Ante Šestan
Nikola Vladimir
Nenad Vulić
Boris Ljubenkov

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A STUDY INTO RESONANT PHENOMENA IN THE CATAMARAN FERRY PROPULSION SYSTEM

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Summary

This paper describes the problem of torsional vibration resonance in the propulsion system of a catamaran ferry. The research was inspired by a practical engineering problem. During the ferry service, the ship crew noticed significant vibrational motions in some operating modes. A series of measurements has been conducted to detect the causes of vibration and to determine ship propulsion system shortcomings. In the first part of the paper some typical causes of propulsion system torsional vibrations are indicated, providing a detailed description of the considered problem. Along with the description of the problem, the goal of measurement, plan, methodology and used instrumentation are described in detail. Special attention is paid to the way measurements are performed. Three measurement programs, which have been established and are already presented in literature, are now expanded to investigate the influence of oil level in the governor box on its operating stability. Further on, measurement results are presented and commented on. Finally, conditions causing torsional vibration resonance have been determined.

Key words: *torsional vibrations, resonance, propulsion system, catamaran ferry*

1. Introduction

Significant torsional vibrations often occur in the dynamic chain of ship propulsion system. Compared to other types of vibrations (lateral, axial), torsional vibrations are more difficult to notice, but their effects can cause serious damage to the ship propulsion system. Torsional vibrations of shafting are a consequence of a number of phenomena and processes. Typical excitation sources of such vibrations are pressure variation in the cylinders of the main propulsion engine, inertial forces of crank mechanisms and sea water - propeller dynamic interaction. Although lateral and torsional vibrations often occur independently, it can happen that the lateral vibrations produce periodic torque and vice versa, and this phenomenon is called cross coupling [1]. In addition to this, torsional vibrations are often coupled with axial vibrations.

Dimensions of a shafting system (i.e. diameters and lengths of particular shafts) have a significant influence on its torsional dynamic behaviour [2, 3], as well as on the coupling of torsional vibrations with lateral and axial vibrations. In addition to the shafting system dimensions which have to be taken into account when assessing and analyzing its vibration response, dynamic properties of each part (engine, shafting, gearbox, clutches, couplings, bearings, propeller, governors, etc.) have to be included as they also influence the system.

Vibration reduction is a rather complex task. Besides numerical procedures which are at disposal, measurements and testing conducted in service may detect causes of resonance and conditions in which it occurs. If the vibration problem fails to be resolved by some minor intervention, the propulsion system has to be redesigned or a vibration damper has to be installed [4].

The problem analysed in this paper is related to the development of torsional vibration resonance in the propulsion system of a catamaran ferry. During the service, in some operating modes, the ship crew noticed significant vibrational motions associated with changes in engine noise, temperature increase in the flexible coupling, and with governor bar oscillations. A basic description of the problem and the results of specific parts of measurements are given in [4]. Based on the obtained results, operating modes and conditions which lead to the resonance of shaft line torsional vibrations were detected [4].

Further measurements and testing have been performed to identify the cause of resonance. Based on the conclusion in [4], the measurement program has been expanded with a particular aim to determine the excitation source which generates torsional vibration resonance. Firstly, some typical causes of torsional vibrations of shafting are indicated and a detailed description of the considered problem is given. Then, measurement details are given and the established measurement programs are described. From the measurement results one can conclude that the operation of the propulsion engine governor is unstable. This instability induces increased vibrational motion of the regulation bar for fuel oil dosage. It is assumed that the governor is affected by a too high oil level in the governor box. Therefore, the measurement programs presented in [4] had to be expanded to investigate a possible influence of the oil level in the governor box on the development of propulsion system torsional vibration resonance. Conditions which lead to shaft line torsional vibration resonance have been determined and the cause of resonance has thus been identified.

