitch propeller data have been obtained from [14] to represent four quadrant propeller performance. The propeller performance data do not include effects due to cavitation.

4.1.5 Propeller Pitch and Shaft Speed Schedules

The propulsion control system for the USCGC Polar Star is capable of operation in three modes: Free Running, Diesel-Electric Icebreaking, and Gas Turbine Icebreaking. For the purposes of this study, only the gas turbine icebreaking schedules for propeller pitch and shaft speed control will be implemented.

The propeller pitch and shaft speed schedules were provided to GasTOPS Ltd. by David Clark Maritime Technologies (DCMT). These data were obtained from tests performed onboard the USCGC Polar Star.

4.2 CCGS Louis St. Laurent Component Model Data

4.2.1 Hull Data

The CCGS Louis St. Laurent hull data are comprised of the most up-to-date information provided by German Marine Inc. (GMI).

Hull resistance data in open water have been derived from model basin tests [15], performed by NRC/IMD, for a design draught of 28 ft. These data have been subsequently modified for a design draught of 31.33 ft., the present design draught, by GMI. Since open water hull resistance for astern operation of the icebreaker were not provided, reasonable astern open water hull resistance based on experience with other icebreaker hull designs have been synthesized.

Hull resistance data in level ice have also been obtained from model basin tests [15], however, these data were not corrected for the change in design draught and correspond to a design draught of 28ft. This is not considered to be a significant inaccuracy, since depth of draught primarily affects wave drag which is a relatively small component of the total drag force acting on the hull during operation in level ice.

The longitudinal added mass of the icebreaker hull in open water and in level ice has not been provided by GMI. For the purposes of these investigations GasTOPS Ltd. has assumed a value of 10% of the icebreaker hull displacement in open water and 25% of the icebreaker hull displacement in level ice.

4.2.2 Fixed Pitch Propeller Data

Fixed pitch propeller data have been derived from model basin tests [16] performed by NRC/IMD. These data, however, represent propeller open water performance for only the first quadrant; i.e. ahead ship speed and ahead shaft speed. For the remaining three quadrants; propeller performance data were synthesized. The propeller performance data do not include effects due to cavitation.

4.2.3 Motor Data

The dc motor data have been supplied by Siemens AG and the Canadian Coast Guard (CCG). Since the dc motor rotor volume constant K_{mTi}, was not provided by Siemens or CCG, it was estimated.

4.2.4 Generator Data

The data in support of the ac synchronous generator model have been supplied by the generator manufacturer Siemens AG. Since Siemens have been unable to provide the generator open circuit characteristic, or a detailed block diagram description of the excitation system required to adequately model the generator AVR loop, the generator open circuit characteristic was synthesized and an IEEE type 2 excitation system design with nominal gains and time constants was assumed.

4.2.5 Diesel Engine Data

The diesel engine data were supplied by Krupp Mak Diesel (KMD) for the 16M-453-C medium speed four stroke engine. Since the diesel speed governor gain pot, stability pot, and compensation pot settings were not specifically available, the diesel engine governor was tuned to reproduce the diesel engine transient performance predicted by Krupp Mak Diesel.

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5. STEADY STATE SIMULATION RESULTS

Steady state simulation results for the USCGC Polar Star and the CCGS Louis St. Laurent are presented in the following subsections to verify that the models simulate reasonable performance. The steady state results for the icebreakers are presented for ahead operation in open water and in level ice at 1/4, 1/2, 3/4 and full power.

Steady state simulation runs were performed by selecting identical throttle settings on each shaft line and allowing the simulation to reach steady state ship speed and shaft speeds.

5.1 USCGC Polar Star Steady State Performance

5.1.1 USCGC Polar Star Open Water Ahead

The open water steady state verification simulation run for the ship operating in the gas turbine drive mode was performed under the following conditions:

- 3 shaft lines operating
- equal throttle position demands on all shafts

The open water steady state simulation results for the ship operating in the gas turbine drive mode are summarized in Table 5.1. Note that the shaft speeds are limited to 130 RPM in the free running mode and that the propeller pitch demand values represent the maximum allowable propeller pitch for the given throttle position. The simulation results are reported for a single shaft only, since all shafts are identical apart from minor variations in rotational inertia which do not affect the steady state results.

Table 5.1 USCGC Polar Star - Gas Turbine Operating Mode
Steady State Results for Open Water Ahead

Parameter	Units	Operating Point			
		¼	½	¾	Full
v_s	knots	7.7	13.4	18.0	22.5
N_s	rpm	105	105	107	130
β_P	deg	8.6	17.2	25.0	25.0
T_{PROP}	N	53288	104970	273500	365960
G_{PROP}	N m	44497	97656	147540	192010

5.1.2 USCGC Polar Star Level Ice Ahead

The level ice steady state verification simulation run for the ship operating in the gas turbine drive mode was performed under the following conditions:

- 3 shaft lines operating
- equal throttle position demands on all shafts
- ice thickness of 0.91 m
- propeller shaft speed demands of 160 rpm (wing shafts) and 177 rpm (centre shaft)

The results of the level ice steady state simulation results for the gas turbine drive mode are summarized in Table 5.2. Note that the propeller pitch demand values represent the maximum allowable propeller pitch for the given throttle position. Results for both the centre and wing propeller shafts are reported, since the centre shaft is operated at a higher rotational speed during icebreaking operations using the gas turbines.

Table 5.2 USCGC Polar Star - Gas Turbine Operating Mode
Steady State Results for Level Ice Ahead

Parameter	Units	Operating Point			
		¼	½	¾	Full
v_s	knots	0.0	3.2	8.3	13.5
$(N_s)_{CNTR}$	rpm	177	177	177	177
$(N_s)_{WING}$	rpm	160	160	160	160
$(\beta_P)_{CNTR}$	deg	5.4	10.9	16.3	21.8
$(\beta_P)_{WING}$	deg	5.4	10.9	16.3	21.8
$(T_{PROP})_{CNTR}$	N	287100	582740	882090	1218700
$(T_{PROP})_{WING}$	N	234950	467940	689540	942370
$(G_{PROP})_{CNTR}$	N m	144050	275900	500770	811600
$(G_{PROP})_{WING}$	N m	117790	222340	392500	632230

5.2 CCGS Louis St. Laurent Steady State Performance

5.2.1 CCGS Louis St. Laurent Open Water Ahead

The open water steady state verification simulation run was performed under the following conditions:

- 3 shafts operating
- equal speed demand on all shafts
- diesel engine speed constant @ 600 RPM
- generator terminal voltage constant @ approximately 6580V
- 5 diesel generator sets operating
- ship services loads for 5 generator operation (1.46 MW @ p.f. = 0.8)
- no bubbler motors running

The open water steady state simulation results are summarized in Table 5.3. Note that the center propeller operates at a lower speed than the wing propellers at the full ahead rated power condition due to a higher wake factor assumed for the propeller which, in turn, causes the load torque to be higher on this shaft.

Table 5.3 CCGS Louis St. Laurent - Steady State Results for Open Water Ahead

Parameter	Operating Points			
	¼	½	¾	Full
v_s (knots)	5.9	12.4	17.8	19.7
N_D (rpm)	50	100	150	200
N_{SW} (rpm)	50	100	150	180
N_{SC} (rpm)	50	100	150	169
G_{1w} (KN•m)	25	87	222	360
G_{1c} (KN•m)	33	123	308	385
T_{pw} (KN)	23	46	178	326
T_{pc} (KN)	40	93	296	413

5.2.2 CCGS Louis St. Laurent Level Ice Ahead

The level ice steady state verification simulation run was performed under the following conditions:

- 3 shafts operating
- equal shaft speed demand on all shafts
- ice thickness of 0.91 m
- diesel engine speed constant @ approximately 600 RPM
- generator terminal voltage constant @ approximately 6580 V
- all 5 diesel generator sets operating
- ship services loads set to 1.46 MW @ p.f. = 0.8
- bubbler motors running and drawing 1.175 MW @ p.f. = 1.0

The level ice steady state simulation results are summarized in Table 5.4.

Table 5.4 CCGS Louis St. Laurent - Steady State Results for Level Ice Ahead

Parameter	Operating Points			
	¼	½	¾	Full
v_s (knots)	0.1	2.3	5.3	5.8
N_D (rpm)	50	100	150	200
N_{SW} (rpm)	50	100	150	153
N_{SC} (rpm)	50	100	150	151
G_{1w} (KN•m)	54	193	422	425
G_{1c} (KN•m)	54	197	410	430
T_{pw} (KN)	93	326	621	637
T_{pc} (KN)	93	335	641	655

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6. TRANSIENT STATE SIMULATION RESULTS

Transient state simulation results for the USCGC Polar Star and the CCGS Louis St. Laurent are presented in the following subsections to verify that the models simulate reasonable performance prior to conducting propeller/ice interaction studies.

Since ships operating in ice-covered waters can be subjected to ice ramming cycles or propeller/ice interaction events, these two manoeuvres were selected to verify that the models simulate reasonable dynamic performance during transients. Furthermore, ice ramming manoeuvres combine both deceleration and accelerations of a propulsion system.

6.1 USCGC Polar Star Transient State Performance

6.1.1 USCGC Polar Star Ice Ramming Cycle

The ice ramming cycle verification simulation runs for the ship operating in the gas turbine drive mode were performed under the following conditions:

- 3 shaft lines operating
- 3 gas turbines driving

A simulation run was initiated with the icebreaker in steady state at bollard conditions at maximum ahead propeller speeds. A bollard crash deceleration was then performed followed by a crash ahead acceleration to approximately 10 kn ahead ship speed. At approximately 10 kn ahead ship speed the icebreaker rammed the ice ridge and began to decelerate.

Ice ramming cycle simulation results for the ship operating in the gas turbine drive mode are summarized in Figure 6.1. The ice ramming cycle time is about 180 seconds and the maximum distance the icebreaker backs up from the ice ridge to ram it at approximately 10 kn is about 80 m.

6.1.2 USCGC Polar Star Propeller/Ice Interaction Events

The propeller/ice interaction verification simulation runs were performed in the gas turbine drive mode under the following conditions:

- 3 shaft lines operating
- 3 gas turbines driving
- ship moving at low speed in level ice
- ice block thicknesses varying up to half the propeller diameter

Simulation runs were initiated with the icebreaker in steady state at maximum ahead propeller speeds in level ice conditions.

Simulation results for a typical propeller/ice interaction event with an ice block having a thickness of 0.91 m is summarized in Figure 6.2 for a wing shaft.

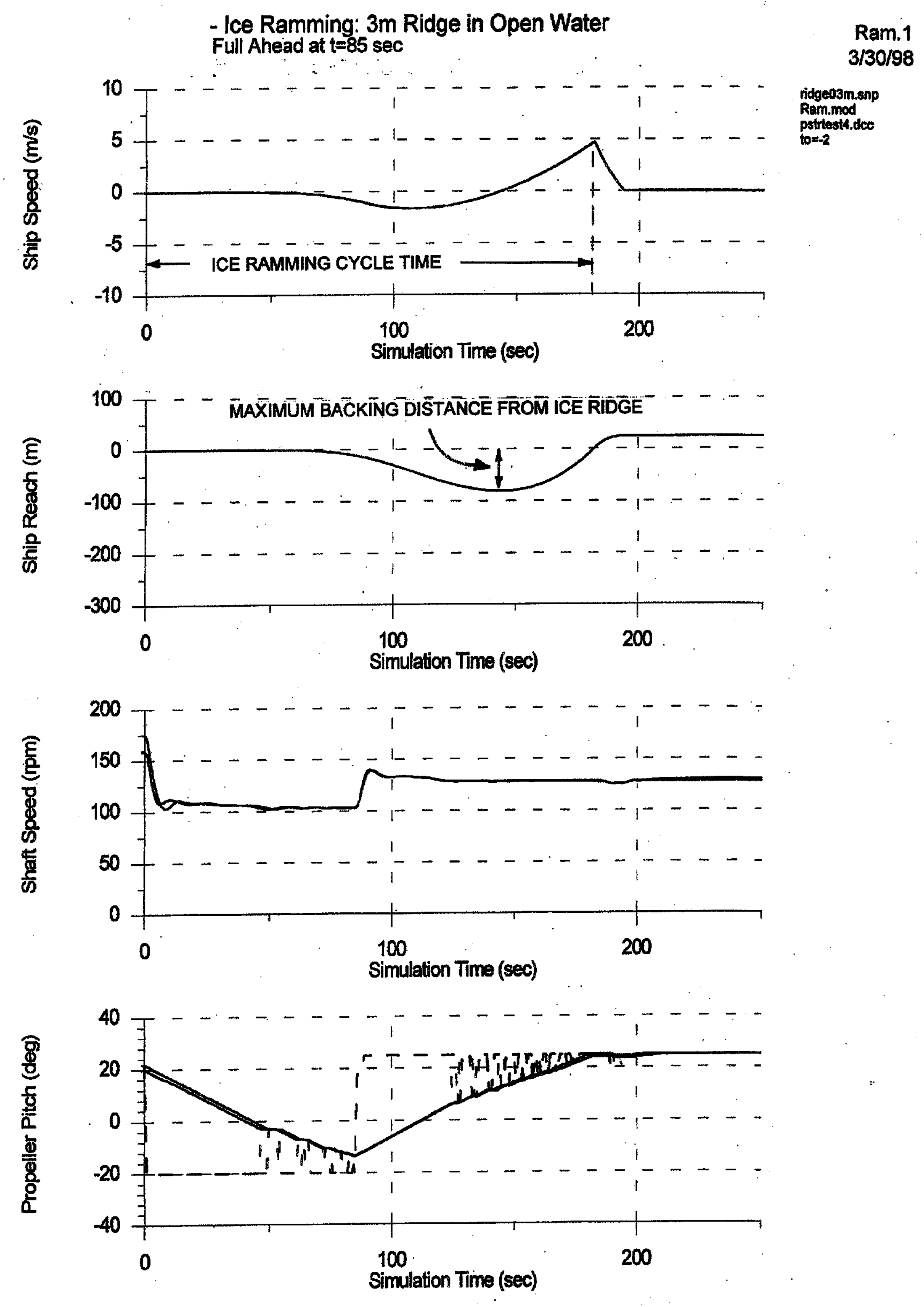

Figure 6.1 USCGC Polar Star Ice Ramming Simulation Results

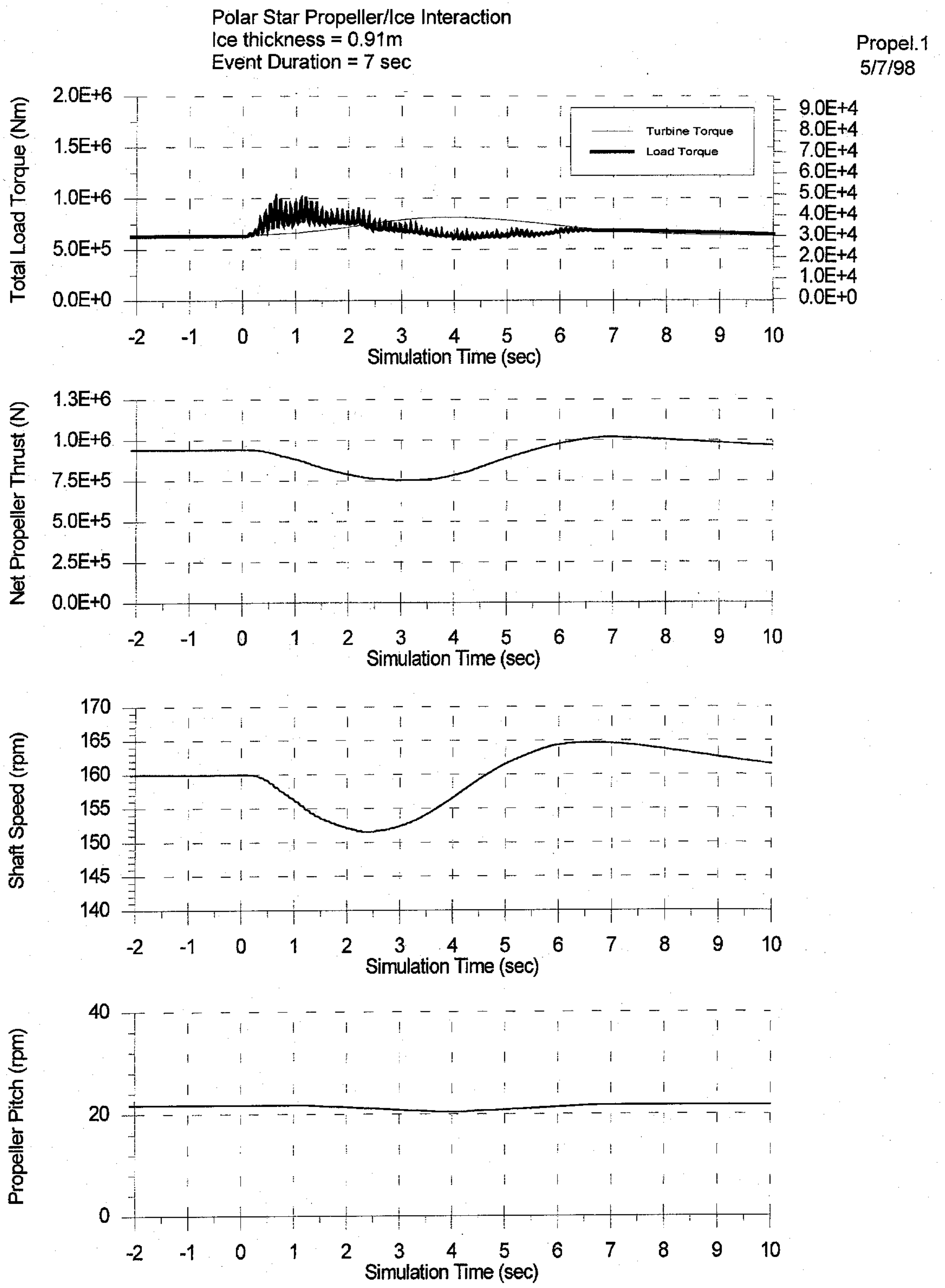

Figure 6.2 USCGC Polar Star Propeller/Ice Interaction Simulation Results

6.1.2.1 USCGC Polar Star Shaft Inertia Variation Effects

For the USCGC Polar Star the sensitivity of drivetrain inertia changes on propulsion system performance in terms of minimizing shaft speed drops was simulated and is summarized in Table 6.1 and illustrated in Figure 6.3 for a wing shaft. Inertia labelled 1.0X represents the baseline case shown in Figure 6.2. As expected, as inertia is increased, shaft speed drop is reduced during propeller/ice interaction events. Torque pulse blade passing frequency is dependent on shaft speed during the event.

