THE APPLICATION OF THE PHOTO OPTIC TORQUE METER TO ESTIMATION OF TORQUE AND ROTATIONAL SPEED FLUCTUATIONS ON THE PROPELLER SHAFT OF A SHIP

Leszek Morawski

Gdynia Maritime University
83 Morska Str., 81-225 Gdynia, Poland
tel.: +48 58 6901256, fax: +48 58 6219938
e-mail: lmoraw@am.gdynia.pl

Zbigniew Szuca

Enamor Ltd.
83 Morska Str., 81-225 Gdynia, Poland
tel.: +48 58 6901751, fax: +48 58 6901701
e-mail: zbigniew.szuca@enamor.com.pl

Abstract

The paper presents the method of measuring instantaneous torque and rotational speed fluctuations on the propeller shaft of a ship. The measured data are significantly deformed, therefore spectral analysis and filtering are used for estimating the real signals. The microprocessor torque meter ETNP-8 described in the paper was designed to measure not only mean values of the torque and rotational speed on the ship's propeller shaft, but also instantaneous fluctuations of the torque and engine rotational speed as a function of the shaft rotation angle. Displaying time-histories of those parameters on the monitor screen of an external PC computer gives the operator an opportunity to make a preliminary performance assessment for each individual cylinder in the engine, and for the drive system as a whole. As an example, the analysis and processing of the measured torque and rotational speed fluctuations are presented. The measurements were done on the training ship m/s Horyzont II, owned by the Gdynia Maritime University.

Keywords: *propeller unit ,main engine, torque measurement, torque fluctuation, torque meter*

1. Introduction

In the Gdynia Maritime University and Research-Production Enterprise for Maritime Industry Enamor Ltd., a device (bearing a symbol ETNP-8) is manufactured for measuring torque, rotational speed, and power at the ship's main drive propeller shaft. Optionally, it also can calculate other ship performance indices, such as fuel consumption per nautical mile, per unit of power, etc.[2]. The torque meter was designed not only for measuring mean values of the torque and rotational speed on the propeller shaft of the ship but also to measure instantaneous fluctuations of the torque and engine rotational speed as a function of the shaft rotation angle. A new version of the torque meter reveals better characteristics than the older ones. One of the first manufactured devices was installed on the board of the training ship m/s Horyzont II. The analysis and processing of the measured data of torque and rotational speed fluctuations is presented below.

2. Measuring torque and rotational speed fluctuations

The general idea of the torque and rotational speed measurement makes use of the torsion angle measurement executed on a shaft section using a photo-optical technique. Two discs with machined teeth are fixed on the propeller shaft at distance L (approx. 400 mm). They are designed in such a way that their teeth are in the same plane. The teeth of these two discs can rotate in (and through) a gap of a transoptor based measuring head (Fig. 1a). The shaft torsion, proportional to the loading torque, makes the teeth of the two discs move with respect to each other, as is shown in Fig. 1b. At the output of the measuring head a rectangular wave is obtained with variable pulse-width modulation (Fig. 1c).

The torque measurement bases on measuring the difference in the time duration of two successive pulses, recorded by the transopting head, that correspond to the clearances between the disc teeth.