2. Description of the problem

As already mentioned, during the exploitation of the catamaran ferry significant torsional vibrations have been noticed. At the same time, the temperature of flexible torsional coupling, located between the main propulsion engine and the reduction gearbox, increased. Significant vibrations occurred in two operating modes, i.e. when the engine runs at or below 700 rpm, and at 1100 rpm, but only in the case when the engine speed dropped from or above 1500 rpm to about 1100 rpm.

The considered ship is a two-screw catamaran ferry, Figure 1, equipped with the two independent propulsion systems, Figure 2, i.e. a port and a starboard propulsion system.

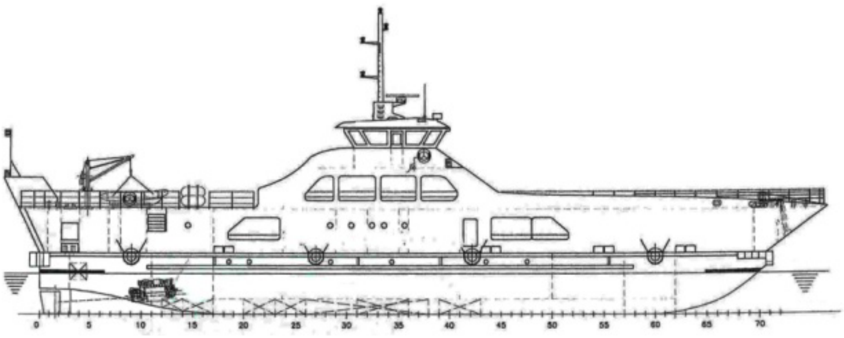

Fig. 1 Lateral plan of the catamaran ferry

Main propulsion engines are of the following type: MAN, D 2842 LE 412, with the nominal power (MCR) of 588 kW at 1800 rpm, with 12 cylinders in "V" layout. The main particulars of the vessel are as follows:

Length between perpendiculars	L_{pp} = 41.00 m
Breadth	B = 15.30 m
Depth	H = 3.60 m
Displacement (full load)	Δ = 650 t
Ship speed	v = 11.5 kn

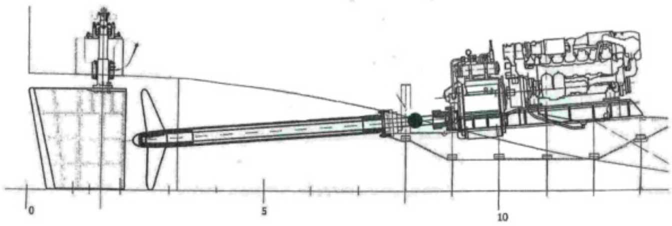

Fig. 2 Ship propulsion system

A series of measurements and testing have been performed in order to find possible causes of the resonance of torsional vibrations in the ship propulsion system. Based on preliminary results, the following possible causes were considered: the shaft line was not aligned properly so the bearing sleeve did not wear uniformly; bearings had large clearances causing significant lateral vibrations increasing thus coupled lateral and torsional vibrations dynamic response; the resilient mounting of main engines was not properly executed; keeping in mind the type of bearings and the type of shaft line setting, the shaft line seemed to be too stiff; the stern structure of the ship was not as stiff as it should have been; the main engine governor operation was not smooth, and the governor had inappropriate regulation characteristics.

Based on the defined situation, the ship-owner decided to eliminate these shortcomings step by step to improve the ship propulsion system features and to avoid possible resonance effects. The reconstruction of the ship aft structure and shaft line as well as the reconstruction of the main engine resilient mounting were done. Also, the elastic springs of main engine governor were replaced with stiffer ones, which resulted in improved regulation characteristics of the governor. Although some of the above listed shortcomings had been eliminated, torsional resonance occurred again, but in a different rpm range. Significant torsional vibrations now occurred at 1500 rpm in a steady state navigation mode about 2 hours after the engines had been started, i.e. after the start of navigation. Vibrations were associated with changes in the engine noise, the temperature increase in the flexible torsional coupling as well as with the movement of angle bar for power change on the governor.

The trouble was that the occurrence of resonance still remained within the operating range of the main propulsion engines. Bearing in mind the above mentioned phenomena, measurements conducted in service were required to investigate the problem fully.

