INERTIAL CONTROL OF MARINE ENGINES AND PROPELLERS

Damir Radan*, Asgeir J. Sørensen*, Tor Arne Johansen †

**Department of Marine Technology*
†Department of Engineering Cybernetics
Norwegian University of Science and Technology
N-7491 Trondheim, Norway
E-mail: [radan, assor]@.ntnu.no

Abstract: An observer-based inertial controller improving the shaft speed control on marine propellers and engines is presented. The proposed inertial observer is used for the estimation of the shaft acceleration from the noisy speed measurements. The proposed control can be used for the class of systems that have a rotating inertial motion, such as: electrical motor drives, prime movers (engines, turbines, etc.), and generating-sets. The inertial control with the inertial-observer is used to virtually increase the inertia of the power transmission system in order to decrease the shaft acceleration and speed variations. The observer-based inertial control concept is presented for the marine applications: electrical variable speed thrusters, marine generators and main propulsion engines.

Keywords: Propellers, Inertia, Propulsion, Marine, Engines, Noise, Observers

1. INTRODUCTION

When vessel operates in harsh weather conditions, the propellers may be subjected to large thrust and torque fluctuations. These fluctuations are generated by the propeller periodic change of submergence condition which leads to ventilation (air suction) and partial or full propeller emergence, see Sørensen *et al*. (1997) and Smogeli (2006). It has been known from the maritime industry that large variations in the shaft speed may be the cause of mechanical failures of the power transmission parts such as shaft bearings, gears and increased wear-out of shaft seals, see e.g. MAN B&W. Moreover, large torque variations on propulsion engines are known to produce high frequency torsional vibrations in the stern shaft which transmits to the engine bearings, gears and vessel structure. The numerous effects of the shaft vibrations are well documented and analysed in the literature, see e.g. MAN B&W.

Typically, the shaft encoder used for the shaft speed measurement produces the noise in the speed signal, see e.g. Tilli, A. and M. Montanari, (2001). If the signal is fed back to the controller, the noise will be interpreted as the disturbance, and the commanded torque may induce undesired torsional vibrations in the power transmission. These vibrations can increase the fatigue of the mechanical components in addition to the increased risk of component failure.

To obtain robustness and noise suppression in the commanded torque, speed controllers are typically proportional-integral (PI), while the derivative term (D) is typically set to zero. The special care is given avoiding noise amplification in high bandwidth actuators, such as the electrical thrusters.

For diesel engines, gas- and steam turbines, the actuator dynamics of the speed governor acts typically as a low pass filter, and the responses of the engine itself are relatively slow compared to the electrical variable speed thruster. Thus, the D-term in the controller may have low positive values improving the speed of response to large disturbances. Since the D-term can not be set high, large diesel engines are typically equipped with fast-acting over-speed cut-out devices used to cut the fuel supply when over-speed occurs preventing possibly serious damages of the engine and stern-shaft components, see e.g. Nikolaos *et al.* (2000). The problems involved in speed control of large diesel engines (2 stroke) are extensively analyzed and tested in the full scale in Nikolaos *et al*. (2000), where the authors proposed using accelerometers and sensors to determine the proximity of the water surface to the propeller blade.

As the D-term can improve the control, the problem remains how to suppress the sensor noise amplified in the D-term. If the low pass filter is used, a phase shift may have detrimental effect on the control – the feedback signal is filtered but delayed. Hence, in this paper we propose the application of the observer (state estimator) to estimate the states from the noise polluted measurements, while heaving low phase shift due to noise filtering. We introduce a new type of the observer termed the *Inertial Observer*, that will be used to calculate the shaft acceleration from the measured or the estimated speed. The proposed strategy is used to improve the PI speed control of electrical thrusters, generating-sets and the main propulsion engines without any additional sensors. The application for the thrusters is demonstrated in the case study.

2 . PROPELLER DISTURBANCES - WAVE INDUCED THRUST LOSSES

Thrust loss effects and the design of propulsion control strategies for electrically driven propellers in normal and extreme conditions have been dealt with in Sørensen *et al*. (1997) and Smogeli (2006).

