O. K. Sag[*]
H. Yildiz[**]

ISSN 0469-6255
(29-33)

THE INFLUENCE OF FIRING ORDER ON THE PERFORMANCE OF A HIGH SPEED MARINE DIESEL ENGINE

UTJECAJ REDOSLJEDA PALJENJA NA PERFORMANSE BRZOOKRETNIH BRODSKIH DIZELSKIH MOTORA

UDK 627.352:627.32:621.869.8

Original scientific paper
Izvorni znanstveni rad

Abstract

The paper describes a parametric study of the influence of firing order on the performance of a high speed marine diesel engine.

A 16 cylinder, 4 valve per cylinder, direct injection, supercharged high speed marine diesel engine was considered for the study. Having inspected the firing order and the phase angles of the cylinders for the base engine case, theoretically possible firing orders were determined as parameters. The computer simulation program employed in the study utilises the Method of Characteristics for the unsteady gas flow in the exhaust and intake manifolds of the engine. In-cylinder calculations are coupled to the unsteady gas flow calculations and they include the gas exchange process and a combustion simulation routine by a heat release scheme. The turbocharger simulation is carried out by a subroutine and it appears as a boundary to the unsteady gas flow calculations. The results were presented in the form of time-resolved graphs for the in-cylinder and intake pipe pressures for each parameter change. The calculated values of specific fuel consumption and power produced per cylinder for the test cases were compared.

Sažetak

Rad proučava parametarsko proučavanje utjecaja redosljeda paljenja na performanse brzookretnih brodskih dizelskih motora. Za proučavanje je uzet u razmatranje brzookretni brodski dizelski motor sa 16 cilindara i 4 vratila po cilindru sa prednabijanjem izravnog ubrizgavanja. Nakon što se provjerio redoslijed paljenja i kutovi faze cilindara kao parametri su bili određeni teoretski mogući redoslijedi paljenja. Kompjuterski simulacijski program, koji se primjenjuje u istraživanju, koristi postupak značajki za nestalni protok plina u ispušnim i usisnim razvodnim cijevima motora. Proračuni u cilindru su povezani sa proračunima nestalnog protoka plina i to uključuje postupak promjene plina i simulacijski rad izgaranja shemom oslobađanja topline. Simulacija rada turbopuhala se ne izvodi uobičajeno i javlja se kao granica za proračune nestalnog protoka plina. Rezultati su bili prikazani u obliku dijagrama nevremenskog razdvajanja u cilindru i na usisu u cilindar za svaku promjenu parametra. Za ispitivanje kućišta su bile uspoređene izračunate vrijednosti specifične potrošnje goriva sa snagom stvorenom po cilindru

[*]O. K. Sag
Professor of Marine Engineering, Dean of ITU Maritime Faculty, Head of Marine Engineering Dept., National Project Coordinator of Marine Safety Training Center of TURKEY

[**]H. Yildiz
ITU Maritime Faculty Research Fellow

Importance of the firing order
Značaj redosljeda paljenja

The several research works on the internal combustion engines still go on with acceleration day by day even though the first engine prototype was invented nearly a century ago. The main purpose of this kind of intensive studies can be summarised as; achieving the minimum exhaust gas emissions, reducing the noise level and vibrations, reducing the fuel oil consumption and optimising the repair and maintenance periods etc.

In this work, a theoretical investigation on the performance characteristics of a high speed marine diesel engine was carried out considering the firing order as the main influencing parameter.

Due to the high revolution numbers, the minor unbalanced masses can cause major inertia forces in the high speed marine diesel engines. Inertia forces, according to the situation may give rise to intensive vibrations and may give harm to moving parts of the engine and its foundation. Therefore the balancing of the inertia forces is needed as much as possible and also the quantity of the unbalanced forces should be decreased. However, during determination of the crank shaft geometry and firing order, it is noticed that the balance calculation of the forces should not offer the irregular power distribution between the cylinders.

The total intake mass flow rate and its variation related to the crank angle show some differences between the cylinders. As the gas flows in the manifolds, the pressure amplitudes of the charge air will be higher whilst the charge air is heading to the cylinder end. For this reason the pressure varies from one point to another. The total intake mass flow rates into the cylinders are different, and combustion pressure inside the cylinders and the power outputs of the cylinders are also different due to the firing order and wave motion of the charge air in the intake manifold.

In the view of smooth running or permissible vibration and noise characteristics of an engine, the firing order arrangement is always checked with respect to minor harmonic forces occurring inside the engine, because minor harmonics of various firing orders may sometimes be of importance regarding to the vibration problem. The major harmonics are not affected by the firing order, as it is determined already by the number of cylinders.