Table 6.1 USCGC Polar Star Shaftline Inertia Sensitivity

Inertia	Shaft Speed Drop (%)	Shaftline Natural Frequence (Hz)	Torque Pulse Blade Passing Frequency Range (Hz)
0.5X	6.7	5.30	9.95 to 10.7
1.0X	5.2	3.75	10.1 to 10.7
2.0X	3.8	2.65	10.3 to 10.7
4.0X	2.6	1.88	10.4 to 10.7
8.0X	1.5	1.33	10.5 to 10.7

6.2 CCGS Louis St. Laurent Transient State Performance

6.2.1 CCGS Louis St. Laurent Ice Ramming Cycle

The ice ramming cycle verification simulation runs were performed under the following conditions:

- 3 shaft lines operating
- all 5 diesel generator sets operating
- ship services and auxiliary loads set to 1.46 MW @ p.f. = 0.8
- bubbler motors running and drawing 1.18 MW @ p.f. = 1.0.

A simulation run was initiated with the icebreaker in steady state at bollard conditions at maximum ahead propeller speeds. A bollard crash deceleration was then performed followed by a crash ahead acceleration to approximately 10 kn ahead ship speed. At approximately 10 kn ahead ship speed the icebreaker rammed the ice ridge and began to decelerate.

Ice ramming cycle simulation results are summarized in Figure 6.4. The ice ramming cycle time is about 120 seconds and the maximum distance the icebreaker backs up from the ice ridge to ram it at approximately 10 kn is about 125 m.

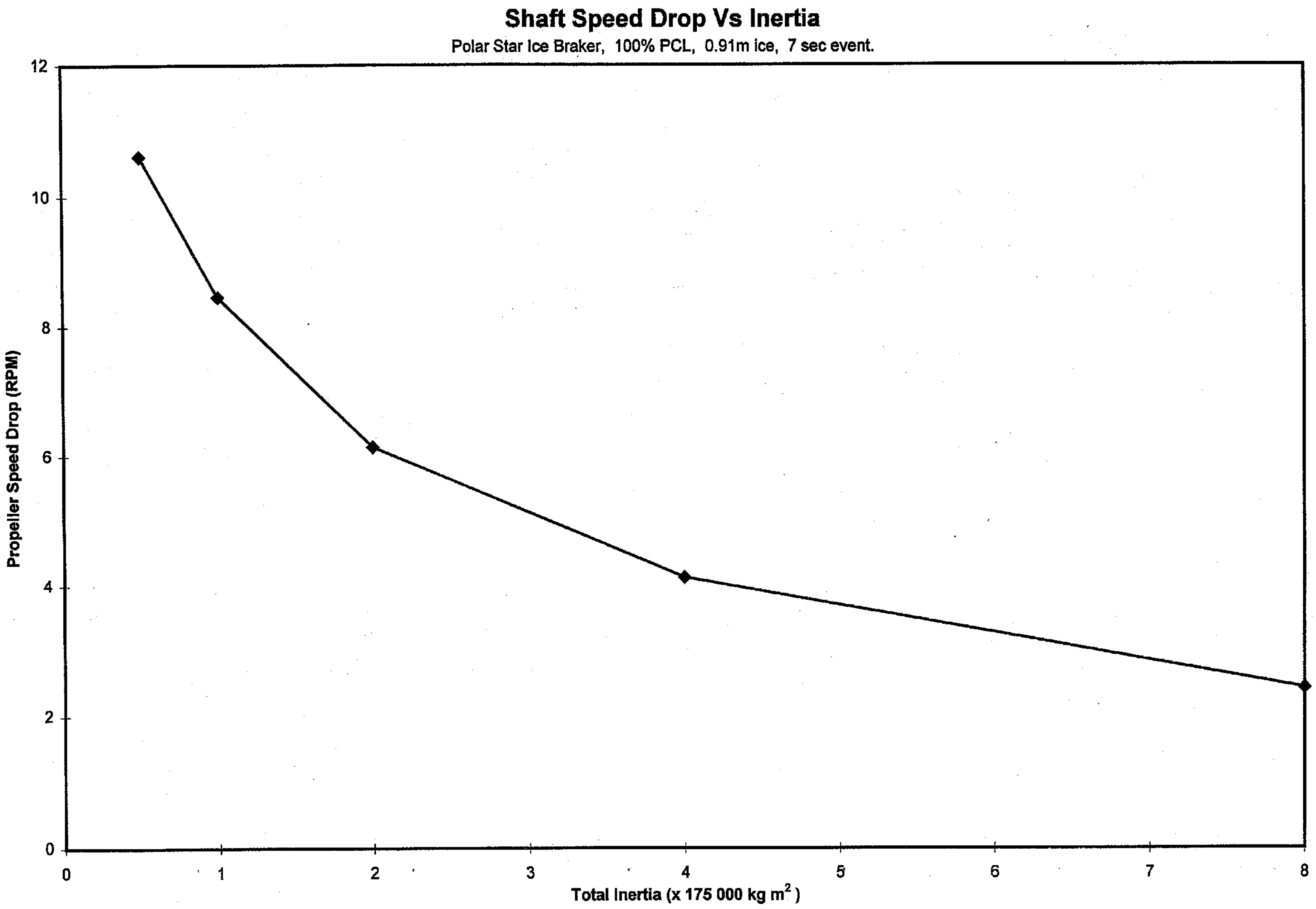

Figure 6.3 USCGC Polar Star Shaftline Inertia Sensitivity on Shaft Speed

6.2.2 CCGS Louis St. Laurent Propeller/Ice Interaction Events

The propeller/ice interaction verification simulation runs were performed under the following conditions:

- 3 shaft lines operating
- all 5 diesel generator sets operating
- ship services and auxiliary loads set to 1.46 MW @ p.f. = 0.8
- bubbler motors running and drawing 1.18 MW @ p.f. = 1.0
- ship moving at low speed in level ice
- ice block thickness varying up to half the propeller diameter

Simulation results were initiated with the icebreaker in steady state at maximum ahead propeller speeds in level ice conditions.

Simulation results for a typical propeller/ice interaction event with an ice block having a thickness of 0.91m is summarized in Figure 6.5 for a wing shaft.

6.2.2.1 CCGS Louis St. Laurent Shaft Inertia Variation Effects

For the CCGS Louis St. Laurent the sensitivity of drivetrain inertia changes on propulsion system performance in terms of minimizing shaft speed drops was simulated and is summarized in Table 6.2 and illustrated in Figure 6.6 for a wing shaft. Inertia labelled 1.0X represents the baseline case shown in Figure 6.5. As expected, as inertia is increased, shaft speed is reduced during propeller/ice interaction events. Torque pulse blade passing frequency is dependent on shaft speed during the event.

Table 6.2

CCGS Louis St. Laurent Shaftline Inertia Sensitivity

Inertia	Shaft Speed Drop (%)	Shaftline Natural Frequency (Hz)	Torque Pulse Blade Passing Frequency Range (Hz)
0.5X	17.3	13.9	8.27 to 10.0
1.0X	16.0	9.80	8.40 to 10.0
2.0X	14.3	6.93	8.57 to 10.0
4.0X	11.0	4.90	8.90 to 10.0
8.0X	8.0	3.46	9.20 to 10.0