3. Measurement technique

3.1. Aim of measurements

The aim of measurements and testing is to determine the relationship between the occurrence of torsional vibrations in the ship propulsion system and increased cyclic movement of the regulation bar of a high pressure fuel pump on the main propulsion engines. Also, the time instant of vibration occurrence has to be determined accurately, as well as the amplitude of vibrations and the amplitude of regulation bar movement when the propeller shaft is disconnected. The influence of oil level in the governor box on its operating stability, which could lead to a stronger vibration response of the regulation bar, has to be investigated.

3.2. Measurement plan

Measurements have been carried out on the propulsion system of the vessel in the conditions which correspond to the conditions in exploitation. The testing location was the Velebit Channel at the Adriatic Sea. Measurement spots are the regulation bar of the high pressure fuel pump, the propulsion shaft between the gearbox and the stuffing box on the starboard propulsion system, the gearbox, the main engine, and the flexible torsional coupling, Figures 3 and 4.

Movements of the port propulsion system regulation bar are measured in the whole operating range of the main port engine. Amplitudes and frequencies of regulation bar vibrations are measured on the starboard propulsion system in the whole operating range. In addition, torsional vibration amplitudes as well as torque are measured on the starboard propulsion shaft. During the testing, oil temperatures in the engine, governor box and gearbox are controlled, and at the same time the oil pressure in the gearbox is monitored.

Three measurement programs have been established, i.e. programs A, B and C. Measurements were performed by the Brodarski Institute, Zagreb [4]. Program A is the initial testing program when the ship is in a seaport. The main engines are running until the operating temperature is achieved, and the range of engine speed is being changed from 700 rpm to 1700 rpm with increments of 100 rpm. After each increment, stabilization is necessary, taking one minute. The propeller shafts are disconnected and the auxiliary engines are running intermittently. Program B is the normal operating mode of the ship when the ferry sails on its route. Program C follows after Program B has been executed and it is done for the free operating mode, i.e. for tramp navigation.

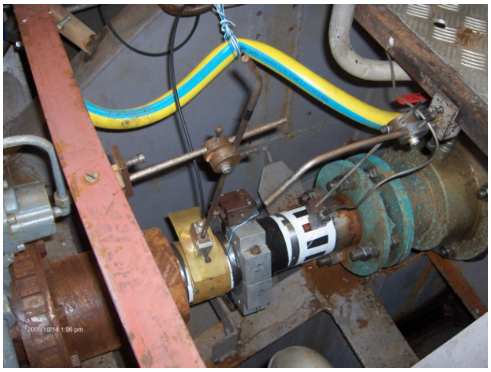

Fig. 3 Torsiometer on the propeller shaft

Fig. 4 Sensors on the main engine

As already mentioned, the expansion of these measurement programs is necessary for the detection of possible (indirect) influence of oil level in the governor box on the development of shaft line torsional resonance. The influence of oil level in the governor box on the vibration amplitude and frequency of the regulation bar for fuel dosage is analysed immediately after resonance has occurred. The main propulsion engine is instantly turned off and a specific volume of oil (approximately 0.5 dm^3) is extracted from the governor box by manual suction. Subsequently, the main propulsion engine is switched on and the propulsion system is reverted to the operating mode in which the torsional vibration resonance occurred. Measurement of regulation bar motion indicates the influence of oil level decrease in the governor box on the main propulsion engine governor behaviour as well as on the behaviour of the whole propulsion system.

3.3. Measurement methodology and instrumentation

Amplitudes and frequencies of vibrations of the regulation bar for fuel dosage are recorded by interpreting the voltage signal on the movement sensor which is installed in the high pressure Bosch pump box. The voltage signal from the sensor located on the port main propulsion engine is transmitted to an amplifier and then to a digital universal voltmeter. The measurement data thus obtained cannot be saved or printed out. The role of signal monitoring is only to indicate the bigger movement of the regulation bar. Therefore, these results are omitted from this paper. Voltage signals from the starboard engine and from the starboard shaft are monitored on the display and saved in the measurement system memory at the same time. The measurement of the oil temperature and pressure in the engines and gearbox systems is carried out by using the same instruments which the ship crew uses during the regular measurement and control of these parameters. The instrumentation for the measurement of regulation bar vibrations is given in Table 1.