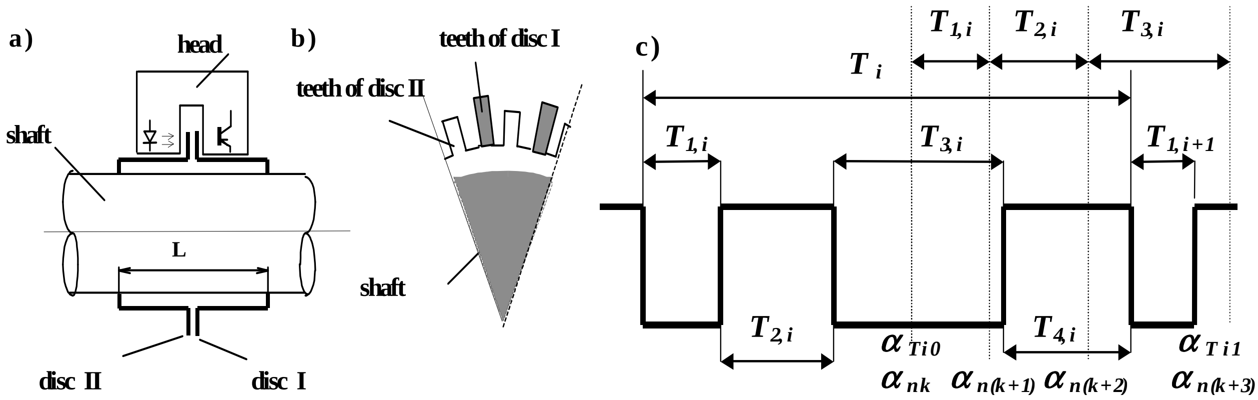

Fig. 1. Principle of the shaft torsion angle measurement: a) method of disc fastening on the propeller shaft; b) cross sections of toothed disc portions; c) time-history of output signal from transoptor head.

One tooth on one disc has a narrow gap to mark a selected shaft position angle. Other shaft position angles are determined by counting pulses transmitted by the transoptor head (Fig. 1c). When the pulse from the narrow gap is estimated, the torque meter starts measuring the passing times T_{1i}, T_{2i}, T_{3i}, T_{4i} (Fig. 1c) of consecutive clearances between the teeth during a given number of revolutions. The results of the time measurements are stored in the RAM memory of the torque meter electronic unit. Then, after the measurement is completed, the data are transmitted to the external computer. Actual values of the torque and rotational speed fluctuations are computed in the off-line mode.

Assuming that the values of the torque and rotational speed are constant during the time when the transporting head passes two consecutive teeth and two clearances, the instantaneous torque is determined from the formula:

$$T_T\ (\alpha_{Ti,j}) = \pm k_T \cdot \frac{|T_{3,i} - T_{1,i+j}|}{T_{1,i+j} + T_{2,i+j} + T_{3,i} + T_{4,i}} = \mathrm{T_{Tji}} + \mathrm{T_{Tjip}} \quad [\%] \quad \mathrm{j=0,1} \tag{1}$$

while the instantaneous rotational speed of the shaft is computed from the formula:

$$n\ (\alpha_{nt,i}) = k_n \cdot \begin{cases} 1/(T_{1,i} + T_{2,i} + T_{3,i} + T_{4,i}) & t=0 \\ 1/(T_{1,i+1} + T_{2,i} + T_{3,i} + T_{4,i}) & t=1 \\ 1/(T_{1,i+1} + T_{2,i+1} + T_{3,i} + T_{4,i}) & t=2 \\ 1/(T_{1,i+1} + T_{2,i+1} + T_{3,i+1} + T_{4,i}) & t=3 \end{cases} \quad [\text{rev/min}] \tag{2}$$

where:

i - number of teeth in one disc,
k_T - proportionality coefficient resulting from the nominal torque, the amorphous elasticity coefficient of the shaft, the shaft diameter, the length of the twisted shaft section, and the unit scaling,
k_n - proportionality coefficient resulting from the unit scaling;
$\alpha_{Tj,i}$ - torque measurement angles (j=0,1),
$\alpha_{nt,i}$ - rotational speed measurement angles (t=0,1,2,3),
$T_{tj,i}$ - torque resulting from the shaft tension angle,
$T_{Tj,ip}$ – average torque correction resulting from the distribution of clearances in the rest position.

It should be stressed here that the number of points corresponding to one shaft revolution during which the torque is measured is equal to the double number of teeth (i) in one disc, while for the rotational speed the number of points is four times as big as the number of teeth.
The mean values of the shaft torque and rotational speed are calculated using formulas (1) and (2) for an integer number of shaft revolutions.

3. Results of measurements on real objects

The measurements were done on the training ship m/s Horyzont II, owned by the Gdynia Maritime University (L=56m; main engine: 4-stroke Sulzer–Cegielski 8S20U, nominal power 1280 kW, nominal rotational speed 1000 rev/min; reduction gear 3.115:1; propeller shaft diameter 180 mm; four-blade variable pitch propeller; number of teeth of the torque meter disc 48). Below the analysis and data processing of the measured torque and rotational speed fluctuations are given.

