Simulating the Torsional Vibration Signal of Two-Stroke Marine Diesel Engine with Normal Firing and Mis-Firing

Simulacija torzijske vibracije signala dvotaktnog brodskog dizelskog motora pri normalnom paljenju i zatajenju paljenja

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Abstract

The article presented the modelling of torsional vibration signal of marine diesel engine, MAN B&W 6S46MC-C7, installed in general cargo ships 34000 DWT, built at Pha Rung Shipyard (Vietnam). The authors imitated the torsional vibration signal, based on the established signal modelling when diesel engine works normal firing and mis-firing state, according to the Class Regulation Rules for new building steel hull ships when calculating and measuring the torsional vibration of marine diesel propulsion shaft-line system. The authors used Matlab software to imitate the torsional vibration signals in the real time domain and then converted them into the frequency order by Fast Fourier Transform (FFT).

KEY WORDS

Marine diesel engine
torsional vibration signal
mis-firing in cylinder
FFT

Sažetak

U radu je prikazano modeliranje torzijskog vibracijskog signala brodskog dizelskog motora, MAN B&W 6S46MC-C7, ugrađenog u brodove za generalni teret, nosivosti 34000, izgrađen u brodogradilištu Pha Rung (Vijetnam). Autori su imitirali signal torzijske vibracije, temeljen na utvrđenom modeliranju signala kada dizelski motor radi s normalnim paljenjem i zatajenjem paljenja, a u skladu s Pravilima za klasifikaciju brodova u gradnji s čeličnim trupom, pri izračunu i mjerenju torzijskih vibracija osovinskog voda porivnog brodskog dizelskog motora. Autori su koristili softver Matlab za imitaciju signala torzijske vibracije u stvarnom vremenu, a zatim ih pretvorili u redoslijed frekvencija pomoću Brze Fourierove transformacije (FFT).

KLJUČNE RIJEČI

brodski dizel motor
torzijski vibracijski signal
zatajenje paljenja u cilindru
FFT

1. INTRODUCTION / *Uvod*

The Class rule requirements from International Association of Classification Societies (IACS) for analyzing and estimating about calculating and measuring torque, stress and forbidden speed range for the rotary shaft-line of the marine diesel engine propulsion (MDEP) which driven with/without shaft generator, Fi-Fi pump.

The Rules for the Survey and Construction of Steel Ships (belong part 3 in chapter 8 [1] in Vietnam (Vietnam Register-VR) and almost famous IACS on the world such as Class NK[2], Lloyds[3], ABS[4],... required the marine vessels were compelled to calculate free tortional vibration of the rotary shaft-line and measure real value at ship directly while sea trial for new building ships to inspect and compare between calculated results and measured results when MDEP operates normal firing and mis-firing cases. In addition to the Class rule requirements from the IACS Rules for the Survey and Construction of Steel Ships, as well as the fact that forced torsional vibrations need to be calculated in two cases: all cylinders work normally in rated engine operating mode and in case one or several of the cylinders does not burn called as mis-firing (the compression process in the mis-firing cylinder still work normally). Therefore, we need to model the forced torque for each cylinder and the total torque of engine in the above mentioned cases.

For the calculation of forced torsional vibrations, it is necessary to determine the dangerous resonant torsional vibrations through the operating frequency range of the propeller shaft system, from the minimum to the maximum operating revolution ($n_{min} \div n_{max}$). The forced torque of the MDEP measured on the intermediate shaft is a multi-harmonic signal, and is usually expressed as the sum of the fundamental trigonometric functions. When resonance or near resonance occurs, the resonant vibration component (forced frequency equals the natural frequency of the oscillation system) will prevail, while other vibration components away from harmonics have a very small amplitude, are negligible and can be ignored. The research results have shown that the non-combustion happens in one or several cylinders of marine diesel engine while it works, the torsional stress will occur on the rotating shaft line of MDEP at any speed. Thus, we have to limit the operation of this forbid revolution range.

To identify which zone is the exploiting or barred zone, we need to calculate and measure the torsional vibration of MDEP and indicate the barred revolution zone on the tachometer. But the non-combustion (mis-firing) in operation process may happen in one or several cylinders, so the working regime will considerably change and breakdown may occur. Thus, the diagnosis for the misfiring status of cylinders by torsional signal is necessary to reach the scientific and practical significance.