Table 1 Instrumentation for the measurement of regulation bar vibrations, (Owner: Brodarski Institute, Zagreb)

No.	Intrumentation	Label
1	Torsiometer	RF: B3 T002/05
2	Accelerometer	B&K4371
3	Accelerometer Calibrator	B&K4291
4	Charge Preamplifier	B&K2635
5	Tape Recorder with Vibration Unit	B&K7005
6	Tape Recorder with FM Unit	B&K7005
7	Oscilloscope	SONY-TEKTRONIX 314
8	FFT Analyzer	B&K2515
9	Measuring Computer	FUJITSU/SIEMENS with NI A/D PCI-MIO-16XE10

Relative lateral vibrations in X, Y and Z (longitudinal, transverse and vertical) directions as well as additional dynamic torsional stresses (rotational) are measured.

4. Results and comments

Results of the measurements and testing confirm the appearance of torsional vibration, accompanied with a flexible coupling temperature increase in both propulsion systems in the identical navigation conditions.

A conclusion is drawn that significant vibrational motions occur in the main propulsion engine speed range from 1440 rpm to 1560 rpm. Vibrations are not generated by rapid changes in engine speed. Moreover, significant vibrational motions occur at critical revolutions when the ship navigates stationary. With regard to the conditions of line service, vibrations occur about 10 minutes after the steady state navigation. It should also be noticed that vibrations occur at least two hours after the first start of the engines. The first start of engines refers to a situation when the engines have been switched off for longer than 2 hours.

Figure 5 shows the motion of the regulation bar for fuel dosage at 1500 rpm, measured according to program A (ship in sea port, propeller shaft disconnected), about 1 hour after starting the engines. Approximate readings of the motion are $H_{max}=4.02$ mm and $H_{min}=3.22$ mm. The mean value of the movement is $H_{mean}=3.66$ mm, and the difference between the maximum and the minimum is $\Delta H = 0.8$ mm.

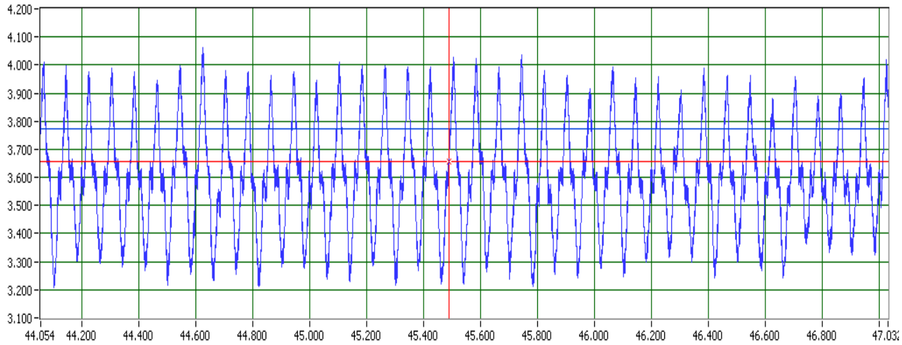

Fig. 5 Regulation bar motion (mm) at 1500 RPM, propeller shaft disconnected (Program A)

The following figure shows vibrational motions of the regulation bar for fuel dosage in the measurement program B, about two hours after starting the engines.