As is well known, the force which is generated by the combustion gas pressure and is tangent to the engine crank creates the torque and determines the power delivered by particular engine cylinders to the crankshaft. Since the energy transmitted by each individual cylinder is usually a function of the rotation angle, the time-history of the total torque transmitted to the propeller shaft and its rotational speed reveal a periodical nature. The reduction gear and vibration damper significantly limit the torque and rotational speed fluctuations on the shaft. The torque fluctuation curves computed, using formula (1), for two different loads and shaft rotations, are shown in Figs 2 and 3.

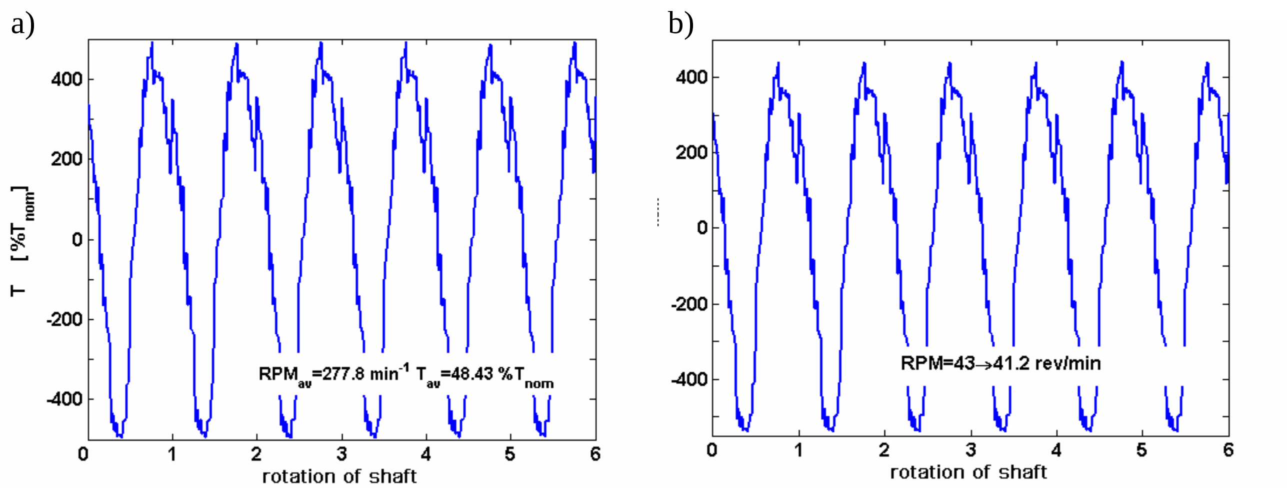

Fig. 2. Propeller shaft torque fluctuations:
a) for n_{av}=277.8 rev/min, torque T_{av}=48.43 %T_{nom} , b) for n_{av}=41.2-43 rev/min, T_{av}=-0.32 %T_{nom}.

The second case corresponds to the situation when the shaft was decoupled from the engine and the shaft rotation was only provoked by the moving ship. The value of the torque was near zero. The both presented signals are significantly deformed. The main source of deformations is an inaccuracy in manufacturing and installing the toothed discs on the shaft, but it can also include possible resonances of free torsion vibrations of the propeller shaft, vibrations of the shaft deflection, propeller load fluctuations, etc. The possibility of free resonances of mechanical parts of the torque meter cannot be neglected as well.

The two presented torque time-histories are similar to each other, with the first harmonics being the dominating component. Its most possible source is the lack of symmetry in fastening of the two halves of the toothed disc, cut apart before the assembly, on the shaft. As is seen in Fig. 2, this component exceeds 400% of the nominal torque. This and other spectrum components deforming the measurement results can be eliminated using a method of spectral analysis which was presented in [1] and [2]. The below presented direct method in time domain consists in cyclic subtracting from the analysed time-histories 96 values (2*number of teeth in one disc), being the torque corrections corresponding to the distribution of gaps and teeth when the torque is equal zero. The torque corrections for the full revolution of the propeller shaft are calculated as averaged over a number of revolutions, following the formula:

$$T_{cor}(\alpha_{Tt,j}) = \frac{1}{n}\sum_{k=1}^{n}\left(T_k(\alpha_{Ti,j}) - T_{kav}\right) \quad (3)$$

where:

$T_k(\alpha_{Ti,j})$ – calculated instantaneous value of the torque for the propeller shaft rotation angle $\alpha_{Ti,j}$ in k-th shaft revolution,

T_{kav} – real mean value of the torque in k-th shaft revolution.