The authors used Matlab software to simulate signals into the spectral domain by FFT and then estimated the harmonic

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values in the operating revolution range of the low-speed two-stroke diesel engine MAN B&W 6S46MC-C7. These research results are the foundation for the comparison between the torsional vibration calculating and the one measured on the shaft line of MDEP during the sea-trial.

2. SIMULATION OF THE TORQUE SIGNAL ON THE ROTARY SHAFT OF MARINE DIESEL ENGINE / *Simulacija signala okretnog momenta na rotirajućoj osovini brodskog dizelskog motora*

The piston torque $M_{piston}(\varphi_k)$ of each cylinder is considered as the sum of three components of the torque due to the aerodynamic torque, the force of inertia and the frictional torque of the piston-cylinder:

$$M_{piston}(\varphi_k) = M_{kt}(\varphi_k) + M_{qt}(\varphi_k) + M_{ms}(\varphi_k) \quad (1)$$

The masses of the connecting rod and the crankshaft form the mass inertia torque of the connecting rod - crankshaft mechanism, which will produce the torque acting on the k^{th} crankpin (the k cylinder of amount z cylinder). The total torque of MDEP is the sum of the torques of each cylinder and shall include the component torques are burn gas (indicative torque), inertia and friction (resistance) moments according to (2):

$$M_0(t) = \sum_{k=1}^{z} M_k(t) = \sum_{k=1}^{z} M_{k.kt}(t) + \sum_{k=1}^{z} M_{k.qt}(t) + \sum_{k=1}^{z} M_{k.ms}(t) \quad (2)$$

When the diesel engine is well balanced in terms of mass distribution, the total torque of inertia is very small (negligible, zero).

$$M_{qt}(t) = \sum_{k=1}^{z} M_{k.qt}(t) \approx 0 \quad (3)$$

Then the total torque equation (2) will be the sum of the two components of the aerodynamic torque $M_{o.kt}$ and the frictional (resistance) torque $M_{0.ms}$.

$$M_0(t) = \sum_{k=1}^{z} M_k(t) = \sum_{k=1}^{z} M_{k.kt}(t) + \sum_{k=1}^{z} M_{k.ms}(t) = M_{0.kt}(t) + M_{0.ms}(t) \quad (4)$$

Assuming that the frictional torque is small (engine is well lubricating, negligible resistance) anddoes not vary much compared with the aerodynamic torque. Therefore, at the intermediate shaft-line, where we measure the torque, the forced torque is the total torque of the MDEP. They are also the effective torques of the diesel engine (when the diesel engine is balanced well and ignores the resistances).

$$M_0(t) = \sum_{k=1}^{z} M_{k.kt}(t) = M_{0.kt}(t) \quad (5)$$

Simulating of aerodynamic torque of each cylinder $M_{kt}(\varphi_k)$ via simulating the burn gas pressure in the combustion chamber and shown on the expansion power graph $P(v)$ or $p_i(\varphi_k)$ of each cylinder k,

$$M_{kt}(\varphi_k) = p_i(\varphi_k).\,TF(\varphi_k) \quad (6)$$

In which: TF(φ) is the transfer function corresponding to the crankshaft-connecting rod mechanism of the diesel engine.

$$TF(\varphi) = (\pi.D^2/4).R.(\sin\varphi + 0.5\lambda \sin 2\varphi) \quad (7)$$

Where $\lambda = R/L$ – crankshaft radius and connecting rod length ratio of diesel engine;

$R = S/2$; S – piston stroke, mm;

L – connecting rod length, mm.

The indicative pressure characteristic $p_i(\varphi_k)$ is simulated when diesel engine is firing and mis-firing in the combustion chamber (only the compression-expansion process is performed without burning). These two characteristics which will be presented by two aerodynamic torsional moment curves: Normal firing (Line 1) and mis-firing (Line 2) in Figure 1 is the basis for simulating their torsional vibration signals.

Since the property of the number of harmonic modes for the torsional vibration signal of a two-stroke diesel engine differs from that of a four-stroke diesel engine, when we calculate the torsional vibration of the MDEP, it is necessary to consider at least 12 first harmonics with the coefficients k = 1, 2, 3.....12 for two-stroke diesel engine and at least 25 first harmonics with the coefficients k = 0.5; 1; 1.5, 2,…, 12.5 for four-stroke diesel engine[5].

