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ARTICLE

New Method for Building Vector of Diagnostic Signs to Classify Technical States of Marine Diesel Engine by Torsional Vibrations on Shaft-Line

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ABSTRACT

Vector of diagnostic signs (VDS) using torsional vibration (TV) signal on the main propulsion plant (MPP) is the vector of z maxima (or minima) values of the TV signal in accordance with the cylinder firing orders. The technical states of the marine diesel engine (MDE) include R= z+1 classes and are presented in z-dimensional space coordinate of VDS. The presentation of Dk, k=1÷R using z diagnostic signs (Vi, i=1÷z) is nonfigurative and quite complicated. This paper aims to develop a new method for converting VDS from z-dimensional to 2-dimensional space (two-axes) based on the firing orders of the diesel cylinders, as an equivalent geometrical sign of the all diagnostic signs. The proposed model is useful for presenting a technical state Dk in two-dimensional space (x, y) for better visualization. The paper verifies the simulation of the classification illustration of the 7–state classes for the MDE 6S46-MCC, installed on the motor vessel (MV) 34000DWT, using the new above mentioned method. The seven technical state classes (for 6-cylinder MDE, z=6) are drawn separately and visually in the Descartes. The received results are valuable to improve smart diagnostic system for analyzing normal/misfire states of cylinders in operation regimes.

1. Introduction

The TV signal (TVS) contains much important information about the misfiring / normal working conditions of every cylinder in the multi-cylinder marine diesel engine (MDE) [1]. The characteristics of the TVS identifying in time or frequency domains are used to estimate the technical states of the diagnostic object (DO) and called diagnostic signs.

In the works [1, 2, 4], the VDS are formed from the maxima (VA) or minima (VB) of the TVS correspondence with firing order of each cylinder. The size of the VDS is equal to the number of cylinders in the DO. The z-dimensional VDS are used for classifying the technical states (normal / misfiring conditions) of every DME cylinder, in this case DO is 6 cylinder MDE type 6S46 MCC-7 of MAN-BW

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manufactory.

It's hardly to illustrate every technical state D_k, k=1÷R in z-dimensional space V= [$V_1 \ldots V_z$] of the VDS (V=VA or V=VB; VA= [VA_1... VA_z] or VB= [VB_1... VB_z]) because imagining mathematic models in the multi-dimensional space is quite complicated. In many cases, the illustration of D_k (V_1, $V_2 \ldots V_z$) is divided in to a number of a pair of two-dimensional space (V_i, V_j); i ≠j, i=1÷z; j=1÷z [4].

To overcome the above-mentioned presentation inconvenience, the authors convert VDS from z-dimensional to 2-dimensional space. From there, the diagnosis and identification processes could be solved in a more visualization way and easily applied in real-world diagnostic problems.

2. Research Method

2.1 Modeling New Two –dimensional VDS from VA or VB

Let us assume that the TV signals are simulated (or measured) in a working cycle of MDE containing z cylinders. The signal normally has a number of samples, N=1024 or 2048. The signal is divided in to z parts, and every part has N_c = [N/z] samples. In the part in accordance with firing order of every cylinder, we find the maximal and minimal values. We conduct the VA and VB vector of the diagnostic signs from these values.

The firing order of every cylinder is given in the MDE technical documents, such as the 6S 46MCC shows the order [6]: 1-5-3-4-2-6. The parameter features (VAm, VBm) of m^{th} –cylinder are de-phased α_m (degree) in accordance with the first cylinder (two-stroke diesel engine): α_1=0; α_5= 60°; α_3= 120°; α_4= 180°; α_2= 240°; α_6= 300° or in radian: α_1=0; α_5= π/3; α_3= 2π/3; α_4= π; α_2= 4π/3; α_6= 5π/3.

In generally, we conduct the de-phase vector of the working cylinders α:

$$\boldsymbol{\alpha} = [0, \alpha_2 \ldots \alpha_z], \text{ (radian)} \tag{1}$$

The new diagnostic vectors VN are calculated as follow:

$$\mathbf{VN_x}=\sum_{i=1}^{z}\mathbf{V(i)\cos(\alpha(i))};\ \mathbf{VN_y}=\sum_{i=1}^{z}\mathbf{V(i)\sin(\alpha(i))} \tag{2}$$

Where, V= [V (1), V (2) … V (z)], and V=VA or V=VB.

Every class D_k is written by two reference parameters: the mean vector μ_k and the covariance matrix K_k in accordance with the two-dimensional VDS VN= (VN_x, VN_y), k=1÷R.

Illustration of the cylinder working conditions in the Descartes (VN_x,VN_y).