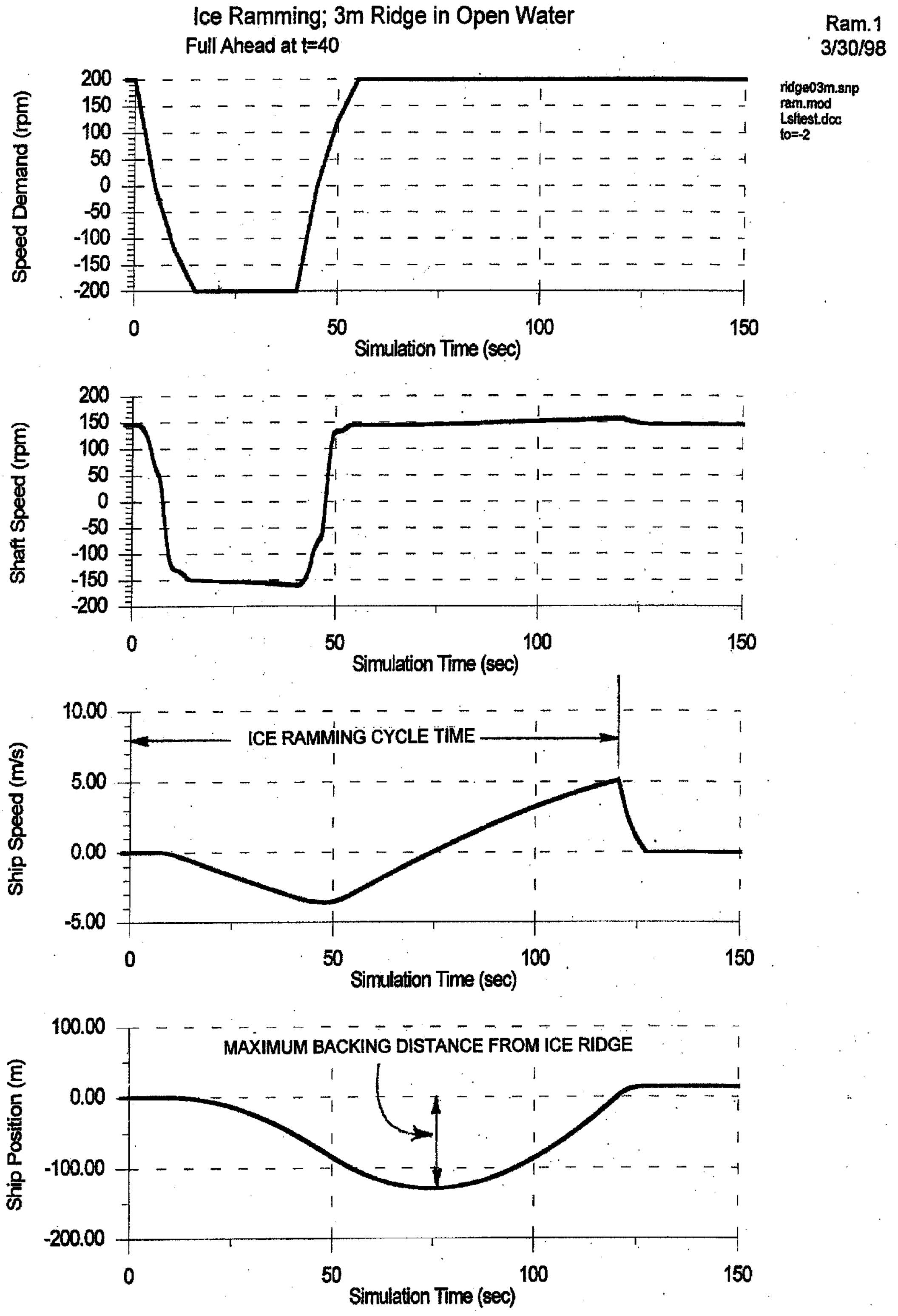

Figure 6.4 CCGS Louis St. Laurent Ice Ramming Simulation

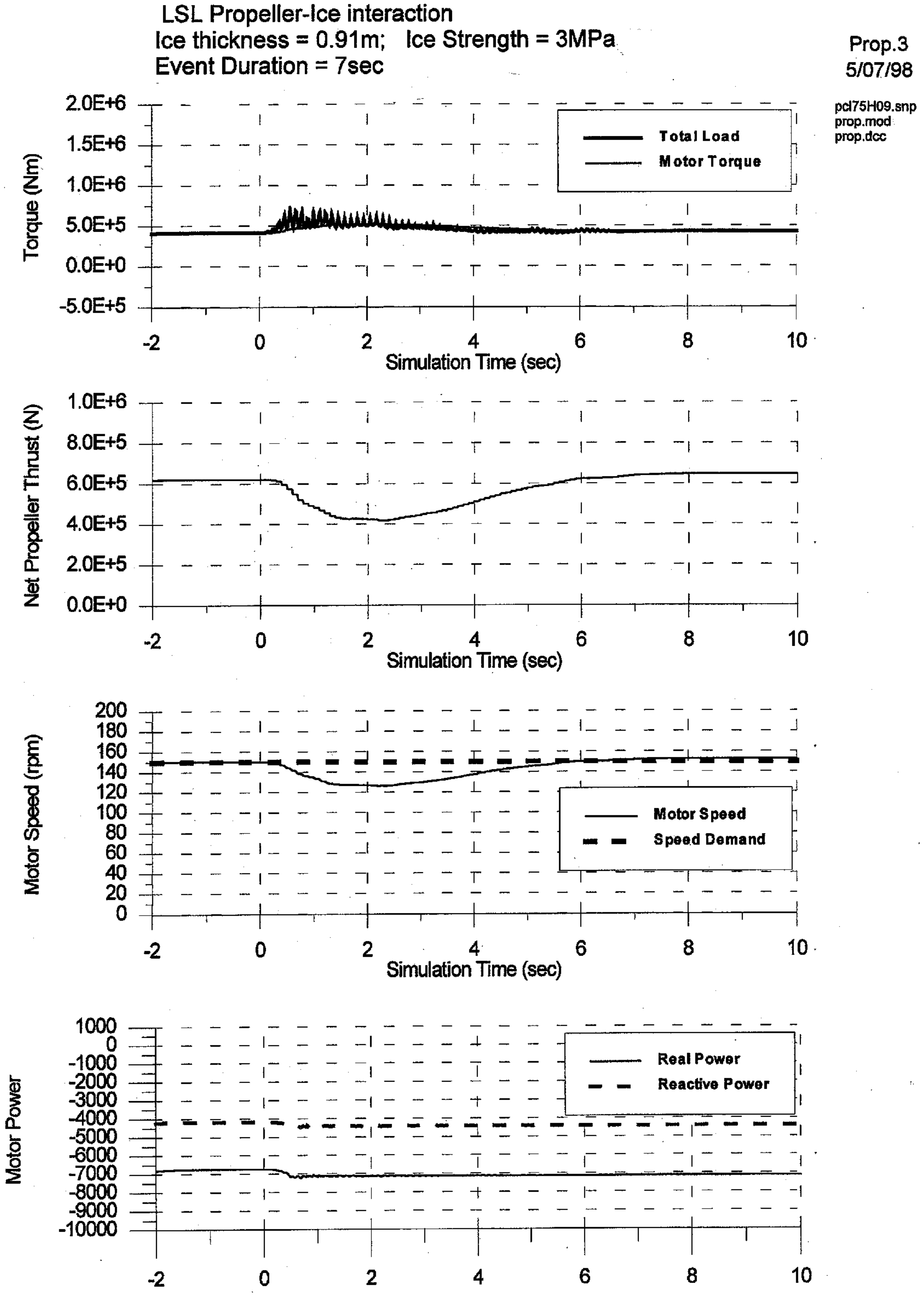

Figure 6.5 CCGS Louis St. Laurent Propeller/Ice Interaction Simulation Results

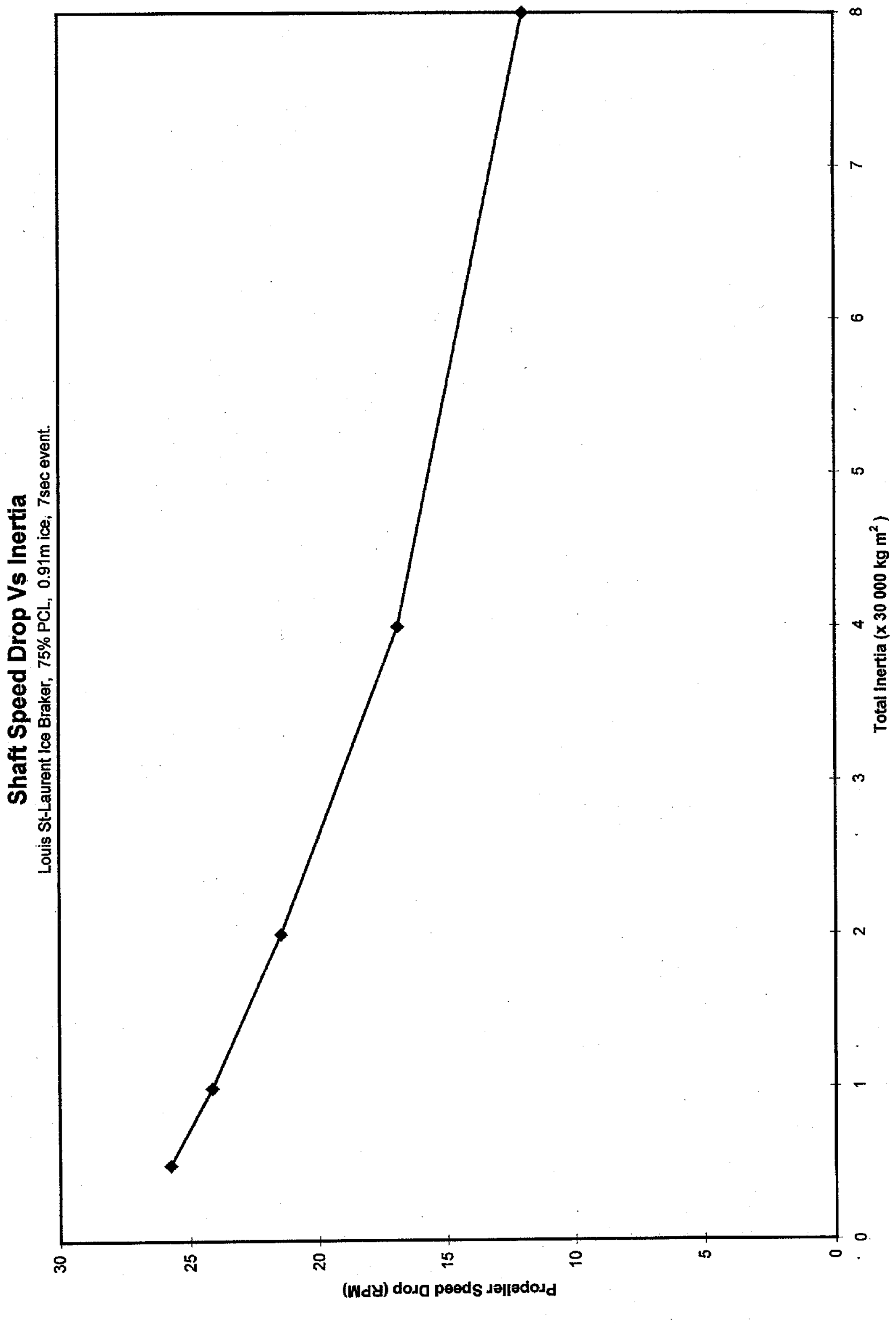

Figure 6.6 CCGS Louis St. Laurent Shaftline Inertia Sensitivity on Shaft Speed Results

6.3 Optimizing Transient State Propulsion System Performance

Optimizing transient performance of the propulsion system depends ultimately on the type of ship. For CAC ships, such as icebreakers, optimizing transient state performance may end up being a compromise between performance under different modes of operation such as ice ramming and propeller/ice interaction events. For Type ships, it may be possible to optimize the propulsion system during propeller/ice interaction events to a greater extent, since Type ships would not normally be called upon to ram ice; they would usually be assisted by a CAC ship under such conditions.

The goal of optimizing the transient performance of a ship during an ice ramming cycle is to reduce cycle time. Reducing cycle time under these conditions implies optimization of the response of the drivetrain during decelerations and accelerations to back the ship from the ice ridge and then cause it to move forward to ram the ridge. For decelerations and accelerations, increased drivetrain inertia slows the transient response of the propulsion system.

The goal of optimizing the transient performance of a ship during propeller/ice interaction events is to minimize the reduction in shaft speed if at all possible. Minimizing shaft speed drop will minimize the reduction in propeller thrust, since thrust is proportional to shaft speed squared. For a ship to maintain continuous progress in level ice conditions, the objective is to maximize thrust under these conditions. A combination of increased shaftline inertia and prime mover response will contribute to minimizing shaft speed drop during propeller/ice interaction events. When the drivetrain suddenly experiences an increased load from a block of ice interacting with a propeller, the increased power to match this load initially comes from the release of kinetic energy of the rotating system machinery with an accompanying reduction in shaft speed. A higher shaftline inertia contributes to supplying this power while minimizing shaft speed drop. As shaft speed is reduced, the propulsion control system then attempts to increase the rate of power generation from the prime movers to restore the initial point of operation.

Comparing the inertia sensitivity results for the USCGC Polar Star and CCGS Louis St. Laurent icebreakers in Tables 6.1 and 6.2 and Figures 6.3 and 6.6 respectively, the larger drivetrain inertia for the USCGC Polar Star certainly minimizes the drop in shaft speed.

Although increases in shaftline inertia act to minimize shaft speed fluctuations as a consequence of propeller load disturbances, care must be taken not to size the inertia of the shaftline so that its natural frequency coincides with potential sources of torque fluctuations from propeller blades during ice milling at a steady state shaft speed of frequent operation. Transient state coincidences are still bound to occur as shaft speed varies, but should not pose a problem if the event is of short duration. For the USCGC Polar Star, the results in Table 6.1 do not indicate any coincidences whereas for the CCGS Louis St. Laurent the results in Table 6.2 illustrate that transient coincidences will occur during propeller/ice interaction events.

7. CORRELATION WITH CCGS LOUIS ST. LAURENT TEST RESULTS

7.1 CCGS Louis St. Laurent Test Results

The only full-scale performance measurements available from the CCGS Louis St. Laurent for correlation with simulated propeller/ice interaction events, using the enhanced MSM model, are the time histories of torque load, thrust, and shaft speed for the event presented in Figure 7.1 (i.e. Figure 12 in [12]). For this propeller/ice interaction event, the shaft speed is observed to drop from 150 RPM to about 45 RPM for a maximum drop of 105 RPM in about 3.6 seconds, a particularly severe event.

Other data relevant to this event such as ship location during the event, ice concentration, and ice thickness are shown in Figures 7.2, 7.3, 7.4, (i.e. Figures 1,2,3 in [12]). Ice thickness in the August 14 time frame could have potentially varied from 4 to 8 feet. (or approximately 1.2 to 2.4 m.) from known measurements.

In Figure 7.1 it can be observed that the shaft speed at the end of the propeller/ice interaction event is lower than it was at the beginning. This difference in shaft speed also corresponds to a difference in hydrodynamic shaft torque load at the beginning and end of the event. Although not shown in Figure 7.1, a change in scheduled shaft speed demand likely occurred at some point in the manoeuvre, otherwise the shaft speed would have returned to its original value prior to the propeller/ice interaction event.

7.2 Simulated Propeller/Ice Interaction Events

In an attempt to correlate with the CCGS Louis St. Laurent full-scale performance measurements illustrated in Figure 7.1, a number of propeller/ice interaction scenarios were simulated as shown in Figures 7.5 to 7.7. For all simulated manoeuvres ship speed was initially in the range of 1 to 5 knots for level ice breaking and varied depending on the ice thickness simulated. In [12] it was concluded that low ship speeds in that range had no significant influence upon propeller/ice interactions loads. Since the propeller/ice interaction event shown in Figure 7.1 was a particularly severe event, the maximum ice block thickness of 2.3 m. or half of a propeller diameter was simulated.

During level ice breaking, attempting to minimize shaft speed drops during propeller/ice interactions and maintain shaft speed at its desired operating point, consistent with available power to do so, is usually the objective to maximize propeller thrust and, hence, ship speed. In Figure 7.5, the power control lever (PCL) throttle setting is not changed during the propeller/ice interaction event. Shaft speed drops from 150 RPM to a minimum of 90 RPM in about 2.2 seconds for a maximum drop of 60 RPM. As expected shaft speed returns to its original value following the event. This simulated scenario, however, does not correlate well with the results of Figure 7.1, and suggests the actual manoeuvre was performed differently.

In Figure 7.6, the PCL throttle setting is changed as shown during the propeller/ice interaction event to simulate backing off on power because of the severity of the event and commanding a lower shaft speed demand as suggested by the results of Figure 7.1. Shaft speed drops from 150 RPM to a minimum of 90 RPM in about 2.2 seconds for maximum drop of 60 RPM. For this simulated scenario, initial and end points of the correlate well with the results of Figure 7.1; however, the maximum speed drop is still 60 RPM instead of 105 RPM.

In Figure 7.7, the scenario in Figure 7.6 is repeated but with an ice torque load calibrated to be greater for a corresponding maximum ice block thickness equivalent to half of the diameter of the propeller. This was achieved by increasing the coefficient affecting the diameter of the propeller in the maximum and average torque equations for the ice load model; i.e. the coefficient designated c_8 in the equation on page 17 was increased from a nominal value of 3.04 to 3.40. Shaft speed now drops from 150 RPM to a minimum of 55 RPM in about 2.3 seconds for a drop of 95 RPM compared to 105 RPM in Figure 7.1. This simulated scenario correlates reasonably well with the results of Figure 7.1.

Although no data were available to precisely determine how the PCL throttle setting was controlled during the propeller/ice interaction event shown in Figure 7.1, the sensitivity of shaft speed response to different PCL throttle settings and some attempt at further calibrating the ice torque load as a function of maximum ice thickness illustrates that the model can be made to correlate reasonably well with the results obtained from the CCGS Louis St. Laurent. The results also suggest that the form of the enhanced MSM propeller/ice interaction model provides sufficient flexibility for further calibration as required.

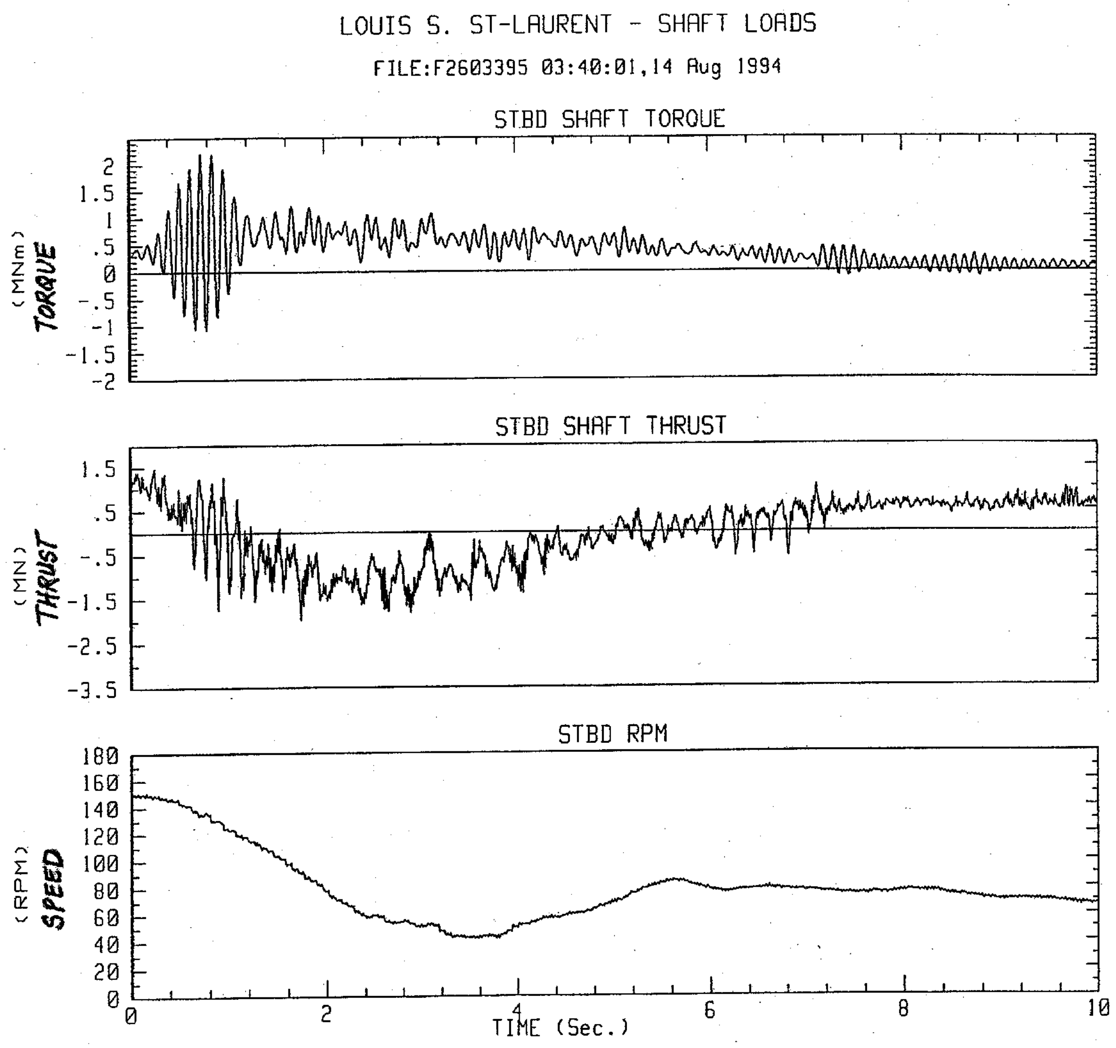

Figure 7.1 CCGS Louis St. Laurent Sample Starboard Shaft Torque, Thrust, and Speed Measurements [12]