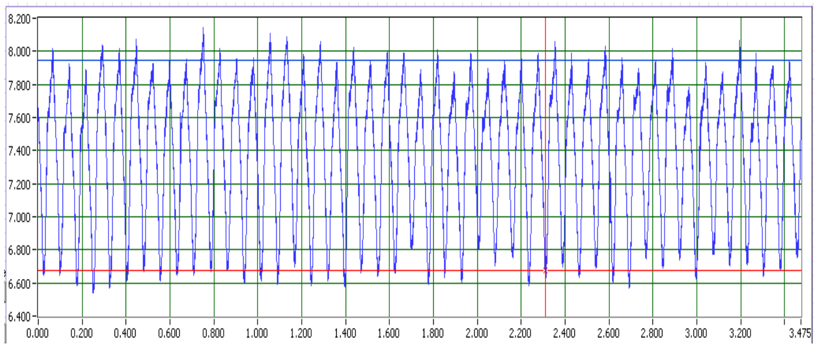

Fig. 6 Time variation in the regulation bar motion (mm) at 1500 RPM, about two hours after starting the engines, (Program B)

The mean value of vibrational motions equals to $H_{\text{mean}}=7.36$ mm. Significant motion of the regulation bar is not present yet, but compared to program A, where $\Delta H = 0.8$ mm, Figure 5, a slight increase is evident since here $\Delta H = 7.95 - 6.68 = 1.27$ mm. A larger increase in vibrational motions of the regulation bar and the development of motion instability are shown in Figures 7 and 8. It is evident that increased vibrations do not occur instantaneously. Moreover, 30 to 40 seconds are needed for the initial instability to develop and it is finalized by the development of full resonance of the bar motion and torque in the ship propulsion system.

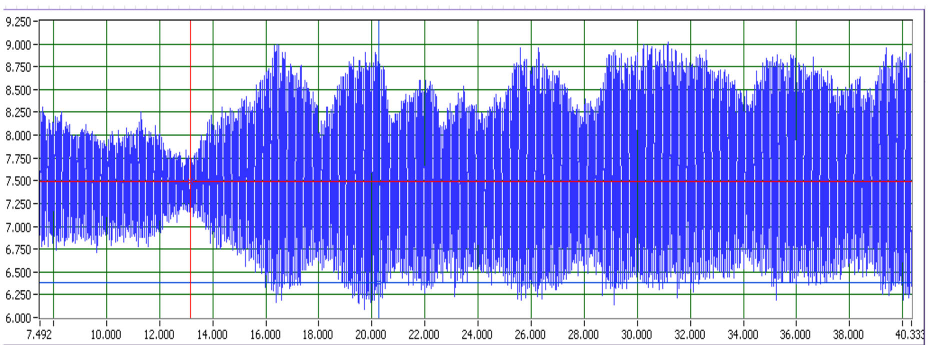

Fig. 7 Significant vibrational motions of regulation bar (mm), about 4 hours after starting the engines (Program B)

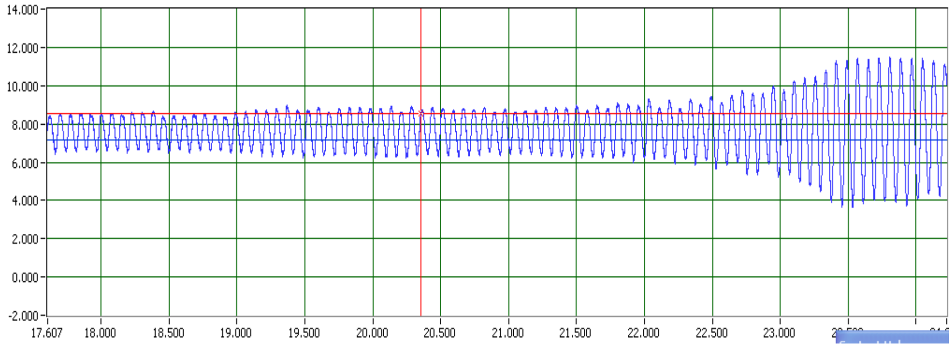

Fig. 8 Development of regulation bar vibration instability (mm), about 4 hours after starting the engines (Program B)