Figure 3 presents the torque correction time-history for the full propeller shaft revolution, based on 96 correcting values determined in the above described way. Corrections determined for other loads and rotational speeds differ by no more than 0.3%. Figure 4 shows the torque time-histories from Figs 2a and 2b after taking into account the correction curves. They are still deformed by high-frequency effects, which, however, can be eliminated using a forward-backward type filter, which gives zero phase shift due to double filtering. The filter used here was the third-order low-pass Butterworth filter, with the cutting frequency $\omega=0.88\pi\cdot i/n$ (i- number of teeth in one disc, n-shaft rotational speed, in rad/s).

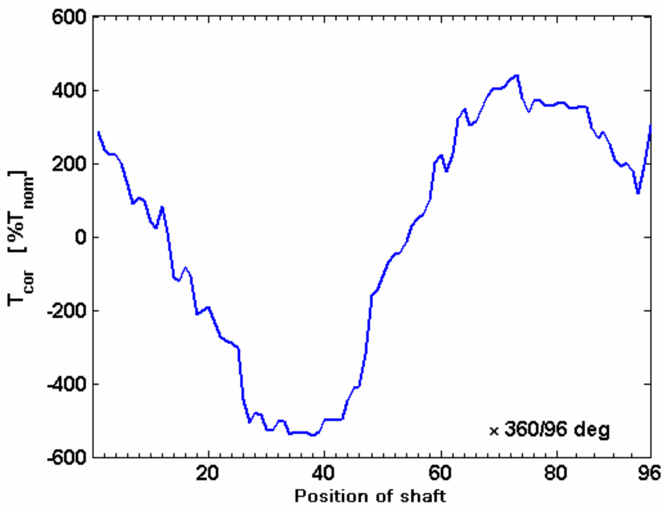

Fig. 3. Torque correction factor for one propeller shaft revolution

The filtered torque time-histories are marked in Fig. 4 as thicker lines. What is noteworthy is torque fluctuations with the amplitude of about 2.5% of the nominal torque (Fig. 4a). Those fluctuations are generated by the running engine and residual torque fluctuations on the engine crankshaft, which were not completely damped. This estimation is confirmed by the torque time-history shown in Fig. 5, significant components of which are the harmonics corresponding to the full cycle of propulsion engine operation (2 crankshaft revolutions). A very small amplitude component, marked with an arrow, which is generated by individual cylinders is significantly damped (the operation of all 8 cylinders during two crankshaft revolutions). In the figure the frequency scale unit is related to one full revolution of the propeller shaft.

Figure 4b shows the time-history of the instantaneous torque measured on the propeller shaft 50 seconds after decoupling it from the propulsion engine. The propeller is rotated, together with the shaft and the gear, by the water flowing down the ship's hull, which moves by its own inertia. That is why the fluctuations caused by the engine in operation are missing in Fig. 4b. The observed low fluctuations are likely to be generated by irregular stream of water flowing down the propeller and friction torques in shaft bearings. The load was approximately equal to 0.4% of the nominal torque.