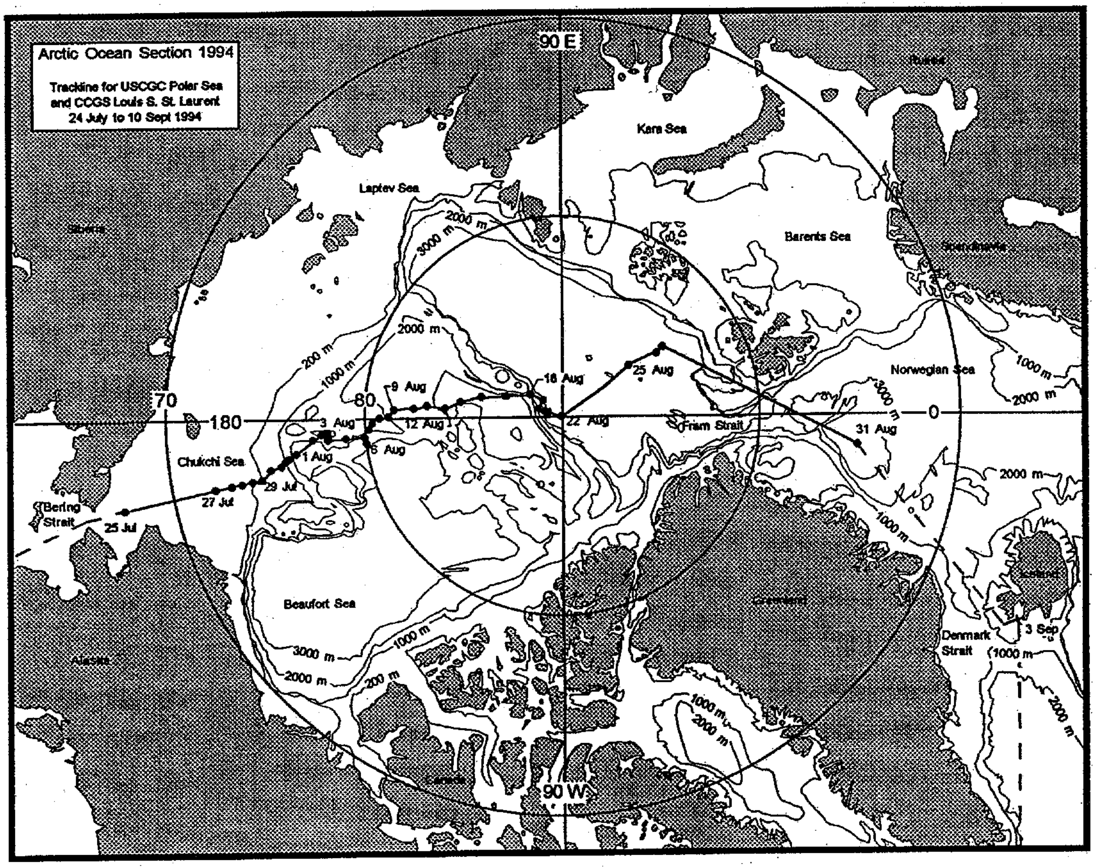

Figure 7.2 CCGS Louis St. Laurent Trackline for Ice Tests [12]

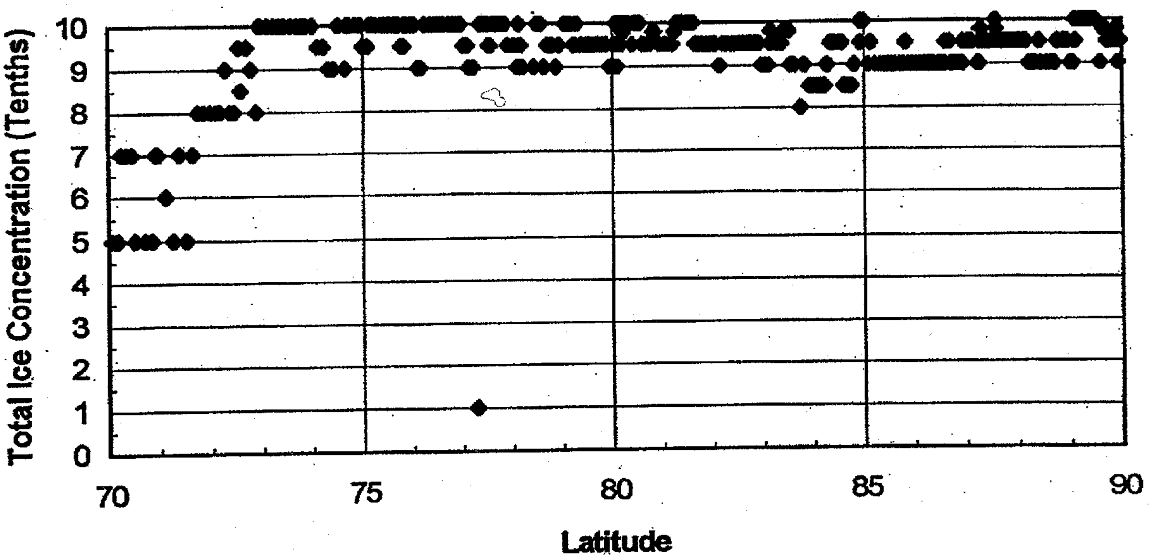

Figure 7.3 Ice Connection from the Ice Edge to the North Pole [12]

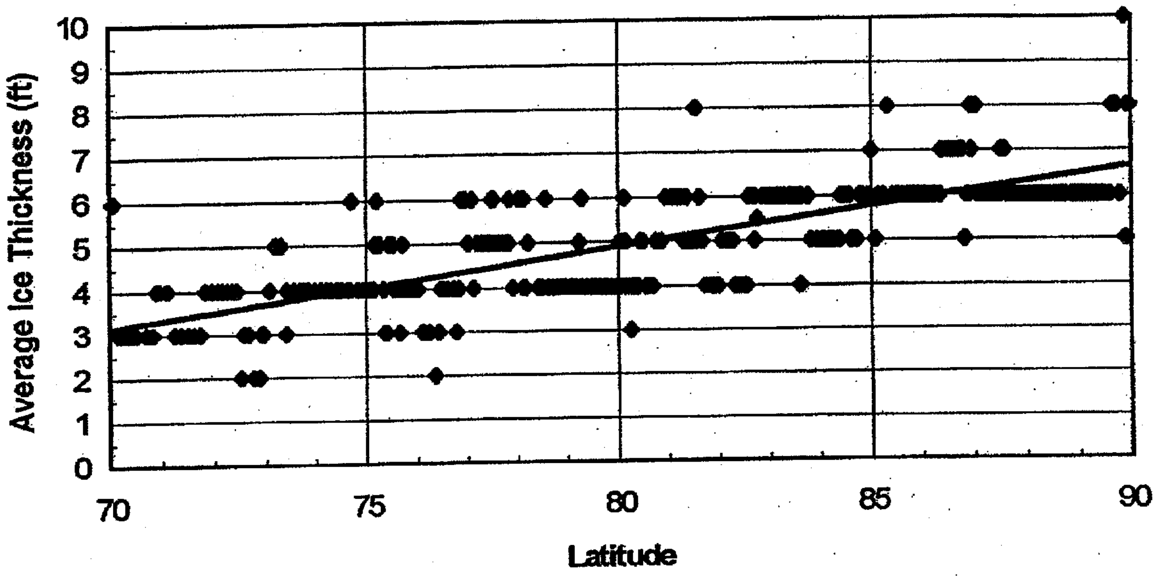

Figure 7.4 Average Ice Thickness from the Ice Edge to the North Pole [12]