The z –cylinder MDE is classified into R =(z+1) technical classes D_k as above mentioned for diagnostics of the normal or misfiring state of cylinder in accordance with the Rules for Classification and Construction of Sea-going Ships [7].

The block scheme for building the new VDS VN (VN_x, VN_y) and illustrating the R states via the 2-dimensional space is shown in Figure 1.

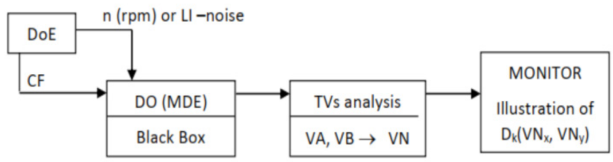

Figure 1. Block scheme for building new VDS in two-dimensional space VN(x, y)

DoE –Design of Experiments, CF –Vector of the z firing coefficients, MDE as a DO; VA, VB –vector of diagnostic signs (z elements of maxima or minima);VN –new vector of two equivalent elements in two-dimensional space (x,y)

In measuring process, we supposed that the revolution n (rpm) and the Load Index (LI) are fixed. However, the real measured signal has some random components and measuring errors. Therefore, we conducted the measuring process ten repeated times with random noises, and the measurement device error is ±5%. This ±5% is bigger than almost thresholds of precise measuring devices in the market today [4].

The main controlling parameters of the technical states of all cylinders are firing coefficients, which are written in the form of vector CF = [Cf (1)… Cf (z)]. The real firing processes are random and for diagnostics model, we assume that firing coefficient Cf (k) is varied with ±5% in accordance with the mean value. In the case of normal working, the Cf = [0.9, 1.0], and with the misfiring state, Cf = [0.0, 0.1]. For every cylinder there are three levels of one firing regime to be examined.

The design of experiments has N_n revolution regimes, for example n_{mean} = 75 rpm, the ∆N=5%.75 =3.75. We would carry out the numerical experiments at N_d = {71÷79} (rpm), for example at the n_{mean} = 75 rpm, N_d = 9 experiments.

The design of experiments has R= (z+1) technical state classes. Thus, we conduct $N_s = 3^z$ experiments for every revolution regime. For example, z=6, N_s = 729.

The total number of experiments of the DoE is N=N_d*Ns. Let us assume z =6, and we conduct each revolution 10 times (in accordance with the real measuring repeat times, N_d =10), the total N is 10* 729 =7290 (experiments).

After building database from the measured (simulated) TVS, the authors analyze TVS to find the VA or VB, and

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finally to draw the new VN-database for the R= (z+1) = 7 states. The VN–database is drawn visually in the two-dimensional (VN_x, VN_y) axes, in accordance with Equation (2).

To diagnose the misfire of any cylinder in the multi-cylinder MDE by classification methodology we have to make the new standard diagnostic characteristics and new diagnostic classifier using the new vector of diagnostic signs VN(x, y).

2.2 Modeling Standard Characteristics of MDE on the New VDS VN(x,y)

The technical states of MDE are grouped in to R=z+1 classes, written with the symbol D_k, k=1…R. Every class has the called referenced (standard) characteristic to identify one with other [1]:

$$\mathbf{D_k:\ D_k(\mu_k, K_k);\ \mu_k = [\mu_{kx}, \mu_{ky}];\ \mu_{kx/y} = \frac{1}{m}\sum_{i=1}^{m} VN_{x/y}}(i)$$

$$\textit{Coded in LabView}: \mathbf{K_k} = \mathrm{cov}(\mathbf{VN});\ \mathbf{\mu_{kx/y}} = mean(\mathbf{VN_{x/y}}) \tag{3}$$

The covariance matrix K_k is calculated.

$$\mathbf{K_k = \frac{1}{m}\tilde{V}_k . \tilde{V}_k^T ; \tilde{V}_k = VN_k - \mu_k} \tag{4}$$

2.3 Diagnostics Classification of MDE on the New VDS VN(x,y)

The current considered state D_c is presented in the similar form with Equation (3) in the following [1, 4]:

$$\mathbf{D_c:\ D_c(\mu_c, K_c);\ \mu_c = [\mu_{cx}, \mu_{ky}];\ \mu_{cx/y} = \frac{1}{m}\sum_{i=1}^{m} VN_{x/y}}(i) \tag{5}$$

The solution of the diagnosis is finding minimum of Mahalanobis distance d_{ck} from distance set:

$$\mathbf{d_{c=m}} = \min\{\mathbf{d_{ck}}, k = 1, 2 \ldots \mathbf{R}\} \Rightarrow \mathbf{D_c} \equiv \mathbf{D_m} \tag{6}$$

The Mahalanobis distance between two classes "c" and "k" is defined below.