The presented propeller load torque model, as given in Smogeli (2006), is used for the analysis:

$$Q_{ap} = Q_{0p}\beta_{QJp}\left(V_a, \omega_p\right)\beta_{QVp}\left(h_p, \omega_p\right), \quad (1)$$

where ω_p is the shaft speed, Q_{0p} is the nominal torque on the propeller, h_p is the propeller shaft immersion, β_{QVp} is the torque loss factor for the ventilation and in-and-out-of-water effects, and β_{QJp} is the torque loss factor for inline water inflow losses.

3. CONVENTIONAL SPEED CONTROL OF MARINE PROPELLERS

The following thruster model is used for the controller design (Smogeli, 2006):

$$J_p\dot{\omega}_p = Q_{mp} - Q_{ap} - Q_{fp}, \\ \dot{Q}_{mp} = \frac{1}{T_{mp}}\left(Q_{cp} - Q_{mp}\right), \quad (2)$$

where J_p is the moment of inertia of the shaft, motor, gear, propeller, and added mass of the propeller, Q_{ap} is the load torque, Q_{mp} is the electrical motor torque, Q_{fp} is the friction torque, T_{mp} is the motor time constant. The commanded torque Q_{cp} is the output from the thruster controller.

3.1. Noiseless controller

Using the feedback from the shaft speed deviation, the standard thruster PI speed controller is obtained:

$$Q_{cp} = k_{pp}e_p + k_{ip}\int_0^t e_p d\tau = PI\left(\omega_{0p} - \omega_p\right), \quad (3)$$

$$e_p = \omega_{0p} - \omega_p, \quad (4)$$

where ω_{0p} is the thruster speed reference, and k_{pp} and k_{ip} are the nonnegative proportional and integral control gains, respectively. PI in eq. (3) stands for the proportional integral control.

Theoretically, with noiseless states, k_{pp} and k_{ip} could be increased until the desired response is obtained.

3.2 Noise suppression capability

Now assume that the above controller (3) is affected by some measurement noise $d_\omega(t)$. Then, instead of (4) the speed variation e_p is:

$$e_p = \omega_{0p} - \left(\omega_p + d_\omega\right), \quad (5)$$

Neglecting the thruster dynamics Q_{mp}=Q_{cp}, and the integral control term, k_{ip}=0 and inserting (5) to (3), and then to (2) the following closed-loop equation of motion (2) is obtained:

$$\dot{\omega}_p = \frac{1}{J_p}\left[k_{pp}\left(\omega_{0p} - \omega_p - d_\omega\right) - Q_{ap} - Q_{fp}\right]. \quad (6)$$

The neglected integral action will compensate for the slowly varying dynamics of Q_{ap} and Q_{fp}.

As can be seen from (6), the undesired measurement noise $d_\omega(t)$, is transferred to the shaft motion through the control action. Due to noise amplification in the controller, the shaft vibrations will increase. This may result in the increased wear rate of the power transmission system. Therefore, as the noise will be amplified when increasing k_{pp}, the speed variations e_p may not be reduced to the desired level. This may be a problem in harsh environmental conditions. As the shaft vibrations are induced by the torque variations, k_{pp} of the PI controller is bounded with a function of torque deviation:

$$k_{pp} \le f\left(\left\|Q_{mp} - Q_{ap}^*\right\|\right). \quad (7)$$

where $Q_{mp} - Q_{ap}^*$ is the torque deviation sensed on the shaft and $Q_{ap}^* = Q_{ap} + Q_{fp}$ is the extended load torque that includes friction.

4. INERTIAL CONTROL CONCEPT

4.1. Inertial Control of Electrical Thrusters

The proposed *inertial control* concept is applied to improve the speed control of swing motion class of systems. In this group belong: marine electric thrusters, engines connected to propellers and generating-sets.