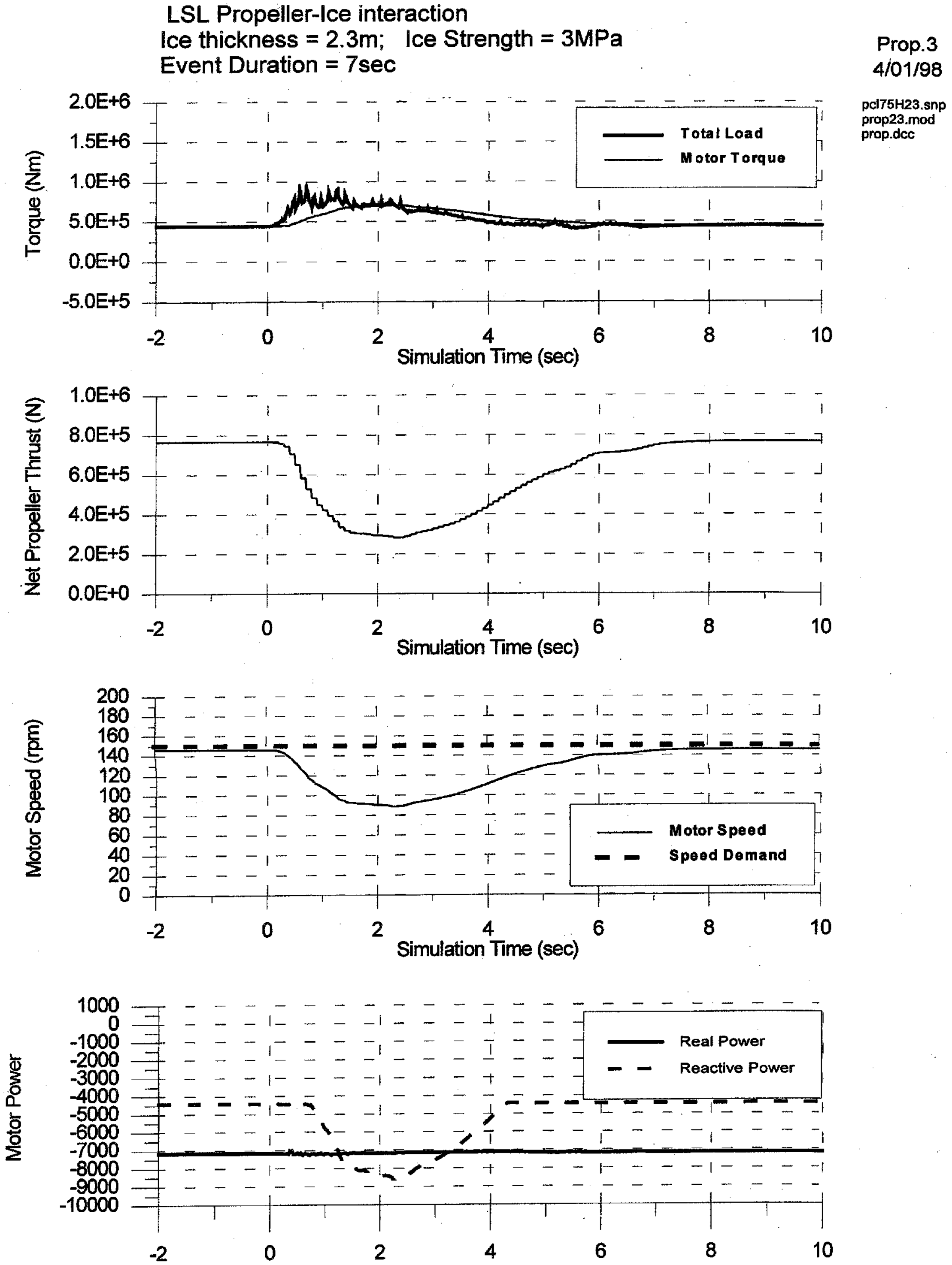

Figure 7.5 CCGS Louis St. Laurent Simulated Propeller/Ice Interaction Test

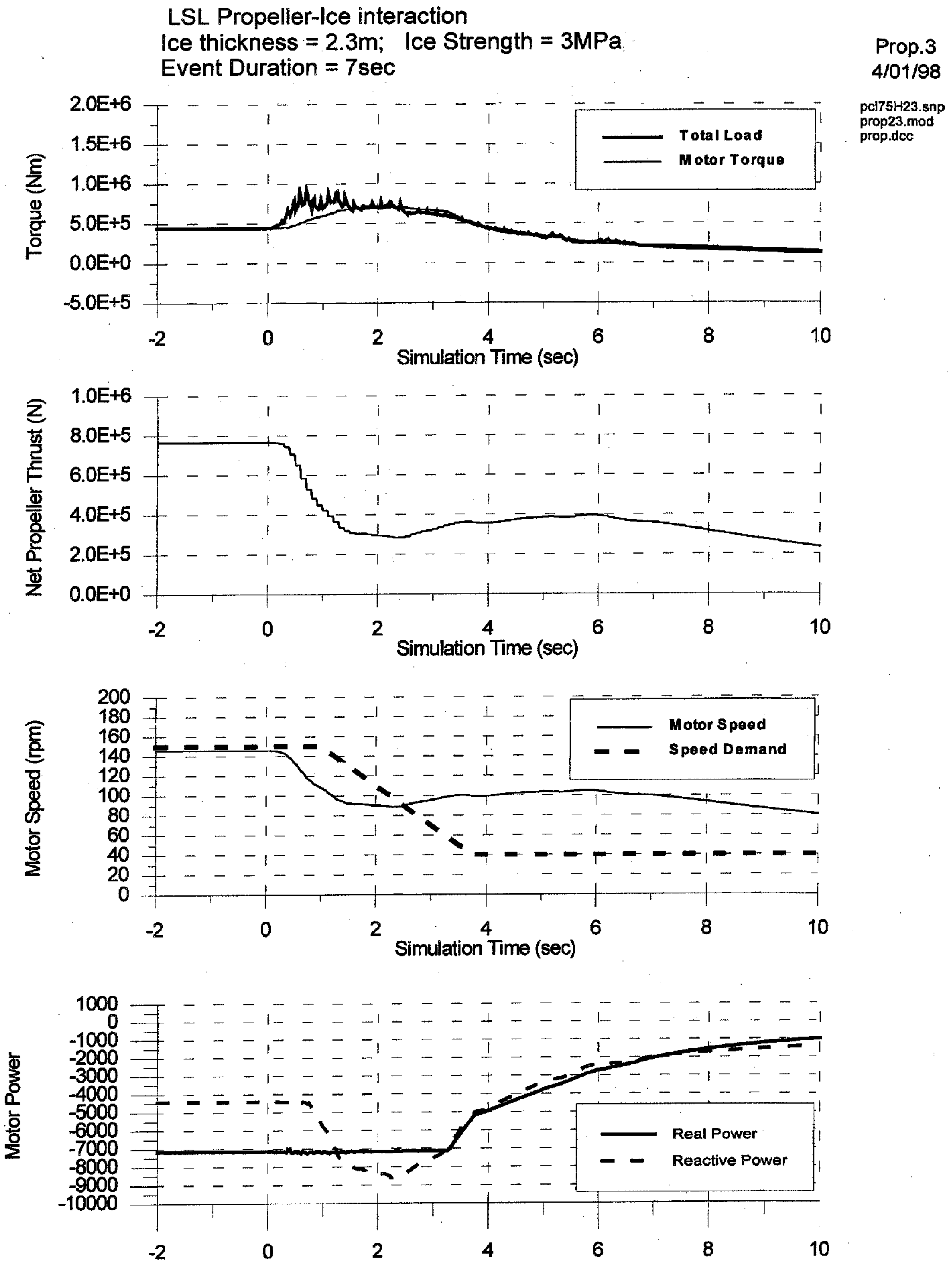

Figure 7.6 CCGS Louis St. Laurent Simulated Propeller/Ice Interaction Test

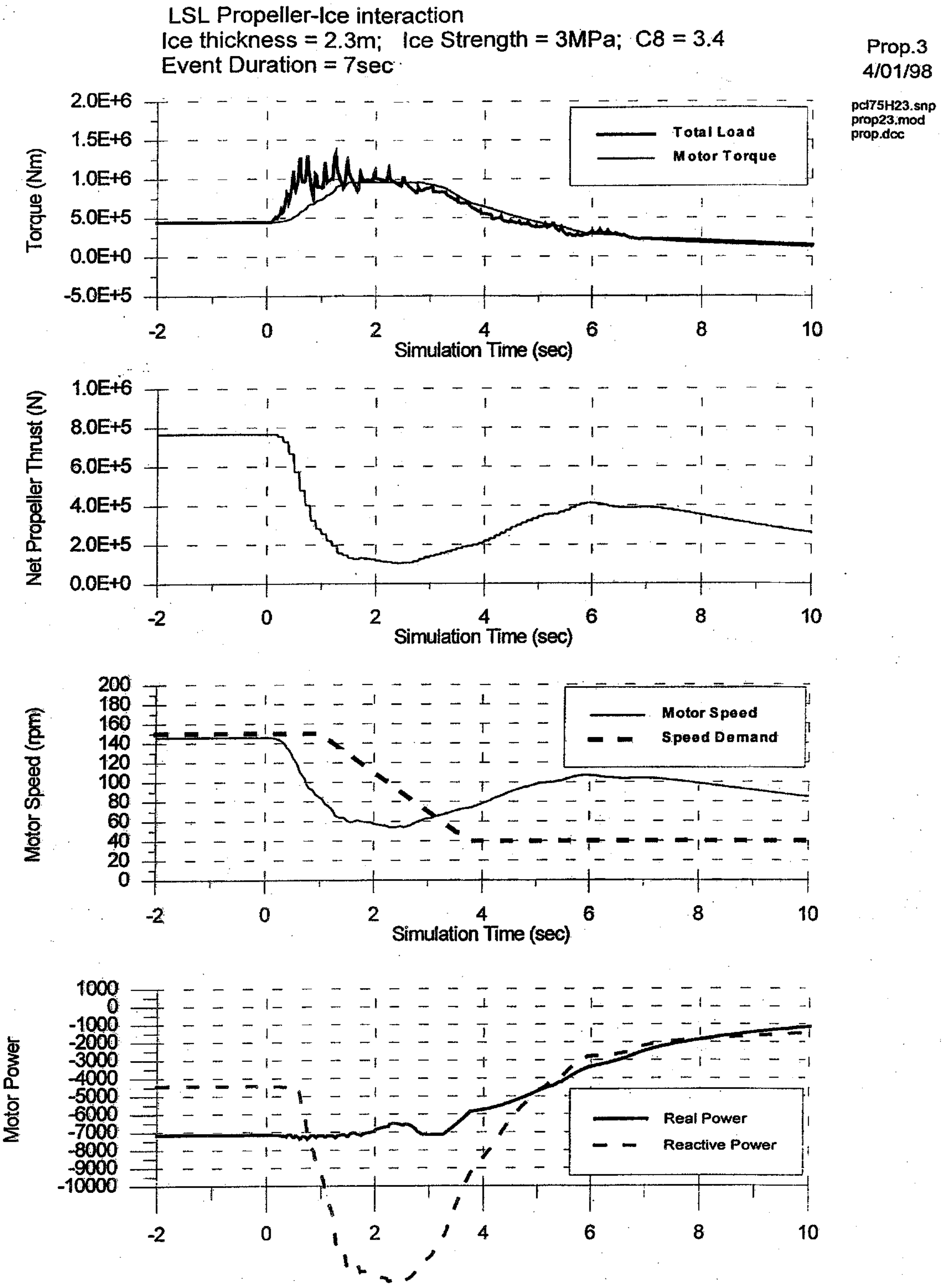

Figure 7.7 CCGS Louis St. Laurent Simulated Propeller/Ice Interaction Test

8. CORRELATION WITH USCGC POLAR STAR TEST RESULTS

8.1 USCGC Polar Star Test Results

The available full-scale performance measurements from the Polar Star for correlation with simulated propeller/ice interaction events, using the enhanced MSM model, are summarized in [17,18]. Since the objective of the ship tests was to primarily characterize propeller loads, the majority of the data collected describes the forces and moments applied to the propeller. Furthermore, the data were collected over intervals of time not greater than 5 seconds. From the available data, shaft speed was found to be a suitable parameter for correlating simulated to actual performance of the propulsion system.

Shaft speed is a good measure of propulsion system performance during propeller/ice interaction events and key characteristics to note about it to correlate simulated and actual shaft speed measurements are:

- maximum drop in shaft speed
- time to reach maximum drop in shaft speed
- duration of propeller/ice interaction event

These characteristics are also illustrated in Figure 8.1.

Of the many events recorded during the USCGC Polar Star ice tests, only a few of them show significant shaft speed deviations for the gas turbine icebreaking mode of operation (where the wing shaft speeds are nominally 160 RPM without ice interference). Figure 8.2 presents a plot of observed occurrences corresponding to different magnitudes in the maximum drop in shaft speed from 160 RPM. Figure 8.3 presents a plot of the time to reach the maximum drop in shaft speed corresponding to different magnitudes in the maximum drop in shaft speed from 160 RPM. A typical time history trace of USCGC Polar Star propeller/ice interaction events is presented in Figures 8.4. Salient event characteristics for this event are:

• Maximum speed drop:	5 RPM
• Time to reach maximum drop in shaft speed:	1.7 seconds
• Duration of event:	4 seconds

8.2 Simulated Propeller/Ice Interaction Events

Simulated tests were run to illustrate the interrelationship among key parameters related to shaft speed deviations and ice loads for the USCGC Polar Star. A multidimensional or carpet plot was generated and is presented in Figure 8.5 to highlight the interrelationship among the following parameters:

- maximum drop in shaft speed
- time to reach maximum drop in shaft speed
- duration of propeller/ice interaction event
- ice block thickness

This plot is a convenient means of visualizing the interrelationship among key parameters that influence overall propulsion system performance during propeller/ice interaction events.

On the assumption that ice loads acting on a propeller can be predicted reasonably well using the enhanced MSM model, the full-scale performance measurements summarized in Figure 8.2 and 8.3 for the USCGC Polar Star were superimposed on this plot to estimate the thickness of an ice block that could have interacted with the propeller. With the exception of one point outside the ice thickness envelope (i.e. maximum shaft speed drop of 9% in about 1.4 seconds), all of the full-scale shaft speed measurements can be reproduced using the enhanced MSM propeller/ice interaction model with JRPA#6 coefficients specified for the maximum and average torque profiles. It should be noted that the exception point can be reproduced by the model if the ice load torque coefficients are calibrated further as was shown for the CCGS Louis St. Laurent in Section 7.2 for a very severe propeller/ice interaction event.

A typical simulated time history in Figure 8.6 for comparison with the actual one in Figure 8.4, also illustrates a good correlation with the USCGC Polar Star full-scale measurements in terms of shaft speed response with respect to maximum speed drop, time to reach this condition, and duration of the propeller/ice interaction event.

Monitoring shaft speed, maximum drop in shaft speed, and time to reach maximum drop in shaft speed for propeller/ice interaction events would certainly yield useful information on the propulsion system performance of Arctic Class and Type ships navigating in ice-covered waters. These three condition indicators could be stored in a historical database that could yield important information on the number of occurrences and severity of shaft speed deviations during propeller/ice interaction events. Such data would provide a basis for the progressive evolution of design standards for Arctic Class and Type ships. Furthermore, the data would continue to enhance models used to simulate overall propulsion system performance and relate it to ice load conditions.

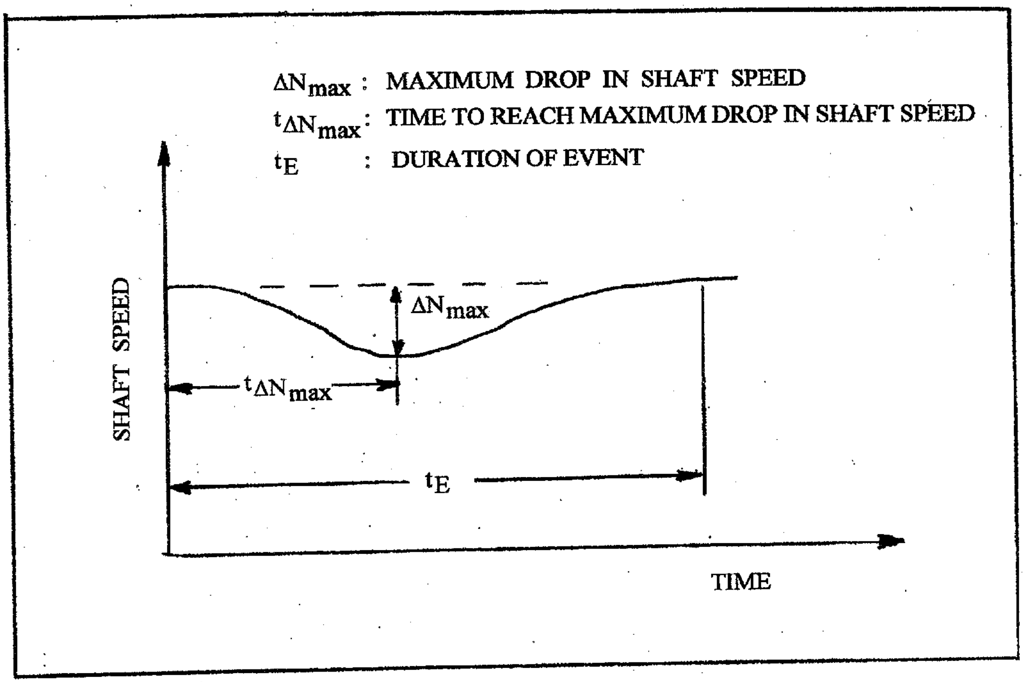

Figure 8.1 Key Characteristics for Shaft Speed Measurement During Propeller/Ice Interaction Events

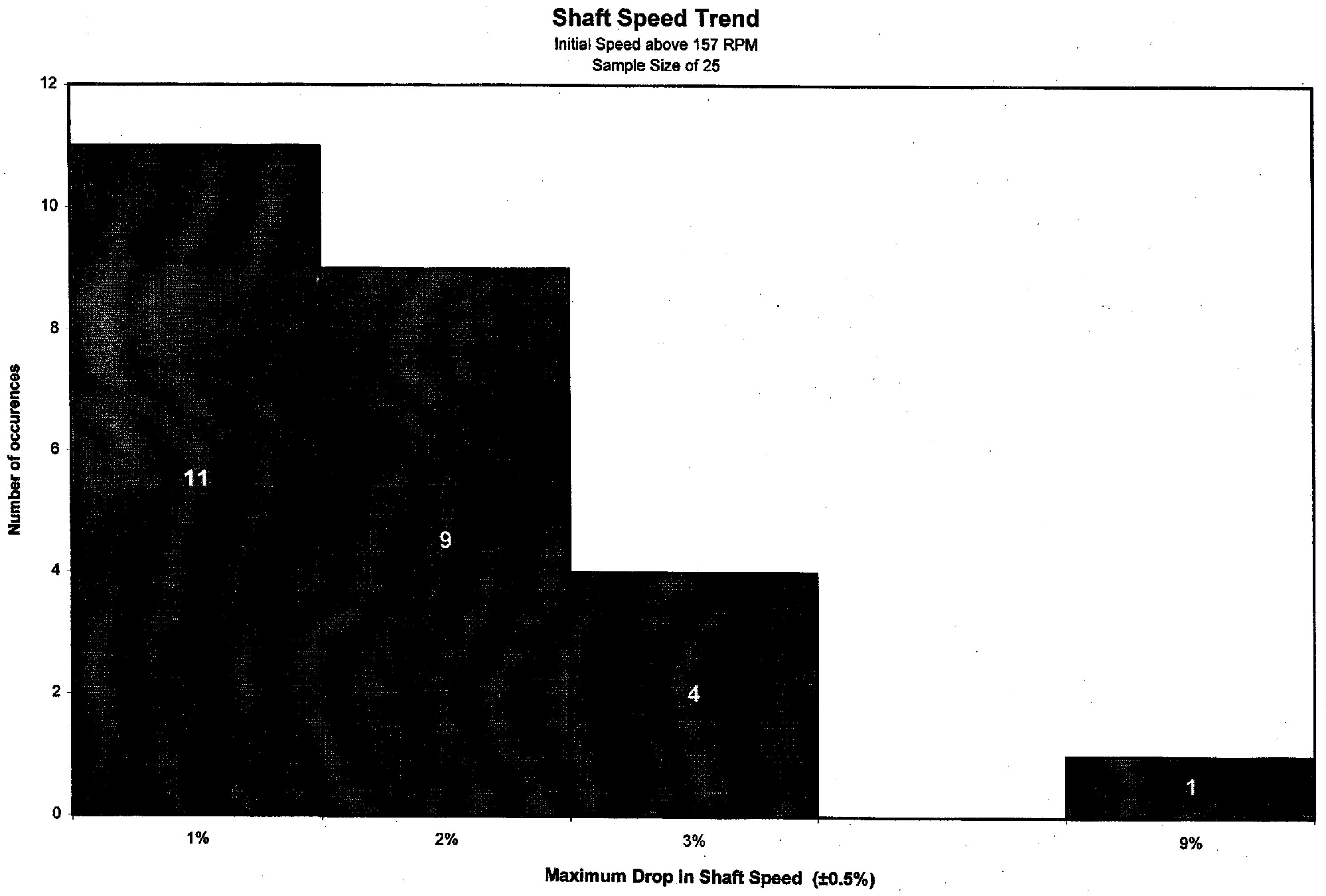

Figure 8.2 USCGC Polar Star Number of Occurrences of Shaft Speed Drops from Initial Speed of About 160 RPM

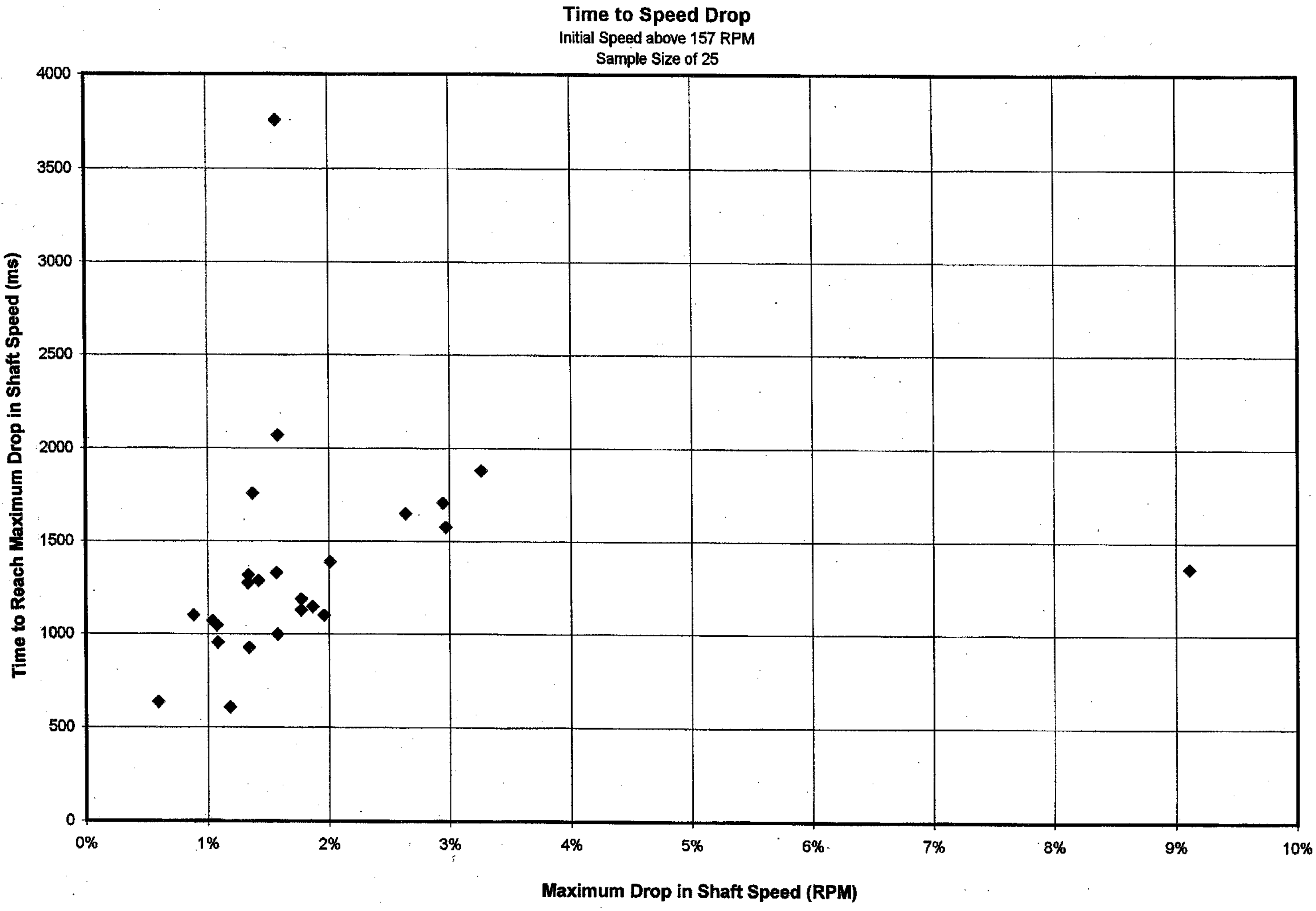

Figure 8.3 USCGC Polar Star Time to Reach Maximum Speed Drops from Inintial Speed of About 160 RPM