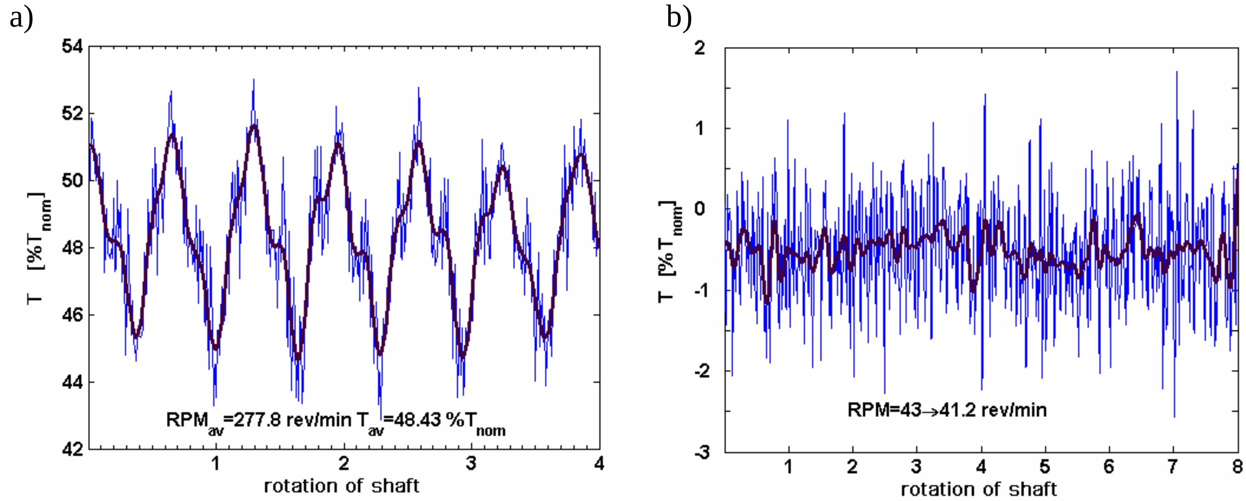

Fig.4. Torque time-histories in consecutive shaft revolutions, taking into account corrections and filtering: a) RPM_{av}=277.8 rev/min; b) RPM_{av}≈41-43 rev/min

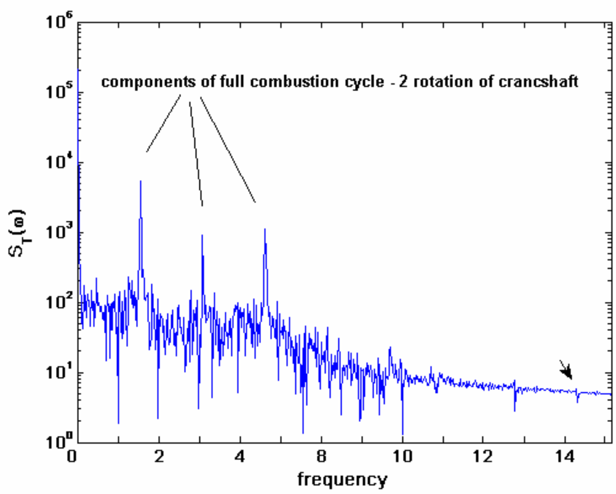

Fig.5. Frequency spectrum of the torque shown in Fig.4a

A similar methodology of measurement data analysis was applied for shaft rotational speed time-histories. Figure 6 presents rotational speed time-histories calculated using formula (2). They correspond to the same measurement cycles as for the torque. Like for Fig. 4, the frequency scale unit is related to one full revolution of the propeller shaft.