The inertia forces of the axially moved masses in a cylinder have an importance along to the cylinder symmetry axes. The resultant inertia force of a multi-cylinder engine depends on the crank geometry and the balancing masses. This resultant force acts as a shear force onto the crank shaft.

More detailed information about the dynamics of crank mechanism can be found in the literature. The acceleration of a piston crown as described by Root [1] is

$$a = r\omega^2(\cos\phi + \lambda\cos 2\phi)$$

where

r - radius of the crank diameter

ω - radial (angular) velocity

ϕ - crank angle

λ - ratio of crank radius to the length of the connecting rod

According to the Newton Law, the total inertia forces can be written as follows,

$$F_i = m_p r\omega^2(\cos\phi + \lambda\cos 2\phi)$$

where m_p represents the total acting force on the cylinder symmetry axes, i.e.

($m_p = m_{piston} + m_{connecting\ rod}$). The major harmonics or the first order inertia forces in a multi-cylinder engine are described by the following relation

$$F_{Ii} = m_p\, r\omega^2 \cos\phi$$

and the minor harmonics or the second order inertia forces are represented by:

$$F_{2i} = m_p\, r\omega\,\lambda\cos 2\phi$$

If the resultant force is zero, that means the engine is well balanced related to the first or second order inertia forces. In such a case, the momentum of this inertia forces should be checked. Because the torsional vibration and the torsional stresses are occurred under the conditions of non-uniform harmonic radial inertia forces.

An easy and practical way for determining the firing order is the vector diagram of the inertia forces acting on the crank shaft. The original firing order of the selected engine is given as follows.

A1		A5		A8		A7		A6	
		A4				A3		A2	
	B5		B8		B3		B6		B7
	B4		B1				B2		

Since the engine has 16 cylinders and its power cycle takes 2 revolution of the crank shaft, the phase angle between the cylinders will be:

phase angle = 2 * 360 / 16 = 45 ^{0} Crank Angle

In order to draw the vector diagram called the Crankstar, the cylinder numbers are placed around a circle representing crank shaft according to the revolution direction. A typical crankstar sketch is given in Figure 1. The cylinder numbered A1 is at Top Dead Centre because it will be fired first. The cylinders are placed on the crankstar as they have 45^0 CA of phase angle. The corresponding cylinders (A1, B1, A2, B2 etc.) are then represented by means of unit vectors in sequence.

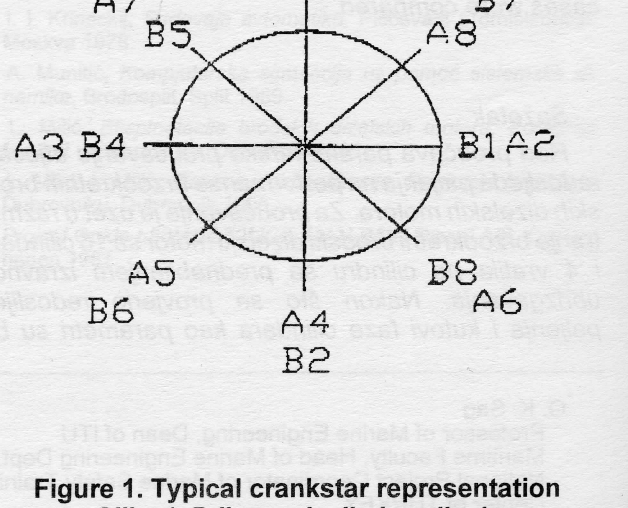

Figure 1. Typical crankstar representation

Slika 1. Prikaz redosljeda paljenja

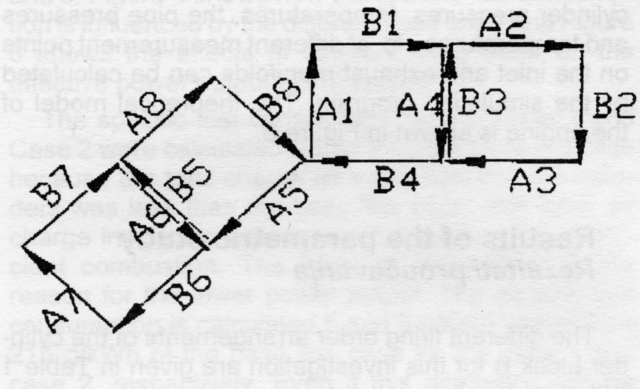

Figure 2. Typical vectoral representation of the inertia forces
Slika 2. Vektorski prikaz sila inercije

If the vector diagram forms a closed area or the last vector returns to the beginning point as shown in Figure 2, this means that the engine has a regular firing order.