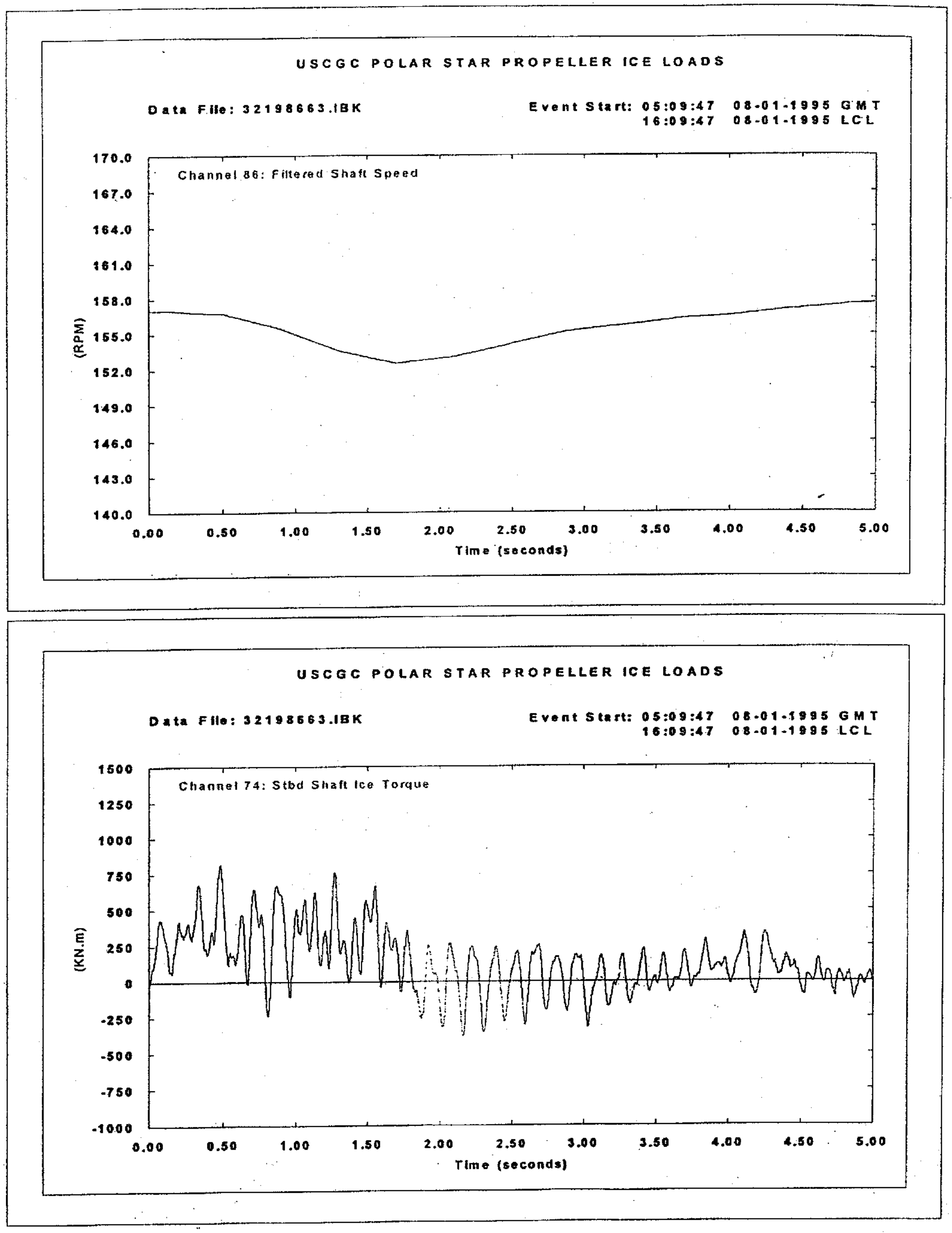

Figure 8.4a USCGC Polar Star Sample Speed and Torque Measurements

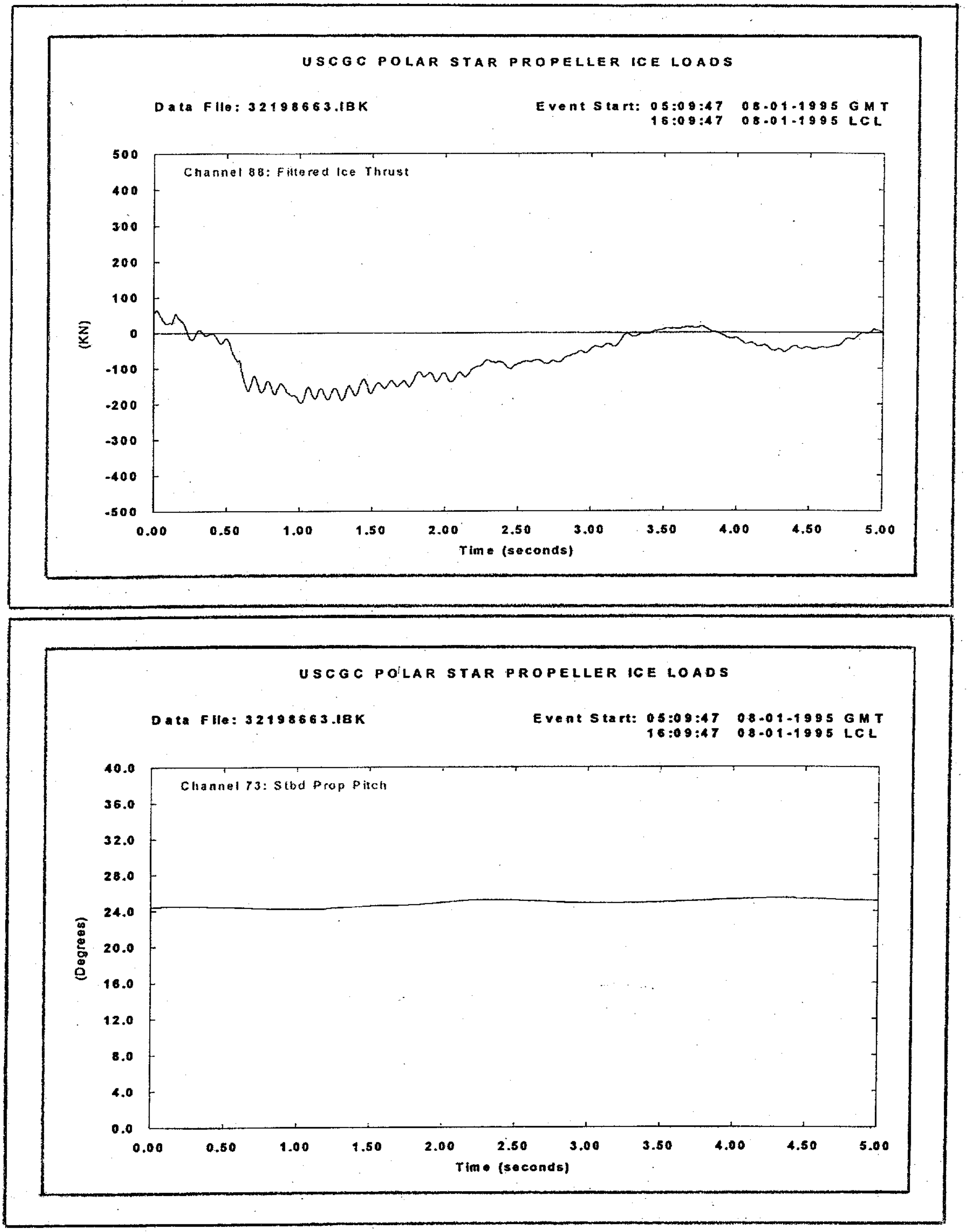

Figure 8.4b USCGC Polar Star Sample Shaft Thrust and Propeller Pitch Measurements

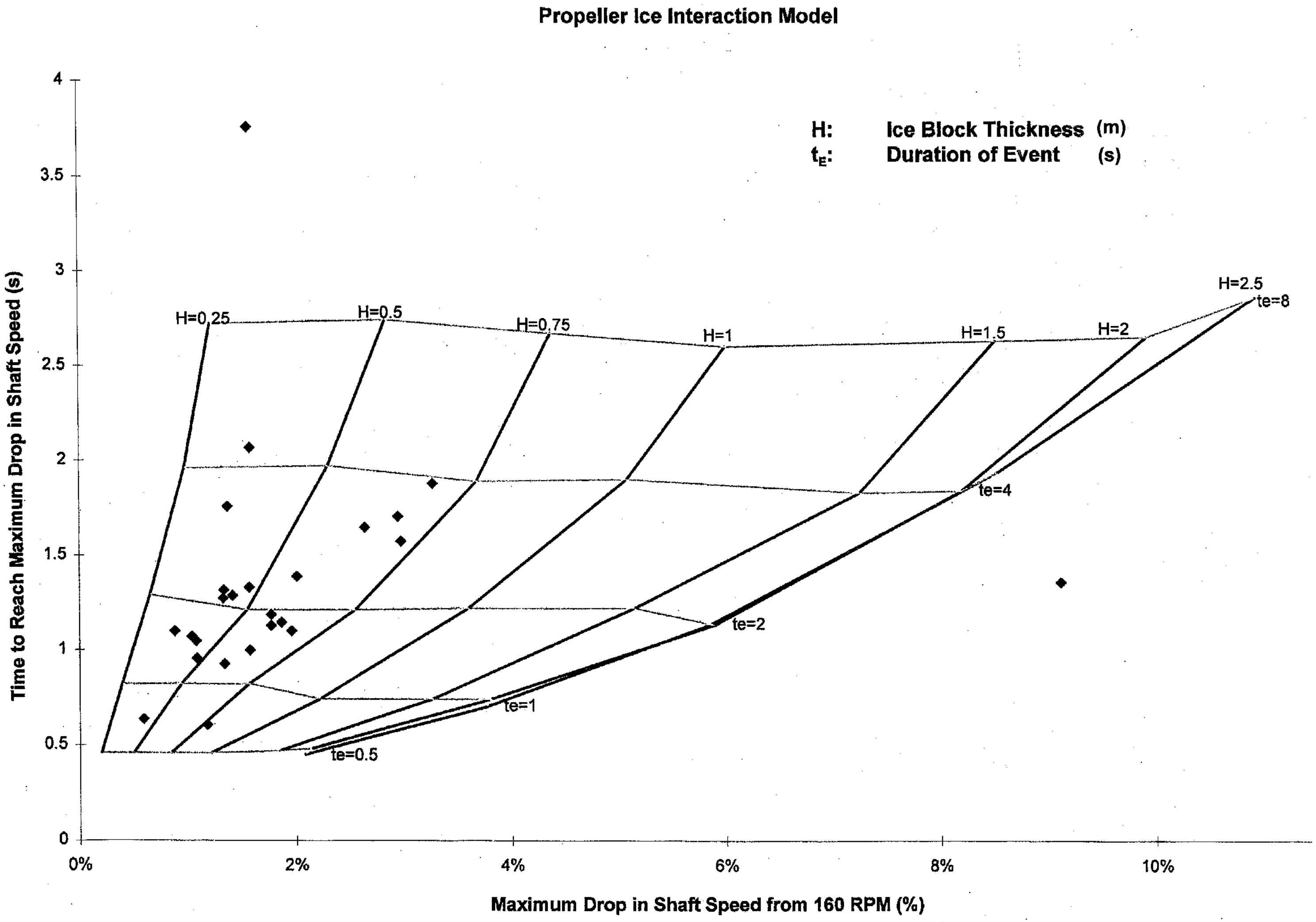

Figure 8.5 USCGC Polar Star MSM Propeller/Ice Interaction Simulation Results

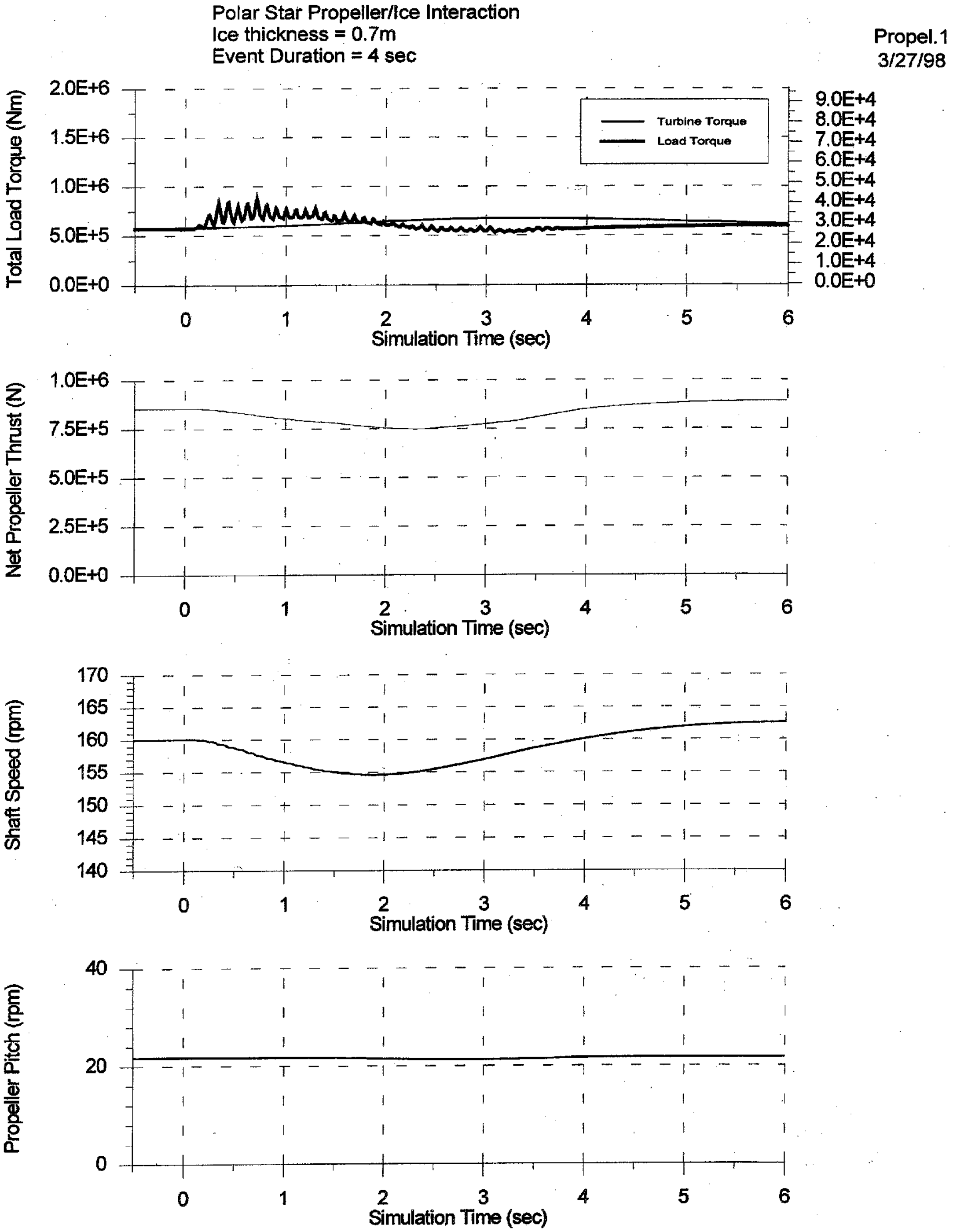

Figure 8.6 USCGC Polar Star Simulated Propeller/Ice Interaction Test

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9. CONCLUSIONS AND RECOMMENDATIONS

An enhanced propeller/ice interaction model has been developed and implemented as a new MSM component. This model was derived from JRPA #6 work targeted at developing a DLM to evolve improved design standards for the propellers and propulsion system of Arctic Class and Type ships. The model is useful in that it relates dynamic propulsion system performance to time varying propeller/ice load conditions and, hence, provides a means of investigating the optimum propulsion system configuration for ships navigating ice-covered waters.

The enhanced MSM propeller/ice interaction model has been shown to correlate reasonably well with available full-scale performance measurements for the CCGS Louis St. Laurent and USCGC Polar Star.

Shaft speed has been found to be a very good parameter to characterize the behaviour and performance of the propulsion system as a whole and to provide a means of calibrating a propeller/ice interaction model. More specifically, the maximum drop in shaft speed and the time to reach that point during a propeller/ice interaction event are key characteristics to note.

It is recommended that shaft speed be monitored as a useful condition indicator of propulsion system performance during propeller/ice interaction events for both Arctic Class and Type ships. Having this kind of information in a historical database can yield important information on the number of occurrences and severity of shaft speed deviations during propeller/ice interaction events. This would contribute to the progressive evolution of suitable design standards for Arctic Class and Type ships.