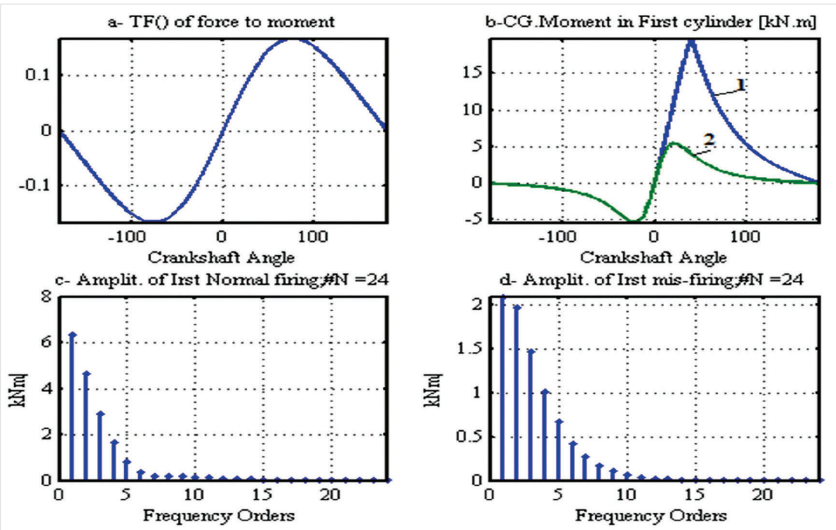

Figure 1 Aerodynamic torque when cylinders are firing and mis-firing
(a) Transfer function TF(φ) of cylinder; (b) Aerodynamic torque when cylinders are firing (Line 1) and mis-firing (Line 2); (c) Amplitude spectrum of aerodynamic torque when cylinders are firing; (d) Amplitude spectrum of aerodynamic torque when a cylinder is mis-firing

Slika 1. Aerodinamički okretni moment pri paljenju i zatajenju paljenja cilindara
(a) Prijenosna funkcija TF (φ) cilindra; (b) Aerodinamički okretni moment kada cilindri pale (Linija 1) i zatajenje paljenja (Linija 2); (c) Spektar amplitude aerodinamičkog okretnog momenta kada cilindri pale; (d) Spektar amplitude aerodinamičkog okretnog momenta kada u cilindru zataji paljenje

Source: [3]

Table 1 Data sheet of two-stroke engine MAN B&W 6S46MC-C7

Tablica 1. Tehnički list dvotaktnog motora MAN B&W 6S46MC-C7

No.	Description	Specification
1	Engine maker	Man B&W
2	Model	6S46MC-C7
3	Nominal Power	7860 kW
4	Nominal Revolution n	129 rpm
5	Bore D/Stroke S	460/1932 mm
6	Crankshaft radius R	966 mm
7	Connecting rod lenght L	1980 mm
8	Fire order	1-5-3-4-2-6

Source: [6]

In order to model the total torque $M_0(t)$ of MDEP, simulations are performed on the 34000 DWT general cargo ships, built in Pha Rung Shipyard (Hai Phong, Vietnam), with the low-speed two-stroke diesel engine driven a fixed pitch propeller. The specifications of marine diesel engine are shown in Table 1.

Based on the graph of the indicated pressure (P_i) according to the revolution of the engine (n) [6], we have the corresponding data relationship (P_i-n) as in Table 2.

Table 2 Function $P_i(n)$ of Engine S46MC-C7

Tablica 2. Funkcija $P_i(n)$ motora S46MC-C7

n (rpm)	40	50	60	70	80	90	100	110	120	129
P_i (bar)	3.5	4.5	5.75	7.03	8.75	10.82	12.80	14.85	17.7	20

Source: [6]

In MDEP operation, we will select a revolution of engine (n, rpm) by choosing the fuel rack position to control the power of engine with the desired load mode. If we know the barred revolution range, then we have to jump out of the dangerous resonance torsional vibration zone quickly and determine a new safety working mode on the range of the revolution presented in Table 2.

3. RESEARCH RESULTS, ANALYSIS AND DISCUSSION / *Rezultati, analiza i rasprava*

For the considered marine diesel engine, MAN B&W 6S46 MC-C7, the fire order is the following: 1-5-3-4-2-6, phase difference in fire order is 60 degrees at crankshaft rotation angle (φ), so the aerodynamic torque of the cylinders has different phases according to the fire order of the diesel engine.