It is possible to draw a number of vector diagrams forming a closed area but the main question in each case is whether the firing order will give the best performance on the same operational conditions of the engine.

This paper compares the effect of different firing orders on the engine performance at the same operational conditions by means of a developed computer code which was well tested before. The detailed conclusions are also given at the end of the paper.

The simulation model
Simulacijski model

The dynamic model of the flow in the multi-cylinder intake and exhaust systems is formed by using the mass, momentum and energy conservation equations [2]. These are the one-dimensional, non-homentropic, unsteady and compressible flow equations. The mass conservation is expressed as the rate of change of mass in the control volume equals the flow through the control volume. The energy conservation is based on the first law of thermodynamics and it states that the total internal energy of the control volume depends on the heat and shear work transfers across the system boundary and changes with any net efflux of stagnation enthalpy resulting from the flow across the control surface. The momentum conservation requires that the net pressure forces plus the wall shear forces acting on the control surface equals the rate of change of momentum in the control volume plus the net outflow of momentum from the control surface.

The Characteristics Method which is well described by Benson et al. [3, 4] is used to solve these hyperbolic type partial differential equations for this analytical investigation

Since the inlet and the exhaust manifolds are separated for each cylinder block, the cylinder block B is selected and the characteristics method is applied to this half part of the engine which consists of 32 junction and 64 pipes. The assumptions for this analytical investigation can be summarised as; the manifold is modelled as a combination of pipes and the gas flow