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APPENDIX 1

USCGC Polar Star Model Block Diagram Nomenclature

CP_{dmi}	diesel charge pressure
E_{mci}	motor back emf
G_{mi}	motor torque
G_{pni}	propeller load torque
G_{gLi}	diesel generator load
I_{DG}	number of active diesel generator sets
I_{gi}	generator current
I_{mai}	motor armature current
I_{maDi}	motor armature current demand
N_{dgi}	diesel generator speed
N_{dgRi}	diesel engine reference speed
N_{mPLi}	propeller shaft speed demand before cutback
N_{mSRi}	propeller shaft speed demand
N_{si}	propeller shaft speed
P_{BMD}	bubbler real power demand
P_{gDpi}	generator real power demand
P_{gLi}	generator real power output
PLC_{Di}	power lever speed demand
P_{mLi}	motor real power consumption
P_{mPri}	power regulator multiplier
P_{SSD}	ship services real power demand
Q_{BMD}	bubbler reactive power demand
Q_{gDpi}	generator reactive power demand
Q_{gLi}	generator reactive power output
Q_{mLi}	motor reactive power consumption
Q_{SSD}	ship service reactive power demand
t_i	ice thickness
T_{pi}	propeller thrust
V_h	ship speed
V_{mai}	motor armature voltage
X_h	ship position
ϕ_{mAi}	motor air gas flux amplitude
ϕ_{mDi}	per unit motor flux
ϕ_v	motor pole magnetic flux

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APPENDIX 2

CCGS Louis St. Laurent Model Block Diagram Nomenclature

CP_{dmi}	diesel charge pressure
E_{mci}	motor back emf
G_{mi}	motor torque
G_{pni}	propeller load torque
G_{gLi}	diesel generator load
I_{DG}	number of active diesel generator sets
I_{gi}	generator current
I_{mai}	motor armature current
I_{maDi}	motor armature current demand
N_{dgi}	diesel generator speed
N_{dgRi}	diesel engine reference speed
N_{mPLi}	propeller shaft speed demand before cutback
N_{mSRi}	propeller shaft speed demand
N_{si}	propeller shaft speed
P_{BMD}	bubbler real power demand
P_{gDpi}	generator real power demand
P_{gLi}	generator real power output
PLC_{Di}	power lever speed demand
P_{mLi}	motor real power consumption
P_{mPri}	power regulator multiplier
P_{SSD}	ship services real power demand
Q_{BMD}	bubbler reactive power demand
Q_{gDpi}	generator reactive power demand
Q_{gLi}	generator reactive power output
Q_{mLi}	motor reactive power consumption
Q_{SSD}	ship service reactive power demand
t_i	ice thickness
T_{pi}	propeller thrust
V_h	ship speed
V_{mai}	motor armature voltage
X_h	ship position
ϕ_{mAi}	motor air gas flux amplitude
ϕ_{mDi}	motor air gas flux demand
ϕ_v	motor pole magnetic flux

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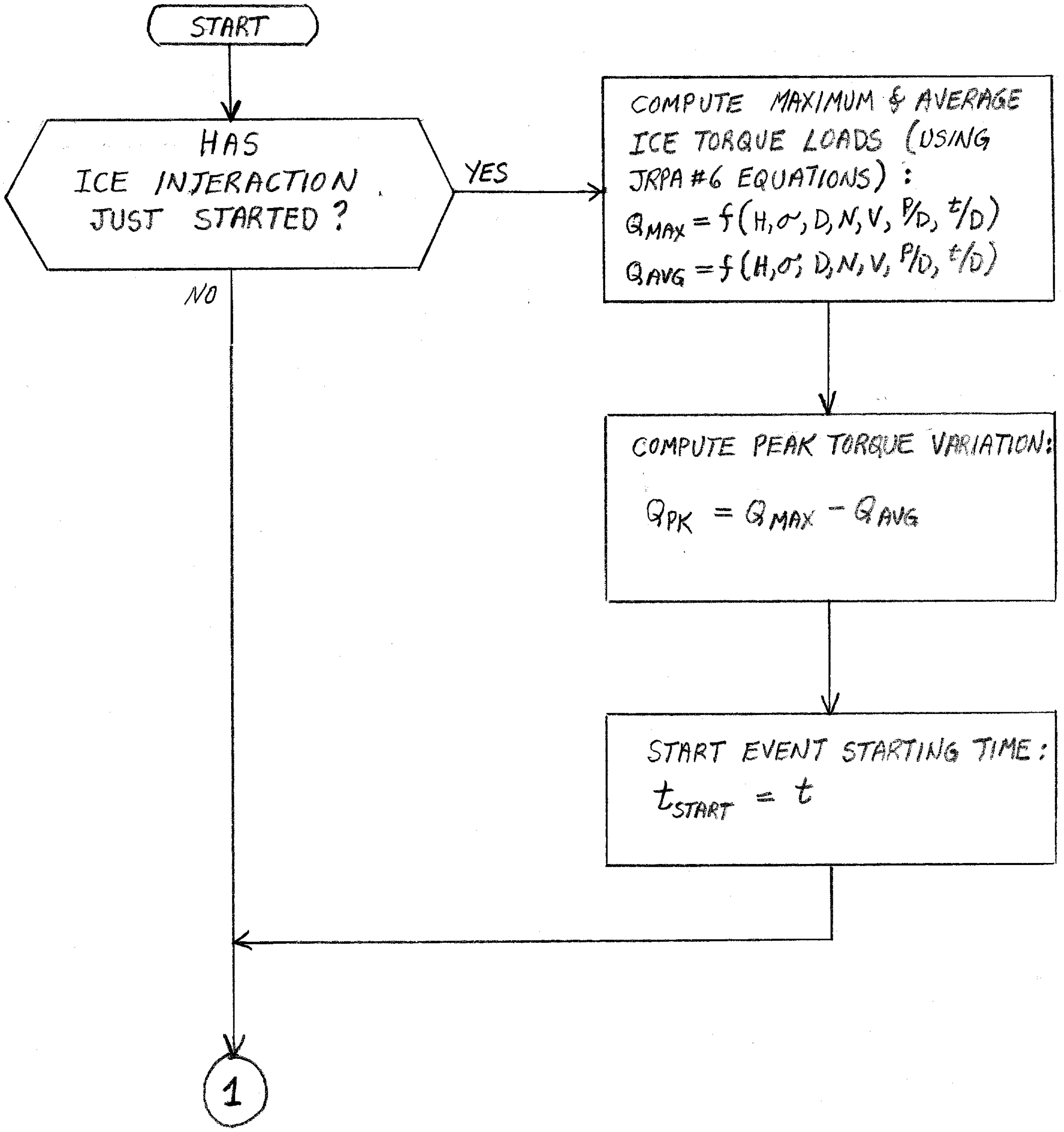
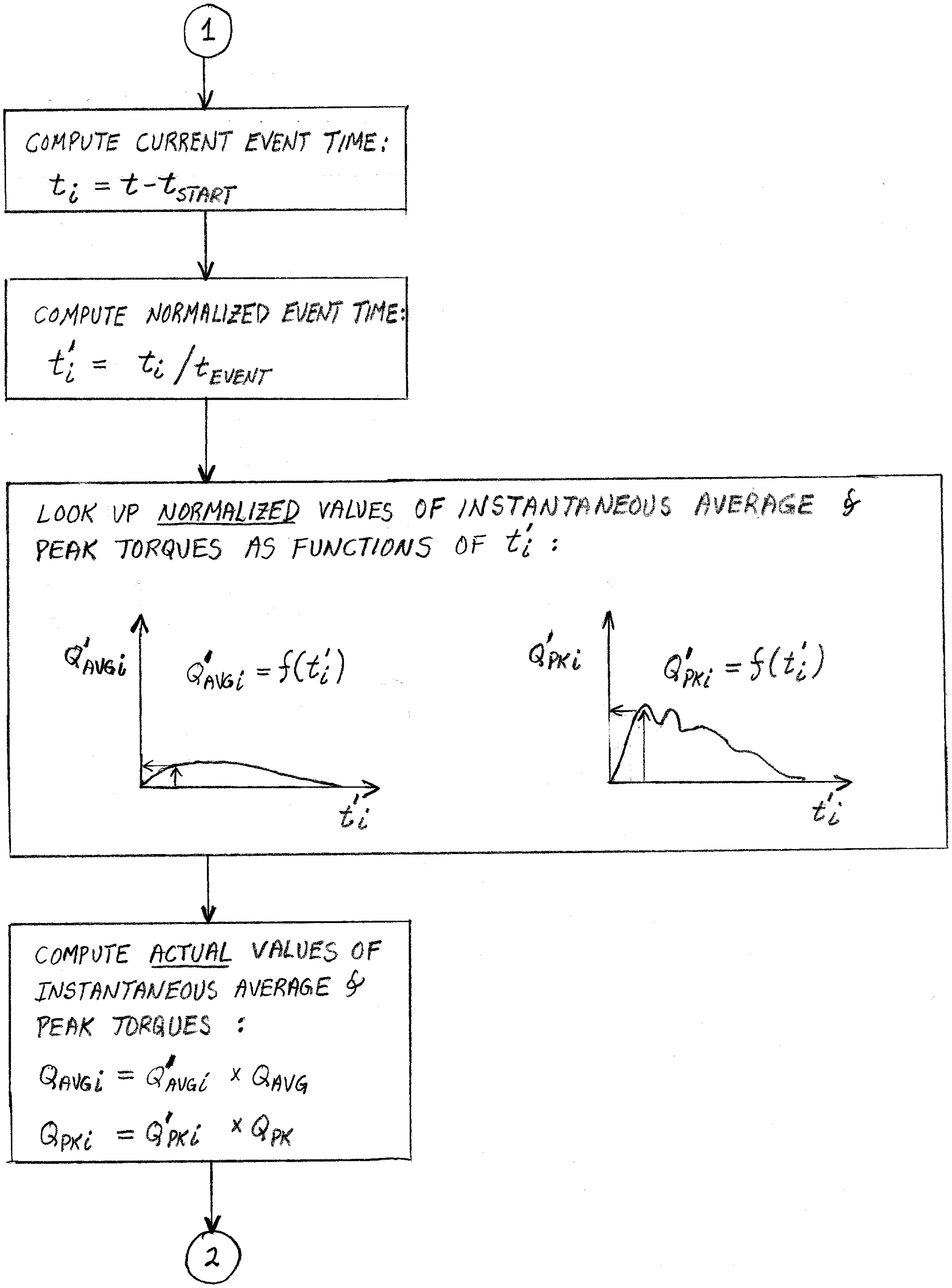
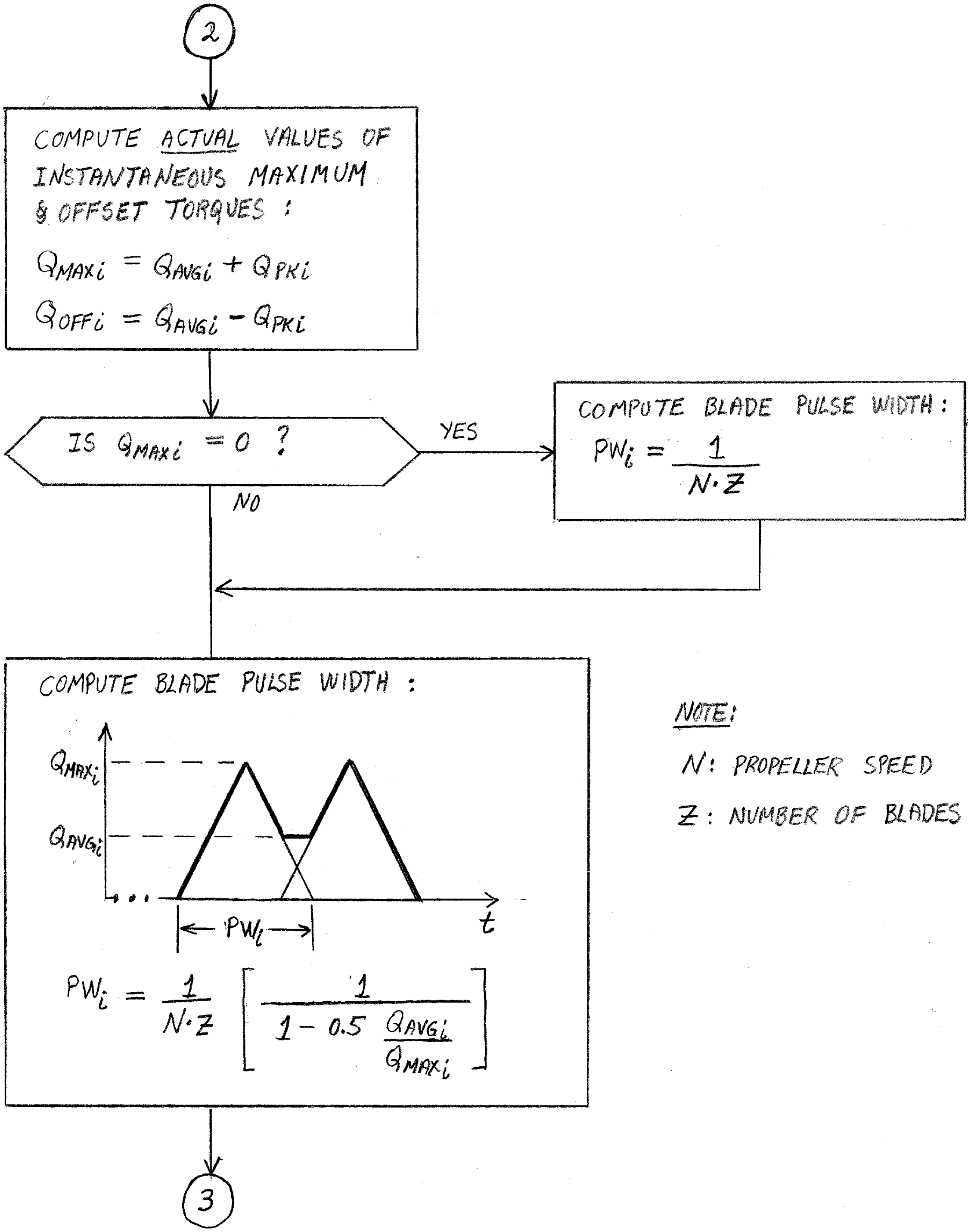
APPENDIX 3