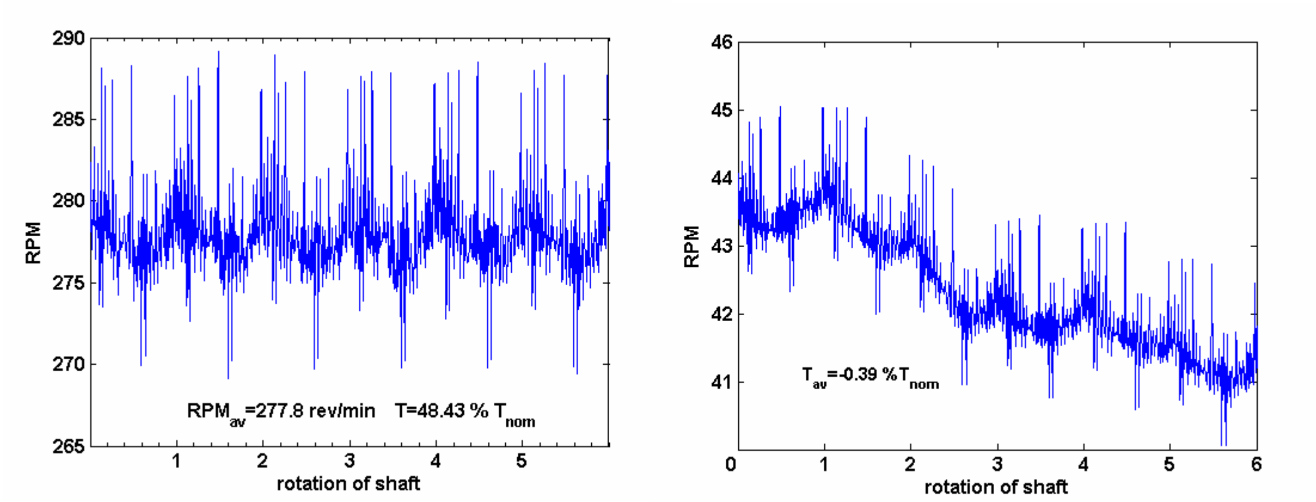

Fig.6. Fragments of rotational speed time-histories for different engine loads

The shape of the angular speed correction curve taking into account the inaccuracy of toothed disc machining and assembly is shown in Fig. 7. It is related to the mean value of the rotational speed in the measurement cycle being the basis for its calculation. The figure shows two, identical in practice, correction curves which were calculated using two different data samples recorded at different mean shaft rotational speeds. The way in which the correction was calculated is similar to that used for torque correction.

$$n_{cor}(\alpha_n(i)) = \frac{1}{n \cdot n_{av}} \left(\sum_{k=1}^{n} \left(n_k(\alpha_{Ti,j}) - n_{kav} \right) \right) \tag{4}$$

As results from formula (2) the amplitude of the correction curve is directly proportional to the shaft rotational speed. For higher shaft rotational speeds the same geometrical inaccuracies of toothed disc machining lead to higher amplitudes of disturbances, which is confirmed by the rotational speed time-histories shown in Fig. 6.

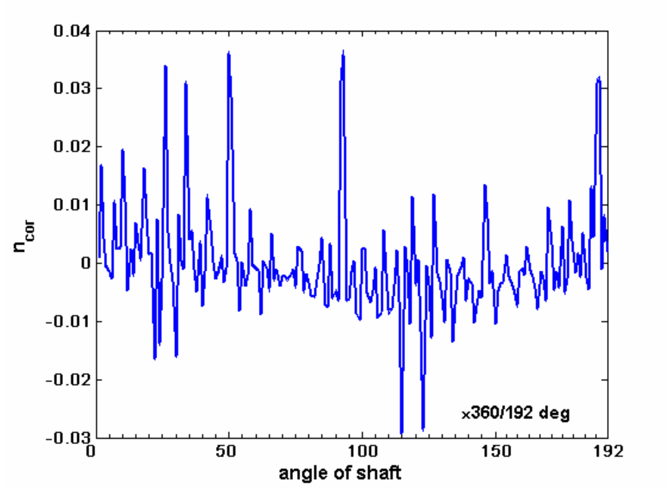

Fig.7. Relative values of propeller shaft speed correction factor

The rotational speed time-histories taking into account the calculated corrections are given in Fig. 8. The figure purposely preserves the same scale of the Y-axis to better illustrate the scale of reduction of the disturbances.