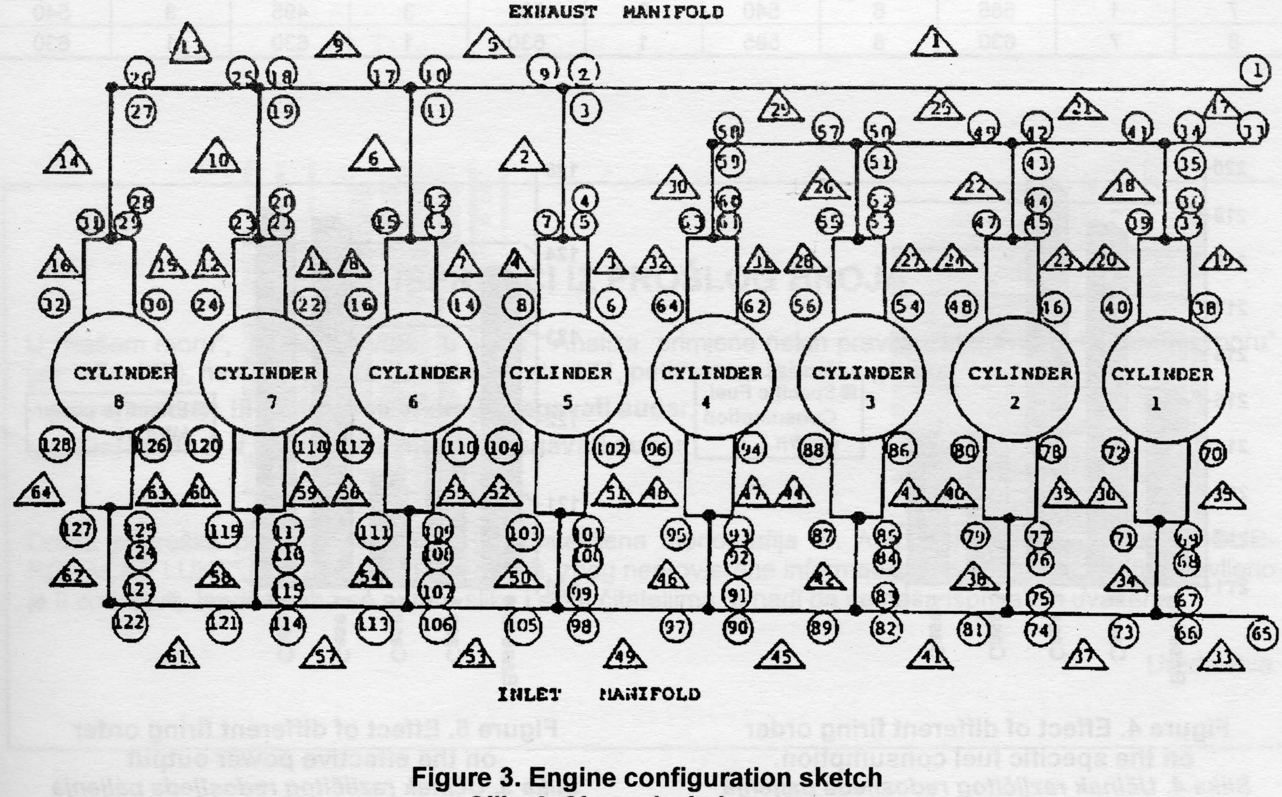

Figure 3. Engine configuration sketch
Slika 3. Shema izgleda motora

in the pipes is simulated by one-dimensional unsteady perfect gas equations with wall friction, heat transfer, gradual area change and entropy gradient change from particle to particle. The gas properties in the cylinders are assumed uniform inside the cylinder at any instant of time. The boundary conditions are considered as quasi-steady. The ideal gas assumption is valid.

The computer simulation code developed by the authors [5] is employed to investigate how the firing order affects the performance of a high speed marine diesel engine by Yýldýz [6]. The code used is able to simulate any type of marine diesel engine such as the single-piston, opposite piston, 2-stroke or 4-stroke, turbocharged or naturally aspirated, motoring or whole cycle including the fuel injection and combustion processes. Main outputs of the program are some cumulative values at the end of the cycle such as specific fuel consumption, mean effective pressure, mass flow rates, power output, maximum combustion pressure, heat losses, thermal efficiency etc. If desired, some gas dynamic variables with respect to time such as the cylinder pressures, temperatures, the pipe pressures and temperatures etc. at different measurement points on the inlet and exhaust manifolds can be calculated by the simulation program. The theoretical model of the engine is shown in Figure 3.

Results of the parametric study
Rezultati proučavanja

The different firing order arrangements of the cylinder block B for this investigation are given in Table 1 with the base line case.

Pressure fluctuations throughout the intake manifold at each case shows different characteristics due to the wave motion of the charge air. For this reason, the engine operational characteristics differs from the base engine case. Effects of the different cylinder firing orders with different phase angle are given in Figure 4

Table 1. Different firing order arrangements for the parametric study
Tablica 1. Različite izvedbe redosljeda paljenja za proučavanje

Firing order	BASE LINE		CASE 1		CASE 2		CASE 3		CASE 4	
	Cyl. No	Phase ang.	Cyl. No	Phase ang.	Cyl. No	Phase ang.	Cyl. No	Phase ang.	Cyl. No	Phase ang.
1	5	0	5	0	5	0	5	0	4	0
2	2	135	2	90	4	135	7	45	8	90
3	8	180	4	135	6	180	6	180	6	135
4	3	315	1	270	7	315	2	225	2	225
5	6	405	7	315	3	405	4	315	5	315
6	6	450	3	405	2	450	8	450	7	405
7	1	585	6	540	8	585	3	495	3	540
8	7	630	8	585	1	630	1	630	1	630

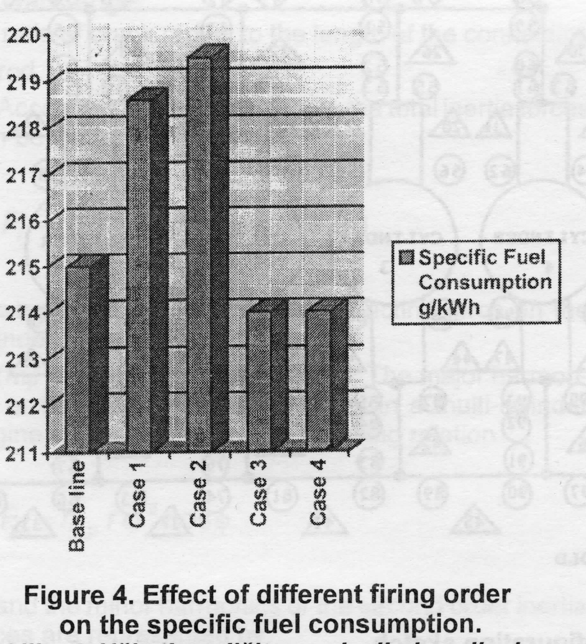

Figure 4. Effect of different firing order on the specific fuel consumption.
Slika 4. Učinak različitog redosljeda paljenja na specifičnu potrošnju goriva