According to the data presented in Table 1 and Table 2, programmed by the authors in MATLAB [7], individual aerodynamic torque curves were obtained for each engine cylinder and total torque in the real-time domain and in the frequency domain in all the cylinders of engine with normal firing in their combustion chambers and no noise consideration (Figure 2). Similar to the above simulation, the authors also simulated the case of cylinder No.1 without burning, representing the total torque in the time domain and in the frequency domain as shown in Figure 3.

Similarly, we studied the torque signal of the MDEP when there is interference with assumed noise amplitude Ar = 1.5 in the cases of normally burning cylinders and the case of one un-burning cylinder.

We also simulated the total aerodynamic torque curve of the engine with random noise. The simulation is similar to the above when we use the noise function in MATLAB. The results are shown in Figure 4 and Figure 5. The Amplitude spectrum of total torque focus at harmonic No. 6 is maximum when all cylinders of engine fired normally as shown in Figure 4, while the maximum amplitude spectrum will be changed into harmonic No. 1 when non-combustion happens in one cylinder of marine diesel engine as in the Figure 5. The total torque (line 0, figure 5a) plus random noise, amplitude Ar = 1.5 presents the acted noise amplitude equal about 8 ÷ 10% of the effective signal.

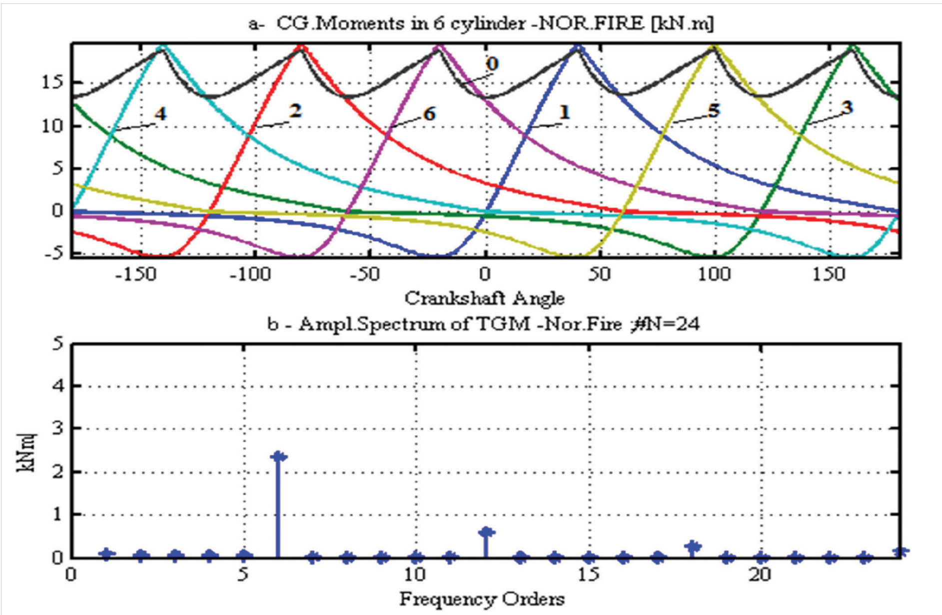

Figure 2 Aerodynamic torque when the cylinders work normal firing

(a) Aerodynamic torque of each cylinder (Cylinder No 1 ÷ No 6) and Total torque (M_0); (b) Amplitude spectrum of the total torque M_0

Slika 2. Aerodinamički okretni moment kada cilindri rade s normalnim paljenjem

(a) Aerodinamički okretni moment svakog cilindra (cilindar br. 1 ÷ br. 6) i ukupni okretni moment (M_0); (b) Spektar amplitude ukupnog okretnog momenta M_0