Enhanced MSM Propeller/Ice Interaction Model Definition



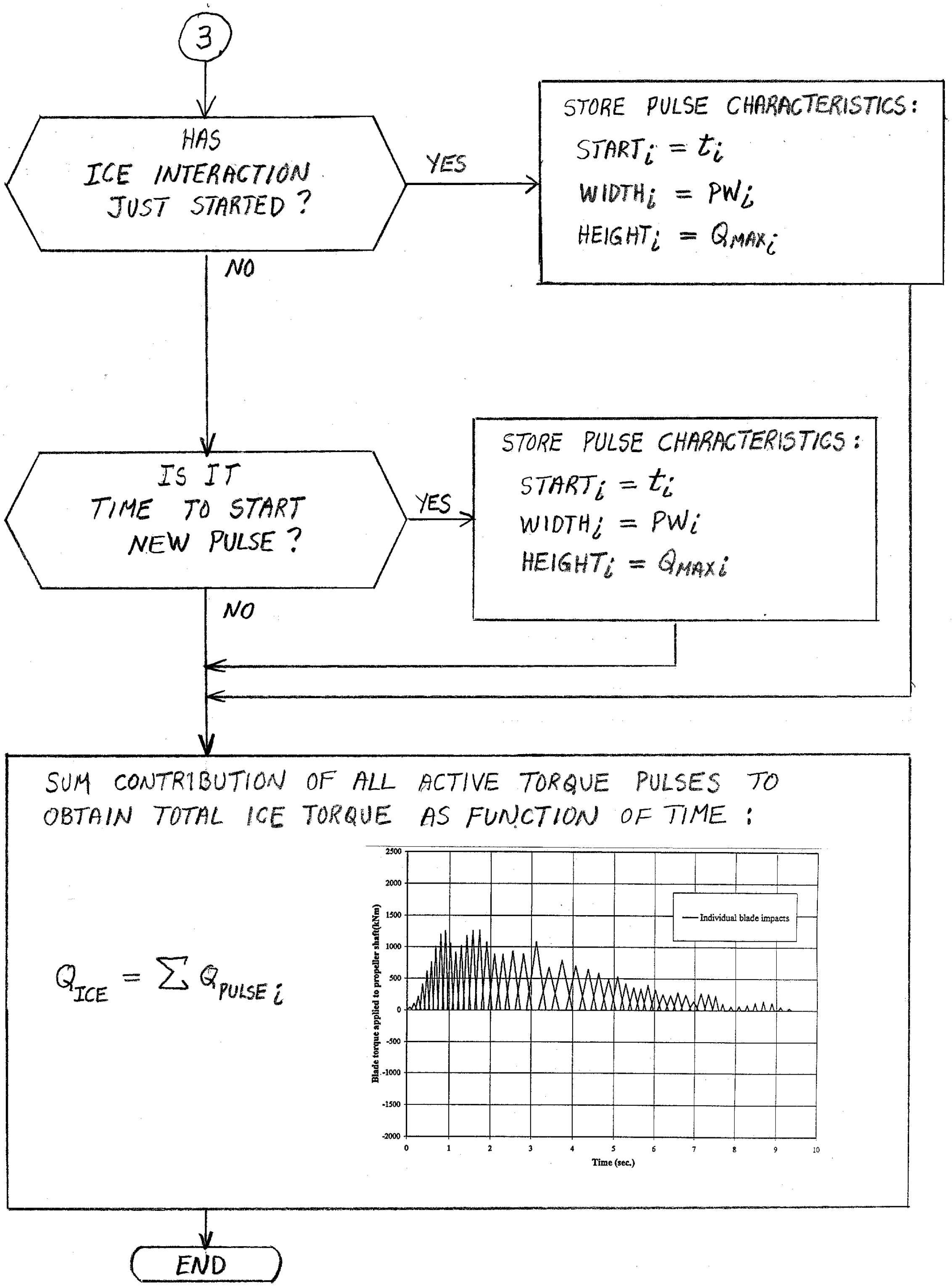

1
COMPUTE CURRENT EVENT TIME:
$t_i = t - t_{START}$
COMPUTE NORMALIZED EVENT TIME:
$t'_i = t_i / t_{EVENT}$
LOOK UP NORMALIZED VALUES OF INSTANTANEOUS AVERAGE & PEAK TORQUES AS FUNCTIONS OF t'_i :
Q'_{AVGi}
$Q'_{AVGi} = f(t'_i)$
t'_i
Q'_{PKi}
$Q'_{PKi} = f(t'_i)$
t'_i
COMPUTE ACTUAL VALUES OF INSTANTANEOUS AVERAGE & PEAK TORQUES :
$Q_{AVGi} = Q'_{AVGi} \times Q_{AVG}$
$Q_{PKi} = Q'_{PKi} \times Q_{PK}$
2



NOTE:

N: PROPELLER SPEED

Z: NUMBER OF BLADES


3
HAS ICE INTERACTION JUST STARTED ?
YES
NO
STORE PULSE CHARACTERISTICS:
$START_i = t_i$
$WIDTH_i = PW_i$
$HEIGHT_i = Q_{MAX_i}$
IS IT TIME TO START NEW PULSE ?
YES
NO
STORE PULSE CHARACTERISTICS:
$START_i = t_i$
$WIDTH_i = PW_i$
$HEIGHT_i = Q_{MAX_i}$
SUM CONTRIBUTION OF ALL ACTIVE TORQUE PULSES TO OBTAIN TOTAL ICE TORQUE AS FUNCTION OF TIME :
$Q_{ICE} = \sum Q_{PULSE_i}$
Blade torque applied to propeller shaft(kNm)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1
2
3
4
5
6
7
8
9
10
Time (sec.)
Individual blade impacts
END

APPENDIX 4

Propeller/Ice Interaction Model Investigation Process

A4.1 Overview of the Process

The objective of the simulation is to investigate the effect of propeller/ice interaction events on the performance of propulsion systems for CAC Class and Type ships.

A4.2 Provide Overview of the Propulsion System

The development of a model begins by having an overview of the propulsion system as in Sections 3.1 and 3.4.

A4.3 Generate System Model Information Block Diagram

From the propulsion system overview the block diagram of the MSM model to be implemented is generated as in Sections 3.3 and 3.6. Appendices 1 and 2 summarize block diagram nomenclature.

A4.4 Implement Propulsion System Model in MSM

Using the propulsion system model diagram, the MSM tool [9, 10, 11] is used to implement the ship model. Appendices 3 and 4 summarize typical MSM model implementations.

A4.5 Prepare Model Data

Data in support of the model is collected and entered into MSM data files. Section 4 describes the typical data collection and data synthesis (when necessary) processes. Appendices 5 and 6 summarize typical MSM data files.

A4.6 Perform Steady State Model Verification

As a minimum the ship model should be verified for the open water ahead and level ice ahead modes of operation as in Section 5.

A4.7 Perform Transient State Model Verification

As a minimum the ship model should be verified for typical ice operating manoeuvres such as the ice ramming cycles and propeller/ice interaction events in Section 6 of [9]. Simulation procedures for the manoeuvres are outlined in Figures A4.1 and A4.2 respectively.

A4.8 Simulate Propeller/Ice Interaction Events

MSM is used to generate time history traces of key parameters. Typical time history traces are summarized in this documentation in Section 6, 7, and 8.

A4.9 Analyse Propeller/Ice Interaction Simulation Results

From the MSM time history traces, the propeller/ice interaction events can be examined in more detail by generating multi-dimensional plots to illustrate the interrelationship among the following key parameters:

- maximum drop in shaft speed
- time to reach maximum drop in shaft speed
- duration of propeller/ice interaction event
- ice block thickness

A summary of a typical MSM propeller/ice investigation is presented in Sections 6, 7, and 8.

A standard spreadsheet, Microsoft Excel, is used to interrelate and display key parameters of interest from the MSM simulation results. A specific spreadsheet has been created to summarize propeller/ice interaction events and instructions on how to use this spreadsheet are given in Section A4.9.1.

A4.9.1 Propeller/Ice Interaction

For a given ship simulation, the two dominating parameters during a propeller/ice interaction are ice thickness (H) and event duration (t_e). The response of the ship to the event may be described in terms of shaft speed drop (ΔN) and time to reach minimum speed (tN_{min}).

In order to understand the relationship between these four parameters, the "driving" variables H and t_e were mapped along ΔN and tN_{min} axes. The size of the ice block hitting the propeller blade can vary in thickness.

A propeller/ice interaction event was simulated from a condition of steady state ice breaking in level ice. Steady state data snapshots of the model were taken at full power for level ice thicknesses of 0.5m, 0.75m, 1m, 1.5m, 2m, and 2.5m or approximately half the diameter of the propeller . The steady state simulations are run at full power with the propeller/ice model turned off. The ice ridge thickness is also set to zero since we are not performing an ice ramming maneuver.

From each ice thickness of 0.5m, 0.75m, 1m, 1.5m, 2m, and 2.5m, propeller/ice interaction is simulated for event durations of 0.5sec, 1sec, 2sec, 4sec, and 8sec. For a given ice thickness, the same steady state snapshot is used and it is only necessary to "change setpoint" for the desired event duration. Since propeller/ice interaction events are essentially random occurrences and would on average typically affect one propeller at a time, only one propeller, in this case the starboard one, was subjected to propeller/ice interaction. A variable "Modification" defines the "propeller/ice model off" signal as "false" at triggering time zero; the "propeller/ice model off" signal is then reset to "true" at a triggering time equal to the event duration.

Propeller/ice interaction is a fast event and the model should be run at 1ms time steps. Data is captured every 10 steps for accurate plotting. The simulations were run from -0.5 to 6 seconds. Even though the event duration could extend up to 8 seconds, we expected the speed minimum to occur within the first few seconds. The data capture files were called p_"A"_"B".out, where "A" is the event duration in seconds and "B" is the ice thickness in centimeters. Starboard shaft speed and starboard shaft torque are the two key parameters that need to be captured over time. Torque was recorded mainly to verify the proper behaviour of the model. Other parameters can be recorded if necessary and the MSM documentation provides instructions on how to do so.

Each data capture file was inserted into the spreadsheet IceLoad.xls. The data for each given ice thickness is gathered on separate spreadsheets where speed minima and time minima are calculated for the different event durations. These values are linked to the worksheet "dNmin" where H and t_e are mapped over ΔN and tN_{min} axes. All points are actually mapped twice; once along a constant ice thickness line, and once along a constant event duration line. For this reason, the points are linked to the appropriate ice thickness worksheet and a change in this worksheet will automatically be updated on the map generation worksheet. Examples of results generated by this spreadsheet are summarized in Section 8.

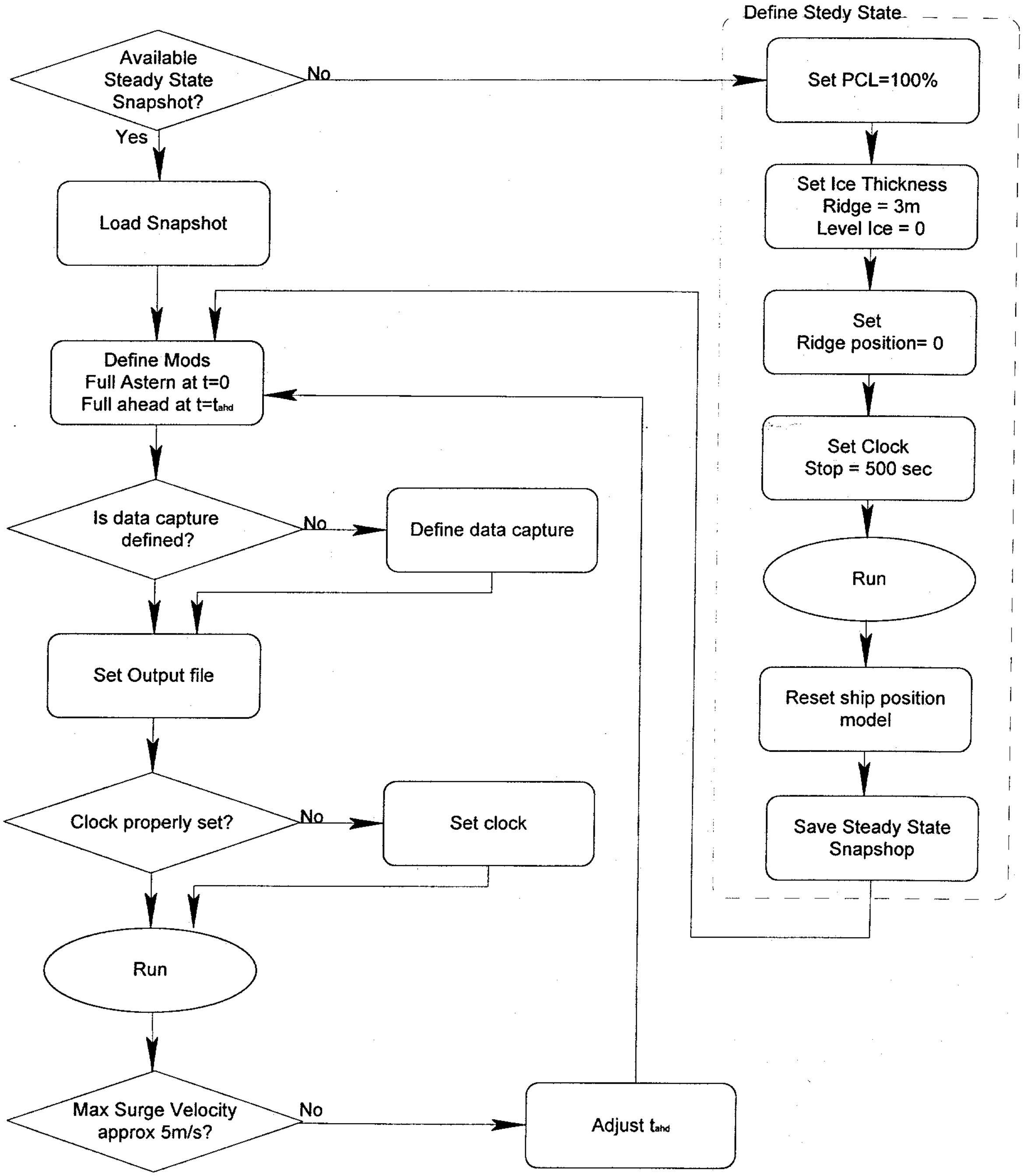


Figure A4.1 Ice Ramming Simulation Procedure

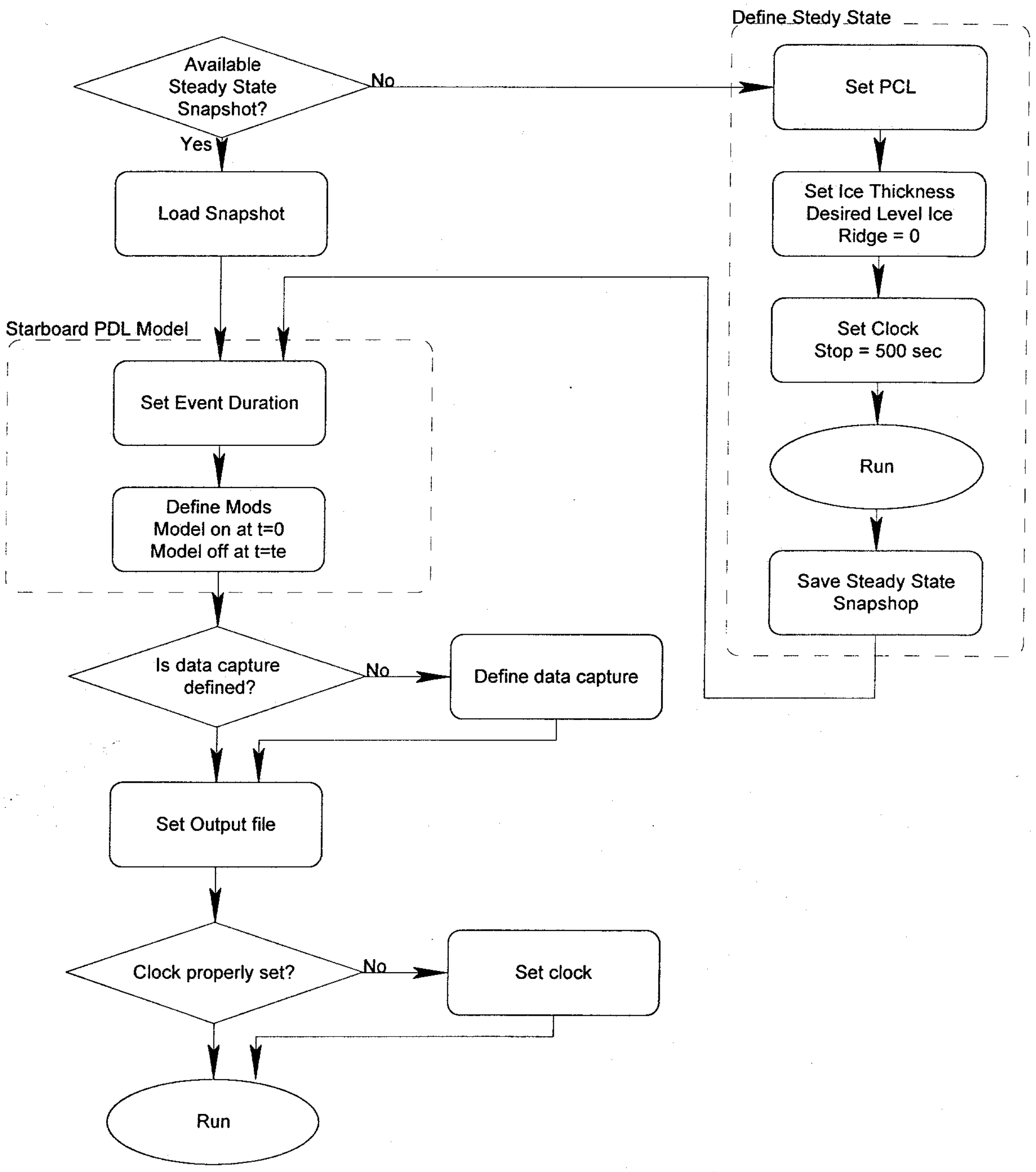


Figure A4.2 Propeller/ice Interaction Simulation Procedure