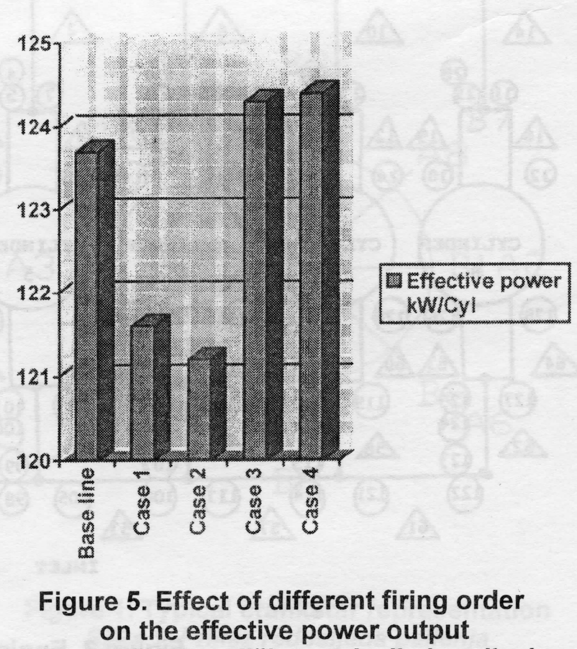

Figure 5. Effect of different firing order on the effective power output
Slika 5. Učinak različitog redosljeda paljenja na učinkovitu izlaznu snagu

and 5. Figure 4 shows how the specific fuel consumption is influenced by the different firing order and Figure 5 shows the effects of different firing order on the effective power output of the engine.

The specific fuel consumption for the Case 1 and Case 2 were calculated higher than the base line case because the total charge air mass flow into the cylinders was less than the base line case. The fresh air charge inside the cylinders is not enough for an efficient combustion. The lower quantity of air is the reason for the lower power output. The specific fuel consumption is calculated 5 and 6 g/kWh higher than 215 g/kWh of the base line case for the case 1 and case 2, respectively. Even if this difference can be thought as negligible, it has a serious importance in the view of operational cost of the engine during the service.

For the Case 3 and 4, the specific fuel consumption is calculated approximately 1 g/kWh less then the base line case. In this situation, the total intake mass flow rates are higher depending on the cylinders. The firing order and phase angles between the cylinders and the effective power outputs of the cylinders are determined higher then the original engine case.

It is obvious that a lot of firing order arrangements can be determined iteratively, because there is no certain rules or a way of implementation for the determination of the optimum crank shaft geometry. The most important point in the design stage is the close relationship between the cylinder firing order and the engine performance (i.e., operational characteristics, thermal stress distribution inside the engine block, vibration and noise level, balancing of the inertia forces, etc).

Conclusion
Zaključak

The main conclusions of the study may be summarised as follows:

1. The phase angles for the firing cylinders play an important role for the pressure fluctuations experienced in the manifolds.
2. Not firing the adjacent cylinders in sequence may reduce the adverse effect on the pressure fluctuations.
3. The effects of the phase angle for the firing cylinders may be observed better with considering the valve timing change.
4. This study may further be extended to cover the optimum manifold design process.

References
Literatura

[1] ROOT R.E., "Dynamics of Engine and Shaft", *John Wiley and Sons*, 1932

[2] HEYWOOD J.B., "Internal Combustion Engine Fundamentals", *Mc Graw Hill Book Co.*, 1988

[3] BENSON R.S., GARG R.D. and WOOLLATT D., "A numerical solution of unsteady flow problem", *Int.J.Mech.Sci., Vol.6*, 1964, pp.117-144

[4] BENSON R.S., HORLOCK J.H. and WINTERBONE D.E., " The thermodynamic and gas dynamic of internal combustion engines", *Vol.1 Clarendon Press.*, 1982

[5] ÖZSOYSAL O.A., "An analytical and experimental investigation of high speed marine diesel engines", *Ph.D. Thesis (In Turkish), Istanbul Technical University*, 1991

[6] YILDIZ, H., "Effect of firing order on the performance of high speed marine diesel engine", *Master Thesis, (In Turkish) Istanbul Technical University*, 1995

ISPRAVCI IZ PROŠLOG BROJA

U "Našem moru", br. 43(5-6)/96., u radu "Analiza primjene nekih pravila izbjegavanja sudara na moru" (str. 171-172), na slici 1. *Križanje kurseva*, str. 171, potkrala se tehnička greška:

- pokraj broda **A III** treba pisati: **mora izbjegavati suda**r, i
- pokraj broda **A II** treba pisati: **može izbjegavati sudar**.

Druga pogreška potkrala se u radu "Predstavljena monografija dr. Antuna Ničetića: POVIJEST DUBROVAČKE LUKE" (str. 233 - 234), preciznije, zbog neprovjerene informacije ime autora fotografije stavljeno je u crni okvir. Ispričavamo se autoru slike i svim čitateljima, u nadi da će naša isprika biti uvažena.

Uredništvo