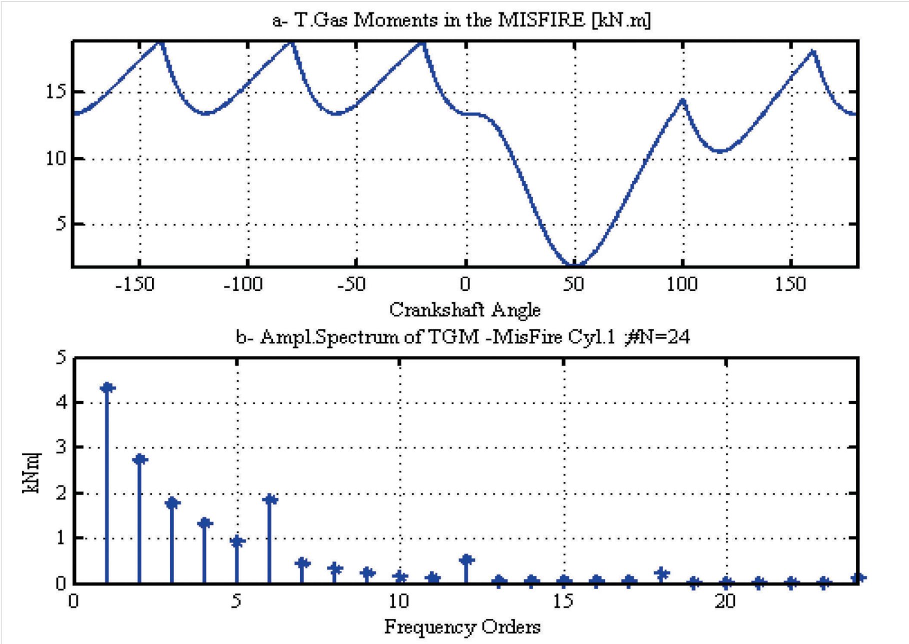

Figure 3 Total torque (M_o) when cylinder No.1 work mis-firing
(a) Total torque $M_o(t)$; (b) Amplitude spectrum of total torque (M_o) when a cylinder is not firing
Slika 3. Ukupni okretni moment (M_o) kada cilindar br. 1 zataji
(a) Ukupni okretni moment $M_o(t)$; (b) Spektar amplitude ukupnog okretnog momenta (M_o) kada cilindru zataji paljenje

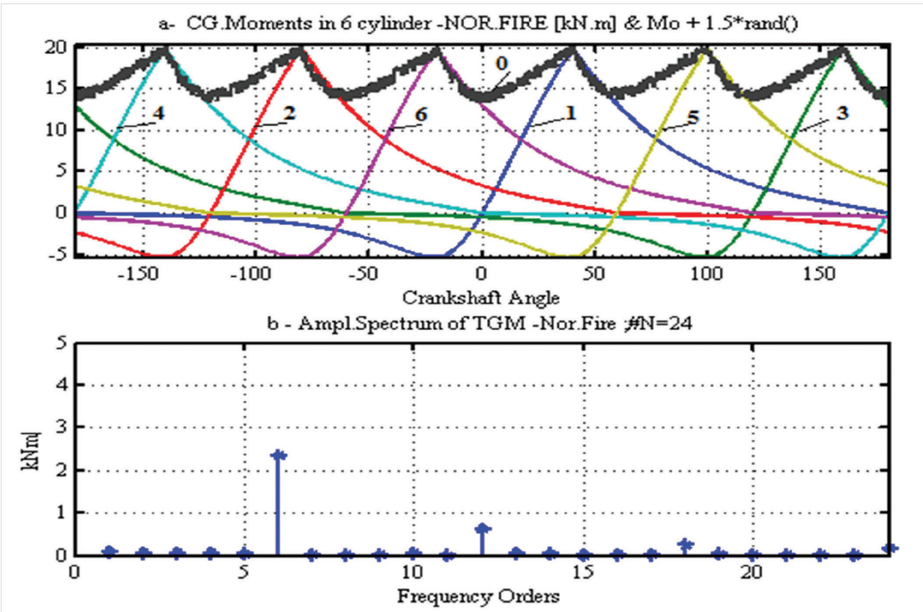

Figure 4 Aerodynamic torque when cylinders work normal firing with noise
(a) Torque per cylinder (No.1 ÷ No.6) and total torque (M_0); (b) Amplitude spectrum of total torque
Slika 4. Aerodinamički okretni moment kada cilindri rade normalno paljenjem uz buku
(a) Okretni moment po cilindru (br. 1 ÷ br. 6) i ukupni okretni moment (M_0); (b) Spektar amplitude ukupnog okretnog momenta