The following control low, based on virtual inertia, can be used to improve the shaft speed control (Morren *et al.*, 2006):

$$Q_{iner,p} = k_{iner,p}\ J_p\ \frac{d}{dt}\omega_p\ , \qquad (8)$$

where $k_{iner,p}$ is the control gain. With the inertial control included, the following shaft speed controller is obtained, as presented in fig. 1:

$$\begin{aligned} Q_{cp} &= k_{pp} e_p + k_{ip}\int_0^t e_p d\tau\ , \\ e_p &= \omega_{0p} - \omega_p - k_{iner,p}\ J_p\ \frac{d}{dt}\omega_p\ . \end{aligned} \qquad (9)$$

Neglecting the integral control term, k_{ip}=0 in (9), the inertial controller is obtained:

$$Q_{cp} = k_{pp}\left(\omega_{0p} - \omega_p\right) - k_{pp}k_{iner,p}\ J_p\ \frac{d}{dt}\omega_p\ . \qquad (10)$$

Neglecting the thruster motor and frequency converter dynamics Q_{mp}=Q_{cp}, and inserting (10) into (2) the following closed-loop equation of motion is obtained:

$$\dot{\omega}_p = \frac{1}{J_p + k_{pp}k_{iner,p}J_p}\left[k_{pp}\left(\omega_{0p} - \omega_p\right) - Q_{ap} - Q_{fp}\right] . (11)$$

Comparing the closed-loop equations (11) and (6) and assuming that the noise is neglected d_{ω}=0, the additional virtual inertia on the thruster is obtained as $k_{pp}\ k_{iner,p}\ J_p$. The problem of noise d_{ω} will be dealt later in this chapter.

The inertial control concept is presented on Figs. 1 and 2. From eq. (11) it can be noticed that the inertial control strategy can be obtained using direct differentiation of shaft speed ω_p if an accurate shaft speed can be measured. The measurement noise in the speed ω_p will limit the performance of the controller as the derivation of noisy measurement $d\omega_p/dt$ may cause the increased wear of thruster components. The performance of the controller can be improved if an observer is used to suppress the noise, see e.g. Busawon and Kabore (2001) and references therein.

4.2. Speed control based on the inertial torque observer

In this paper, the PI speed controller with D-term estimated using the so called *inertial torque observer* is proposed. This is the main result of the paper. The *inertial torque observer* is used for the noise suppression i.e. disturbance attenuation.

The load torque observer is used to estimate the speed acceleration as can be seen in Fig 2. In this paper, the following control law is proposed:

$$Q_{iner,p} = k_{iner,p}\left(Q_{mp} - \hat{Q}^*_{ap}\right) . \qquad (12)$$

The extended estimated load torque includes friction:

$$\hat{Q}^*_{ap} \approx Q^*_{ap} = Q_{ap} + Q_{fp}\ , \qquad (13)$$

and is calculated using an observer. With the inertial control included, the following shaft speed controller is proposed, see Fig. 2:

$$\begin{aligned} Q_{cp} &= k_{pp} e_p + k_{ip}\int_0^t e_p d\tau\ , \\ e_p &= \omega_{0p} - \hat{\omega}_p - k_{iner,p}\left(Q_{mp} - \hat{Q}^*_{ap}\right) . \end{aligned} \qquad (14)$$

Neglecting the integral term k_{ip}=0 in (14), the commanded torque is equal to:

$$Q_{cp} = k_{pp}\left(\omega_{0p} - \hat{\omega}_p\right) - k_{pp}k_{iner,p}\left(Q_{mp} - \hat{Q}^*_{ap}\right) . (15)$$

<u>Load torque observer</u>
Based on the thruster model in (3), the propeller load torque is estimated using an observer (Smogeli, 2006):

$$\begin{aligned} \frac{d}{dt}\hat{\omega}_p &= \frac{1}{J_p}\left(Q_{mp} - \hat{Q}^*_{ap}\right) + l_{1p}\left(\omega_p - \hat{\omega}_p\right) , \\ \frac{d}{dt}\hat{Q}^*_{ap} &= l_{2p}\left(\omega_p - \hat{\omega}_p\right) , \end{aligned} \qquad (16)$$

where l_{1p}, l_{2p} are the observer gains.

<u>Inertial torque observer</u>
In this paper, we propose the inertial torque observer which will be used to estimate the speed differentiation. Equating (8) and (12) the estimated shaft acceleration is obtained from the inertial torque:

$$\frac{d}{dt}\hat{\omega}^*_p = \frac{1}{J_p}\left(Q_{mp} - \hat{Q}^*_{ap}\right) = \hat{Q}_{iner,p} / J_p k_{iner,p}\ , (17)$$

where the load torque and the speed are estimated using the observer (16).