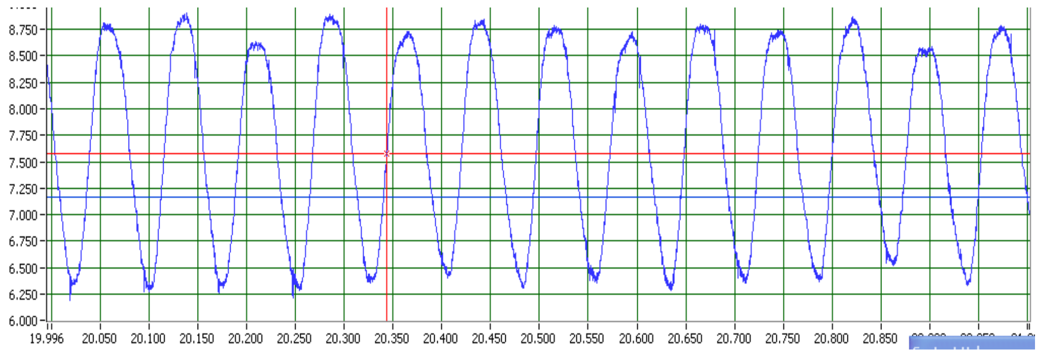

Fig. 9 Zoomed view of the regulation bar vibration instability (mm) development, about 4 hours after starting the engines (Program B)

In the zoomed view of the regulation bar movement, Figure 9, one can see that the maximum and the minimum value of movement are 8.85 mm and 6.35 mm, respectively. The mean value equals 7.60 mm, and the difference between the maximum and the minimum value is $\Delta H = 2.5$ mm (just before the appearance of resonance).

Vibrational motions of the regulation bar and the torque of the propulsion system throughout the resonance development period are shown in Figures 10 and 11. It is evident that the appearance of significant vibration of the fuel dosage regulation bar precedes the torque resonance.

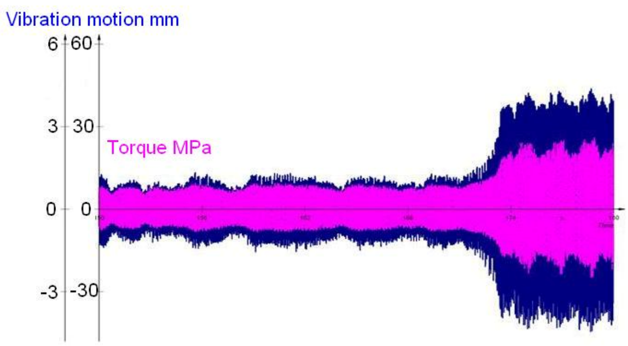

Fig. 10 Common presentation of the regulation bar motion and torque throughout resonance development

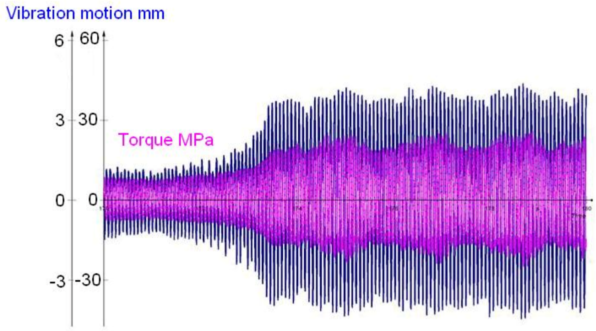

Fig. 11 Common presentation of the regulation bar motion and torque throughout resonance development, zoomed view

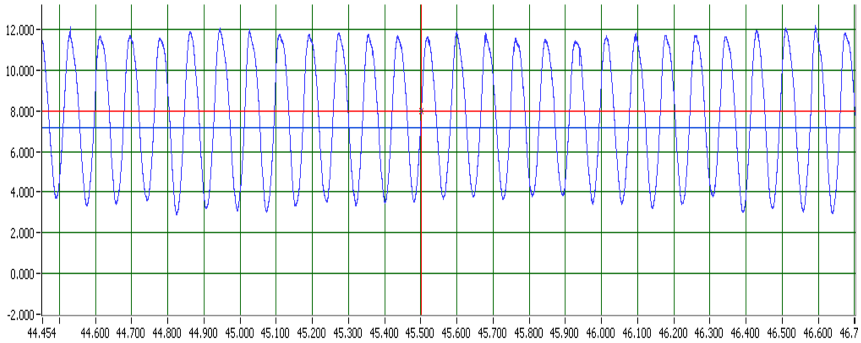

Fig. 12 Motion of regulation bar (mm) throughout the resonant period at 1500 RPM, (Program C)