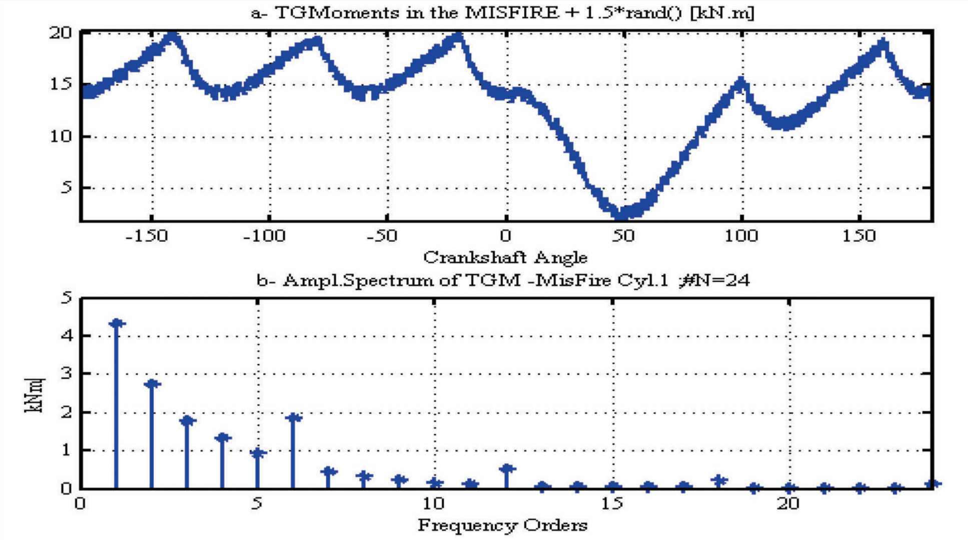

Figure 5 Total torque when cylinder No. 1 work mis-firing with noise
(a) Total torque; (b) Amplitude spectrum of total torque

Slika 5. Ukupni okretni moment kada cilindar br. 1 zataji paljenje uz buku
(a) Ukupni okretni moment; (b) Spektar amplitude ukupnog okretnog momenta

Table 3 shows dR - the error of the harmonic amplitude spectrum of the total torque signal with noise R_c and without noise R_0 when diesel engine works with normal firing.

With the main harmonics H_6, H_{12}, the noise amplitude Ar = 1.5 gives the calculated deviation from the noiseless signal (R_0) as H_6 = 0.0141/2.3440 = 0.6%; H_{12} = 0.0027/0.5966 = 0.4%. For other secondary harmonics, the torque value is very small relative to the level of the acted disturbance, thus confirming the results that the secondary harmonic has zero amplitude if the cylinders are equal, as shown in Figure 6.

The results of calculating FFT for torsional signal with and without noise gave the correlation of noise level and the harmonic amplitude of the secondary total torque.

Table 3 Harmonic amplitude M_o has noise (Ar = 1.5), cylinders burn normally
Tablica 3. Harmonijska amplituda M_o s bukom (Ar = 1,5), normalno izgaranje u cilindru

Harmonic	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}
R_0	0.0775	0.0656	0.0531	0.0479	0.0504	2.3440	0.0170	0.0108	0.0116	0.0119	0.0185	0.5966
R_C	0.0330	0.0551	0.0513	0.0659	0.0618	2.3299	0.0169	0.0366	0.0413	0.0175	0.0366	0.5993
dR	0.0445	0.0105	0.0017	-0.0180	-0.0114	0.0141	0.0001	-0.0258	-0.0298	-0.0056	-0.0181	-0.0027

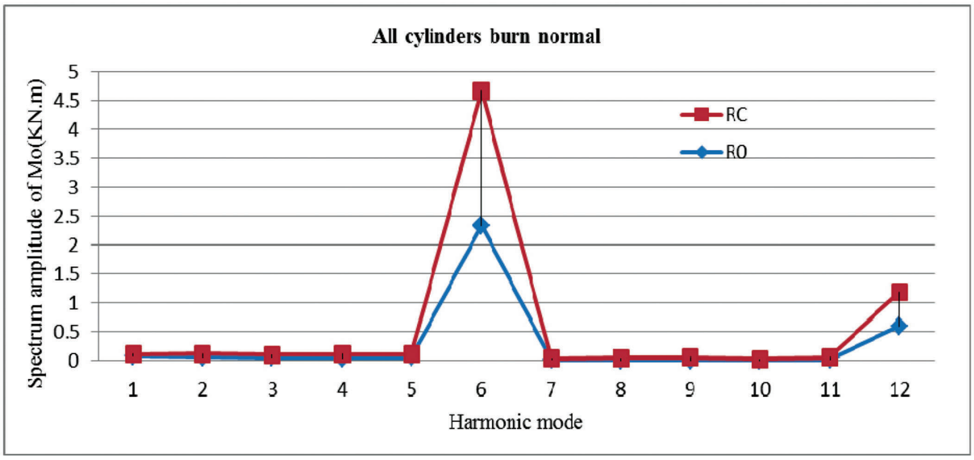

Figure 6 The error of the harmonic amplitude spectrum of the total torque signal when all cylinders burn normally
Slika 6. Greška harmonijskog spektra amplitude signala ukupnog okretnog momenta kada je normalno izgaranje u svim cilindrima