The proposed inertial torque observer (17) is used for the estimation of the inertial torque $Q_{iner,p}$ which is equivalent to the shaft acceleration. Thus, D-term of the controller is estimated through the estimation of the inertial torque.

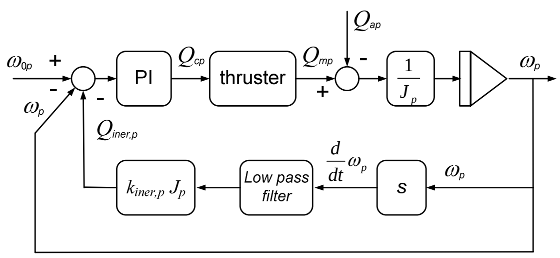

Fig. 1. Acceleration based inertial control of electrical thruster.

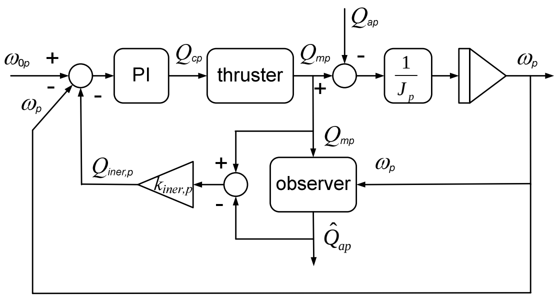

Fig. 2. Proposed inertial torque observer used to suppress the noise in the *D*-term.

4.3. Noise suppression in D-term using the inertial torque observer

If the observer is used mainly for the noise suppression, then it should provide improvements over the low pass filter. In this paper, the two main objectives for the observer design are distinguished:

- obtain low phase shift between estimated and real signal, i.e. stabilize error dynamics, by increasing the gains l_1 and l_2 in (16),
- suppress the noise.

However, these objectives are usually conflicting and trade-offs must be made, see e.g. (Busawon and Kabore, 2001) and references therein.

When using the proportional observer (16) to estimate the D-term, the sensor noise d_ω is proportional to the observer gain l_{1p}, used to stabilize the error dynamics. Then, the noise is amplified, as can be seen if sensor noise is added in (16):

$$\frac{d}{dt}\hat{\omega}_p = \frac{1}{J_p}\left(Q_{mp} - \hat{Q}^*_{ap}\right) + l_{1p}\left(\omega_p + d_\omega - \hat{\omega}_p\right),$$
$$\frac{d}{dt}\hat{Q}^*_{ap} = l_{2p}\left(\omega_p + d_\omega - \hat{\omega}_p\right), \tag{18}$$

The noise amplification due to the observer gain l_{1p} can be avoided when the *inertial torque observer* (17) is used.

As can be seen in (17), the $l_{1p} = 0$ only when the speed differentiation is calculated. The speed estimate is calculated in (18) after the time integration of $l_{1p}d_\omega$. The time integration will provide additional noise suppression, as shown for the *Integral Observers,* and the *Proportional-Integral Observers* in Busawon and Kabore (2001) and references therein.

5. APPLICATION OF PROPOSED CONTROL

5.1 Application to electrical FP propellers

For the variable speed thrusters, with fixed pitch propellers (FPP) the controller have to accommodate change in the speed reference. In order to provide acceptable acceleration and deceleration of the thruster, the control gain should adjust to different load conditions according to:

$$k_{iner,p} = k_{c,p}\ Q_{0p}, \tag{19}$$

where Q_{0p} is the expected nominal torque of the propeller:

$$Q_{0p} = \frac{1}{4\pi^2} K_Q \rho D^5\ \omega_{0p}^2 = g_{Q0}\left(\omega_{0p}\right). \tag{20}$$

Conventional PI speed controller typically has a constant proportional and integral control gains k_{pp} and k_{ip} for the whole region of the propeller operation. This means that the noise will not be properly suppressed when the thruster operates on low load and when the disturbances on the thruster are low. Hence, the controller gains should change with the propeller loading. This noise suppression can be improved when using the inertial controller with adjustable controller gains as proposed in (17).