Figure 12 shows an increase in the regulation bar motion to approximately $\Delta H = 8.0$ mm, and at the same time stresses derived by torque are negative (about -30 MPa), Figure 13, which confirms the existence of resonant behaviour.

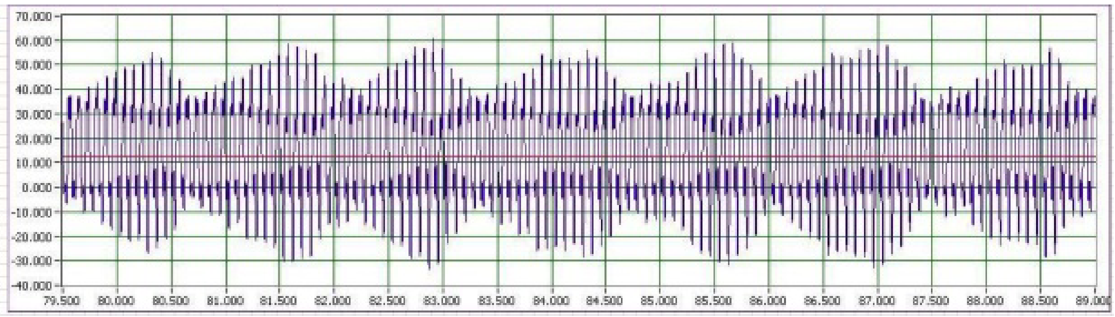

Fig. 13 Time variation of torque at 1500 RPM throughout the resonant period, (Program C)

At the same time, a sharp increase in the temperature of the flexible coupling silicone core is recorded. The rate of temperature increase is approximately 1°C per second. During the resonance period (about 30 seconds) the temperature of silicone core increased from 28°C to 58°C with a tendency of further nonlinear increase.

During the whole testing process, oil temperatures were within the prescribed range for that particular operating mode. The same remark is valid for the values of oil pressure in gearboxes of the ship propulsion system. The synchronization of engine speeds of the main propulsion engines and the auxiliary engines was done in order to register the influence of auxiliary engines on the vibration response of the system. The influence of auxiliary engine running on the main engine fuel dosage regulation bar and on the torsional vibration resonance was recorded. The testing showed that when all measuring conditions exist, resonance will always occur, i.e. the recurrence of resonance is proved.

After the torsional vibration resonance had occurred in the ship propulsion system, according to the measurement plan, a selected volume of oil (approx. 0.5 dm^3) was extracted from the governor box. This caused a decrease in the regulation bar motion, and now the difference between the maximum and the minimum value was $\Delta H = 0.554$ mm, Figure 14, which corresponds to the values obtained in Program A (about 14 times less than throughout resonance).

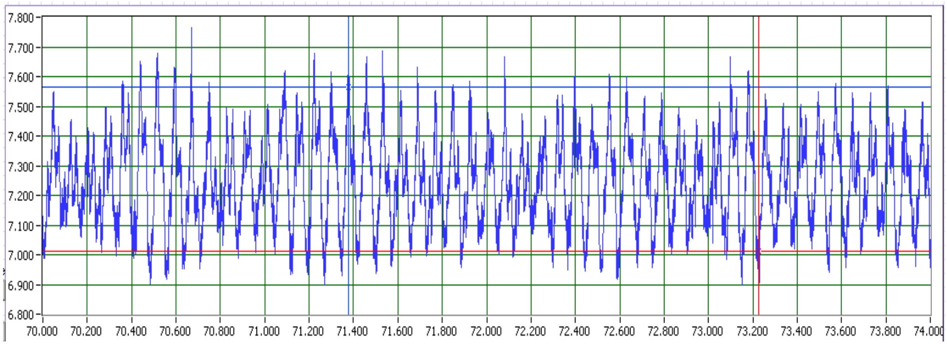

Fig. 14 Motion of regulation bar (mm) at 1500 RPM after oil extraction, (Program C)