Table 4 Harmonic amplitude M_o when one cylinder got mis-firing with noise Ar = 1.5
Tablica 4. Harmonijska amplituda M_o kada je došlo do zatajenja paljenja jednog cilindra uz buku Ar = 1,5

Harmonic	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}
R_0	4.3275	2.7333	1.7725	1.3345	0.9192	1.8486	0.4560	0.3194	0.2347	0.1483	0.1180	0.5212
R_C	4.3681	2.7316	1.7859	1.3220	0.9173	1.8370	0.4325	0.3001	0.2666	0.1376	0.1113	0.5541
dR	-0.0406	0.0018	-0.0133	0.0125	0.0019	0.0116	0.0236	0.0194	-0.0319	0.0107	0.0067	-0.0329

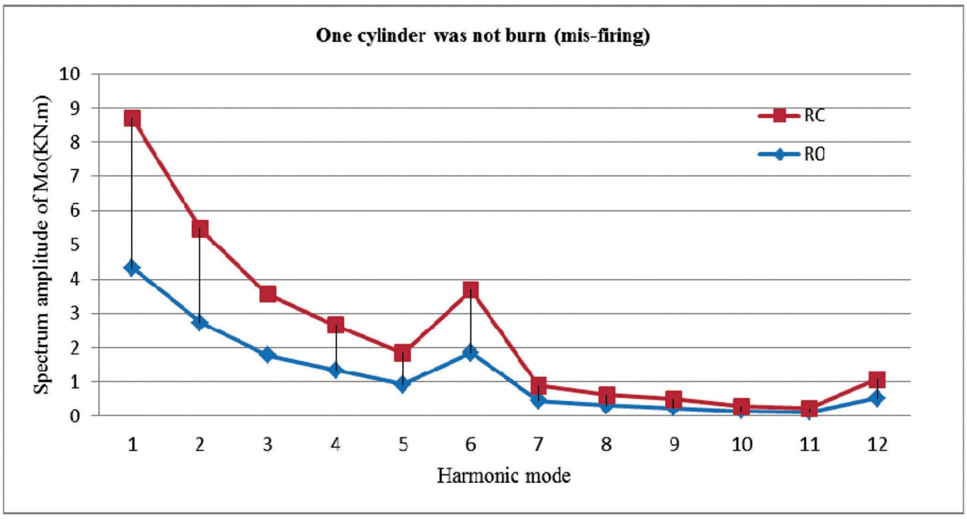

Figure 7 The error of the harmonic amplitude spectrum of the total torque signal when one cylinder was mis-firing
Slika 7. Greška spektra harmonijske amplitude signala ukupnog okretnog momenta kada jednom cilindru zataji paljenje

In real operation regimes, the noise and non-combustion may occur in one or several cylinders. As a result, the new dangerous resonance of the torsional vibration may happen. In this case, the amplitude of the secondary harmonics of the total torque is very big, even bigger than that of the main harmonics. On Table 4, we see that the amplitude of the main harmonics H_6, H_{12} is smaller than many other secondary harmonics (H_1, H_2,...H_{11}), as shown in Figure 7. This is correct and in line with the rule from the total torque analysis of harmonics which has been given in professional literature [8, 9, 10].

4. CONCLUSION / *Zaključak*

Simulation results of the multi-harmonic torque signal are the input basis for digital signal processing and disturbance acting assessment while deploying the torque signal measurement on the MDEP in the real-time domain.

Modelling the signal processing in the real-time domain and then converting it to the spectral domain by Fast Fourier Transform (FFT) in MATLAB has high reliability and accuracy in the absence and presence of noise.

The research results have shown that the spectrum error of the torsional signal is very big in the main and the secondary harmonics.

The simulation results show the reliability of the FFT algorithm in MATLAB, and in many cases it is not necessary to use the noise filter for the signal with random noise when the mathematical expectation of noise is zero.

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