5.2. Inertial Control of Prime Movers

The inertial controller can be used to improve the speed control on any prime mover installed on board marine vessels, including diesel engines, gas- and steam turbines. The inertial controller can be beneficial in the following power plant configurations:

1. Electrical power generation,
2. Mechanical propulsion,
3. Mechanical propulsion with shaft-generator.

When the diesel engine is used for the main propulsion, the problems that occur when the propeller is subject to large thrust and torque losses in bad weather conditions involve increased wear of cylinder liner and rings due to high piston speed, increased loadings and wear of the crank shaft and main bearings together with the increased risk of turbo-charger surging. For more details see Theotokatos and Kyrtatos (2001) and the references therein.

The block diagram that represents the proposed inertial control law for the marine main propulsion engines is shown in the Fig. 3. The index *m* stands for the main engine. The mechanical engine torque torque Q_{mm}, is also referred in the literature as the indicated torque or the combustion torque. The main propulsion engines are usually equipped with a torsionmeter measuring the effective torque on the engine. However, the measurements of the indicated torque on board the vessel are not always accurate enough (noise polluted) to be used for in the controller. Hence, an observer can be designed to estimate the Q_{mm}. The derivation of such an observer involves a more detailed model of the diesel engine and will not be derived in this paper. A convenient method to estimate the combustion torque using the average of the instantaneous torque can be found in Khiar *et al.* (2005) and references therein. With the inertial controller included, the following controller is obtained:

$$Q_{cm} = k_{pm} e_m + k_{im} \int_0^t e_m d\tau \ ,$$
$$e_m = \left(\omega_{0m} - \omega_m\right) - k_{iner,m} \left(\hat{Q}_{mm} - Q^*_{am}\right) \ , \qquad (21)$$

where k_{pg} and k_{ig} are the positive PI controller gains. In order to simplify the analysis, the actuator dynamics has been neglected in the controller output Q_{cm}.

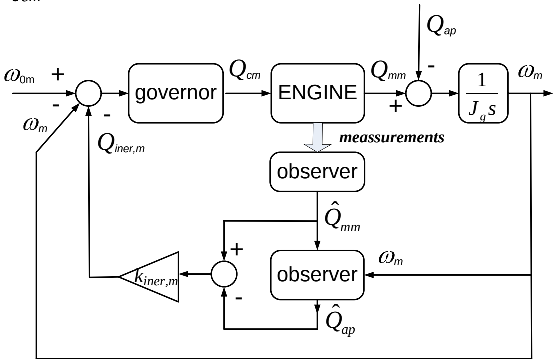

Fig. 3. Observer-based inertial control for main propulsion engine.

6. STUDY CASES

A case study simulation of electrical thruster operating in harsh environmental conditions is performed using MATLAB/SIMULINK and results are presented in Figs. 4 to 6 and Table 1. The simulated thrust loss peak is 95% nominal, which corresponds to almost full propeller emergence.

The following controllers are compared in this study:

- *IC – inertial controller*, the controller presented in this paper, based on the speed and load torque observer;
- *PI+D controller* – represents the PI controller with additional D term with low pass filter;
- *PI controller* – represents the conventional controller widely used for the speed control of marine thrusters.

The noisy measurements in shaft speed ω_p and electrical torque Q_{mp} are simulated by adding the signal perturbations, uniformly distributed, with min/max relative error of ± 2% and 5% respectively. All variables, as well as the controller gains, are normalized. The nominal speed of the thruster is $\omega_{0p} = 0.3\ \omega_{p,rated}$ and after t=30 seconds it becomes $\omega_{0p} = 0.65\ \omega_{p,rated}$, so the controllers can be compared with different thruster loadings.

CASE 1. *IC* and *PI+D* controllers:
In Fig. 4 the *IC* is compared to *PI+D* controller. The controller gains are selected in order to obtain almost equal speed variations for both of the controllers, as shown in the Fig. 4. The *PI+D* controller gains are: k_{ip}= 6, k_{ii}= 4, k_{id} = 2. The *IC* gains are: k_{ip}= 3, k_{ii}= 1, k_{cp} = 8 (see eq. (19)). The observer gains for *IC* are: l_{1p} =10 and l_{2p}= –100.
From the Fig. 4, it can be noticed that the variations in the electrical motor torque Q_{mp} and torque variations $Q_{mp} - Q_{ap}$ are several times lower when using the proposed *IC*, e.g. the maximum amplitudes of torque variations are almost four times lower with IC, 0.1 vs. 0.4 on the lowest graph of Fig. 4.