The time variation of torque presented in Figure 15 shows that torque amplitudes are in a regular range, and that there is no resonance of torsional vibrations any more. It should be mentioned that the temperature of flexible coupling silicone core is again stabilized to normal operating value of 28°C.

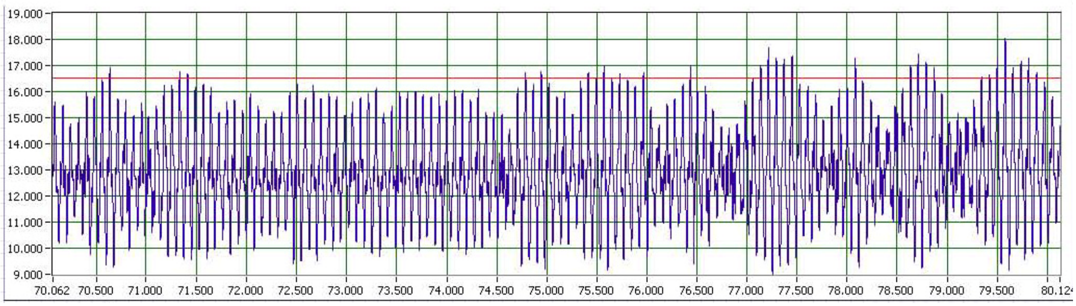

Fig. 15 Time variation of torque at 1500 RPM after oil extraction, (Program C)

5. Conclusion

Issues related with the torsional vibration resonance of a catamaran ferry have been investigated. Because of the complexity of propulsion system, full scale measurement seemed to be the best approach to this challenging problem. The problem is described in details and the measurement technique is discussed. Based on the obtained results, it is again shown that torsional vibration resonance in the ship propulsion system occurs under the following conditions: the propulsion system has to be in operation for at least two hours; revolutions of main engines are in the range from 1440 rpm to 1560 rpm, vibration occurs spontaneously when the ship navigates at critical revolutions after 5 to 10 minutes. The occurrence of significant vibrational motion of the main engine regulation bar for fuel dosage (about 14 times more than out of resonance) leads to torque instability, and the final result of this process is fully developed propulsion system torsional vibration resonance.

Since the intention of this study was to detect a true cause of the resonance, it was necessary to conduct further measurements to investigate the influence of oil volume on the governor operation. The assumption was that the cause of torsional vibration resonance does not belong to typical causes of vibration. Moreover, it has been shown that the oil volume in the governor box can cause the governor operating instability and can lead to significant regulation bar motion, which finally leads to fully developed torsional vibration resonance of the ship propulsion system.

The investigated problem shows that proper design of the ship propulsion system is not sufficient for reliable ship operation. Moreover, it is very important to maintain the ship properly in exploitation because non-typical causes of vibration which cannot be detected easily can cause severe damages to the propulsion system.

Although the measurement instrumentation presented in this study is used for the ship propulsion system in a marine engineering case, it can be used for a wide range of general vibration problems in mechanical engineering.

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Ante Šestan
ante.sestan@fsb.hr
Nikola Vladimir
nikola.vladimir@fsb.hr
University of Zagreb
Faculty of Mechanical Engineering and Naval Architecture
Ivana Lučića 5, 10000 Zagreb, Croatia

Nenad Vulić
Croatian Register of Shipping
Marasovića 67, 21000 Split, Croatia

Boris Ljubenkov
boris.ljubenkov@fsb.hr
University of Zagreb
Faculty of Mechanical Engineering and Naval Architecture
Ivana Lučića 5, 10000 Zagreb, Croatia