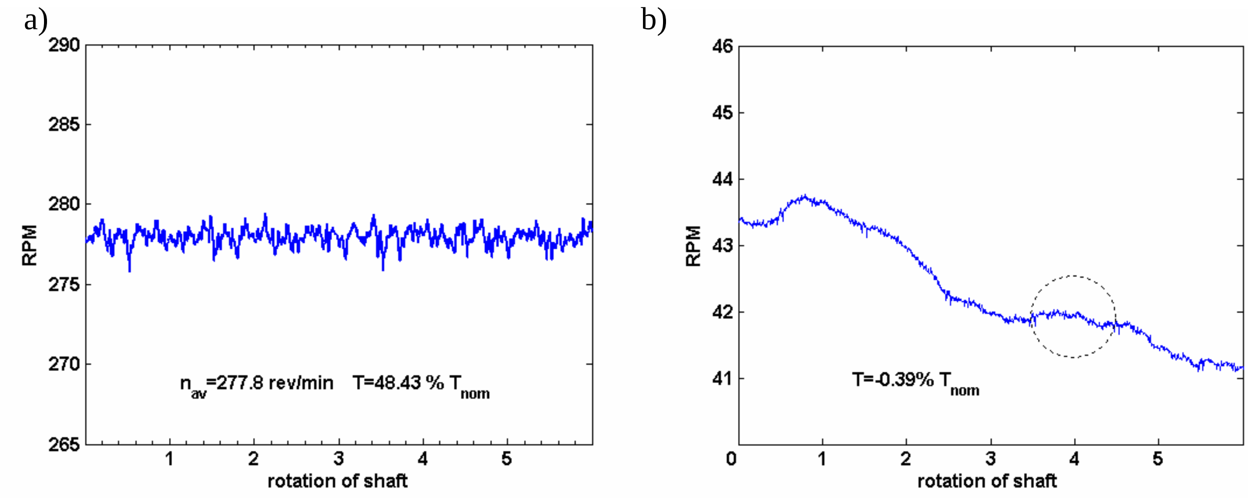

Fig. 8. Time-histories of the propeller shaft rotational speed after taking into account the correction from Fig.7: a) the coupling connected; b) the coupling disconnected

The propeller shaft rotational speed fluctuations shown in Fig. 8a result from power transmission from the engine to the propeller. When the propeller shaft is decoupled from the propulsion engine, the amplitude of fluctuations is significantly lower (Fig. 8b). The time-histories of instantaneous values of shaft rotational speed can also be filtered using the forward-backward method. The result of this filtering, applied to selected fragments of time-histories from Fig. 8, is shown in Fig. 9.

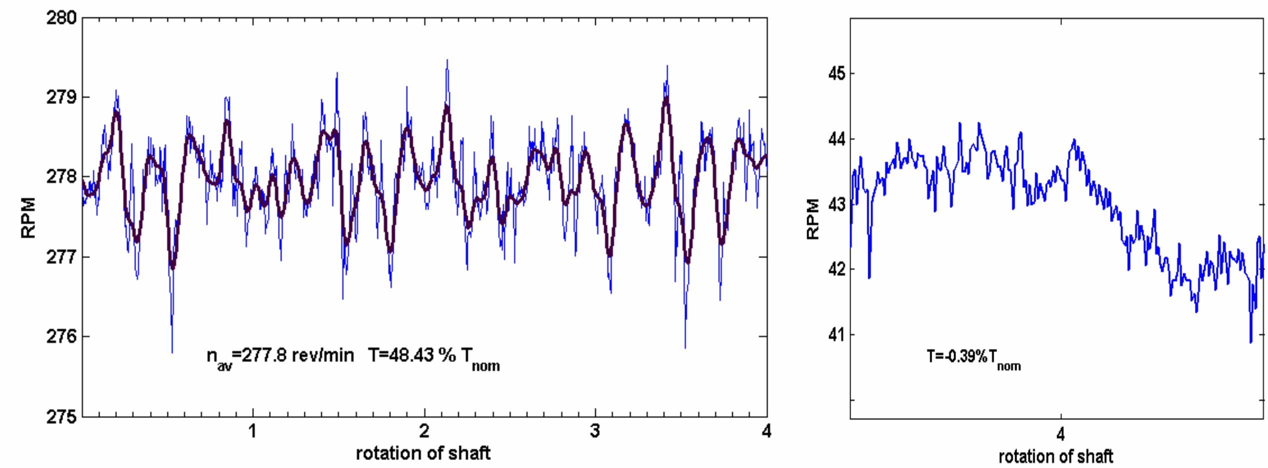

Fig.9. Detailed fragments of rotational speed time-histories shown in Fig.8

4. Final conclusions

The presented results of measurements of instantaneous torque and rotational speed, and the methodology of their processing confirm much higher measuring potential of the newly developed torque meter ETNP-8. The ship on which the measurements were done has a 4-stroke medium speed engine and the power transmission system which to a considerable extent damps torque and rotational speed fluctuations. The analysed time-histories reveal basic harmonics corresponding to the full cycle of engine operation (2 crankshaft revolutions). The components corresponding to the operation of individual cylinders are not recognised in the analysed spectra.

The experience gained from numerous measurements of operating parameters of the power transmission system, performed with the aid of specialised measuring instrumentation on sea-going cargo vessels, allows concluding that along with typical application for continuous measurements of moment and rotational speed, the presented torque meter ETNP-8 can also be used by the measuring staff for diagnostic measurements. Easy use in the operating mode „Diagnostics" allows the machine crew to perform on-line measurements, with their immediate analysis, data storage, and transmission to the shipowner.

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