CASE 2. *IC* and *PI controllers*:
The PI gains are selected to obtain almost the same speed variations for both controllers. For the *PI controller* the gains are selected: k_{pp} = 8 and k_{ip}= 6 and for the inertial controller: k_{pp} = 3, k_{ip}= 1, k_{cp} = 8, see eq. (16). The observer gains are: l_{1p} =10 and l_{2p}= –100.

CASE 3. *IC and PI controllers*:
The *IC* is compared to standard *PI controller* and results are presented in the Fig. 6. The PI gains for *IC* and the *PI controller* are the same: k_{pp} = 3 and k_{ip}= 1. The other parameters of *IC* are the same as in the CASE 2.
From the Fig. 6, it can be noticed that the torque and speed variations are both lower when using the proposed *IC* compared to conventional *PI controller*, e.g. the maximum amplitudes in torque variations are about 50% reduced with *IC* (0.1/0.2) and the speed variations are about 15% reduced with *IC* (0.7/0.8).

Fig. 5. demonstrates the use of the observer to filter the noise in the speed signal.

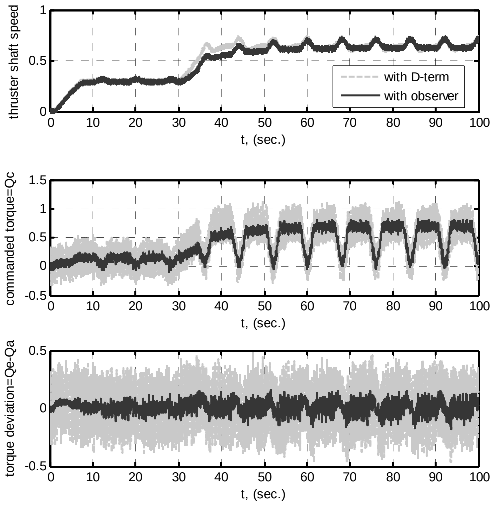

Fig. 4. Propeller shaft speed ω_p (upper), commanded torque Q_{mp} (middle) and torque deviation $Q_{mp} - Q_{ap}$ (lower), with *IC* (solid) and *PI+D* controller (dashed) for CASE 1.

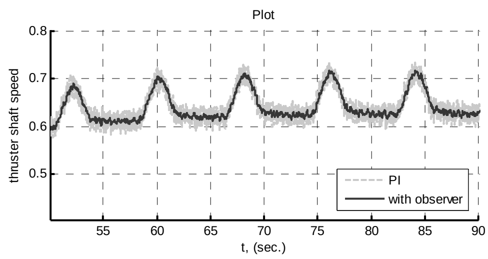

Fig. 5. Thruster shaft speed: estimated (solid) vs. measured (dashed).

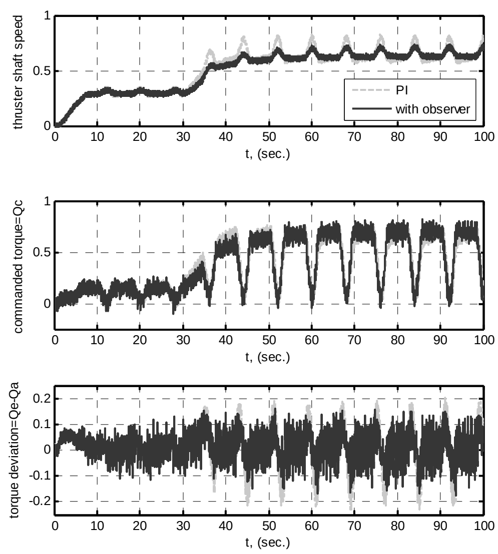

Fig. 6. Propeller shaft speed ω_p (upper), commanded torque Q_{mp} (middle) and torque deviation $Q_{mp} - Q_{ap}$ (lower), with *IC* (solid) and *PI controller* (dashed) for CASE 3.

Table 1. Comparison of different controllers

Controller:	Speed deviation: $\omega_{0p} - \omega_p$	Torque deviation: STD($Q_{mp} - Q_{ap}$)
CASE 1:		
IC	Nearly same	0.0500
PI+D	Nearly same	0.1576
CASE 2:		
IC	Nearly same	0.0500
PI	Nearly same	0.0843
CASE 3:		
IC	15% lower then	0.0500
PI	with PI	0.0712

In Table 1, all controllers are compared according to speed and torque variations. Lower the torque variations, lower the mechanical stress to the thruster components will be. The optimal controller should obtain the lowest possible speed and torque variations. The standard deviation (STD) for $Q_{mp} - Q_{ap}$ is calculated for all cases and it is shown that the reductions in the torque variations using *IC* are higher than 75% in CASE 1, or 40% in the CASE 2. In the CASE 3, the reductions of the torque variations of nearly 30% are obtained when using *IC*, in addition to reductions in the speed variations of about 15%.

7. CONCLUSIONS

An observer-based inertial speed controller applicable for the marine applications is proposed in this paper. The *inertial observer* is proposed as a convenient method of noise suppression. The *inertial observer* can be used for the class of systems that have the rotating motion and a rotating inertia, such as: electrical motor drives, prime movers (engines, turbines, etc.), and generating-sets.

An electrical thruster was selected to show the benefits of the controller. It has been demonstrated that the inertial controller can improve the speed control for the electrical thrusters in addition of heaving good noise suppression ability. The proposed control method is mainly analyzed for the speed control of electrical thrusters due to the importance of having good noise suppression in the controller output signal. Similar analysis and comparison of simulation results are possible for other applications of inertial control, namely: electrical power generation, mechanical propulsion and propulsion engine with shaft-generator. It is believed that the proposed observer-based inertial controller can be successfully used to improve the shaft speed control of propulsion engines without the need to install any additional sensors proposed in Nikolaos *et al.* (2000).

8. ACKNOWLEDGEMENTS

This work has been carried out as apart of the research project on Energy-Efficient All-Electric Ship, http://www.ivt.ntnu.no/imt/ electricship/.
The Norwegian Research Council is acknowledged as the main sponsor EEAES.

REFERENCES

Busawon K. K.; Kabore P. (2001), Disturbance attenuation using proportional integral observers, *International Journal of Control*, Taylor and Francis Ltd, Vol. 74, Nu. 6, pp. 618-627(10)

Khiar, D., J. Lauber, T. Floquet, T.M. Guerra (2005), *An observer design for the instantaneous torque estimation of an IC engine*, Vehicle Power and Propulsion, 2005 IEEE Conference, Sept. 2005

Kundur, P. (1994), *Power System Stability and Control*, New York: McGraw-Hill, 1994.

MAN B&W, Project Guides for Marine Plants, Dual-fuel Engine, 48/60DF, L+V 48/60 B, L+V 32/40 (http://www.manbw.com/)

Morren, J., J. Pierik And Sjoerd W.H. De Haan (2006), Inertial response of variable speed wind turbines, *Electric Power Systems Research*, Vol. 76, Issue 11: 980-987

Nikolaos I. Xiros, Nikolaos P. Kyrtatos (2000), A Neural Predictor Of Propeller Load Demand For Improved Control Of Diesel Ship Propulsion, Proc. of the 15th IEEE Inter. Symposium on Intelligent Control (ISIC 2000), Rio, Patras, GREECE

Smogeli, Ø.N. (2006), Control of Marine Propellers: from Normal to Extreme Conditions, PhD thesis, Dept. Marine Technology, NTNU, Trondheim, Norway

Sørensen, A.J., A.K. Ådnanes, T.I. Fossen and J.P. Strand (1997), A New Method of Thrusters Control in Positioning of Ships Based on Power Control, 4th IFAC Conf. on Manoeuvring and Control of Marine Craft, Brijuni, Croatia.

Tilli, A. and M. Montanari, (2001), A low-noise estimator of angular speed and acceleration from shaft encoder measurements, Journal Automatika, 42(2001) 3-4, 169-176