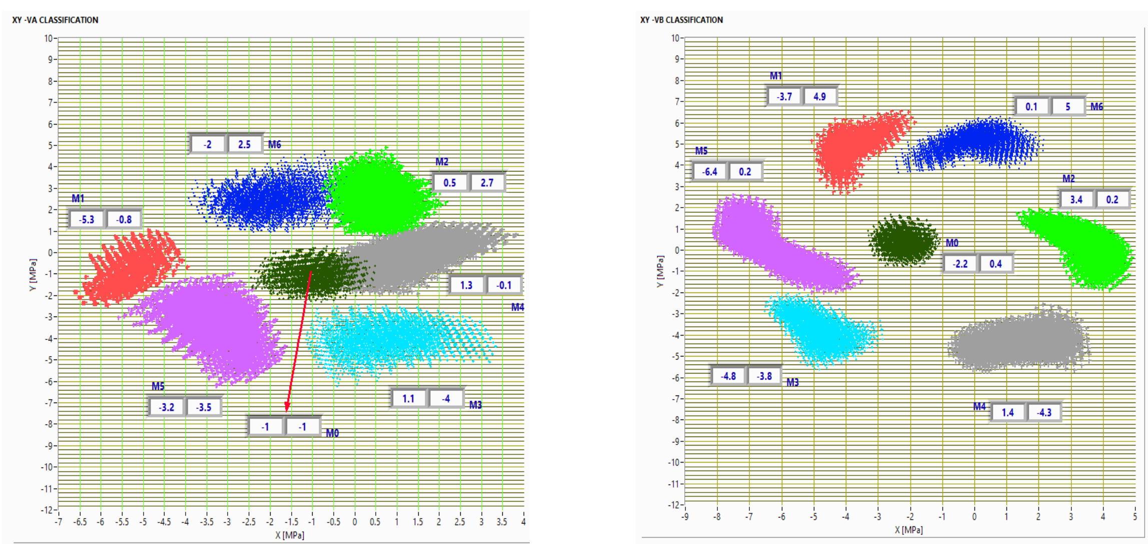
$$\begin{aligned} &\mathbf{d_{ck} = (\mu_k - \mu_c) K_{ck}^{-1} (\mu_k - \mu_c)^T};\\ &\mathbf{K_{ck} = 0.5(K_c + K_k)} \end{aligned} \tag{7}$$

Where, K_{ck} – compound covariance matrix of the two matrixes K_c and K_k.

3. Cases Study: Building the Two-dimensional VDS for Diagnosing the 6S46 MCC

The MDE type 6S46 MCC is installed on the general cargo motor vessel with 34000 DWT (MV 34000 DWT). The TVS of the ship MPP are conducted and supposed to DNV (register) approve by HuDong manufactory [6]. The method and software for automatic torsional vibration calculation (SATVC) are developed at Vietnam Maritime University [0, 5] for this MPP on LabView platform. The SATVC has the features to automatically calculate one of the 7 normal/ misfiring states of the 6 cylinders with revolution regimes N= [0.4, 1.2] NMCR, where N_{MCR} -maximal continuous rate (rpm) and in this case of MV 34000 DWT, N_{MCR} =129 rpm.

For diagnosing technical states normal / misfiring, the diagnostic revolution regimes have to be far from reso-



(a) (b)

Figure. 2 Illustrating the seven classes of the MDE 6S46MCC on MV 34000 DWT via new two-dimensional space (VN_x, VN_y) in accordance with VDS VA (a) and VB (b)

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nance revolution ranges of the torsional vibrations of the MPP because in the resonance or near–resonance revolutions the TVS are quite excited and too large. Therefore we have to calculate the freedom TV for the MPP.

Table 1. Freedom resonances of the MPP on the MV 34000 DWT

n01 (rpm)	**337.16**							
Harmonic	k	7	6	5	4	3	2	
nE(rpm)		48.2	56.2	67.4	84.3	112.4	168.6	
n02 (rpm)	**1436.02**							
Harmonic	k	15	14	13	12	11	10	9
nE(rpm)		95.7	102.6	110.5	119.7	130.5	143.6	159.6

The resonances of the first and second modes of the MPP on the MV 34000 DWT are also defined by the SATVC, especially by the freedom torsional vibration module. The results of the freedom TVs are shown below[3,4]: n_{01}=337.16 rpm; n_{02}= 1436.02 rpm. The revolutions of the DME on the MV 34000 DWT at the interval [52, 155] rpm are resonances that are shown in Table 1.

The interval N_d = [71, 80] is selected for diagnostic revolution regimes.

The two-dimensional illustrations of the seven technical normal or misfiring conditions in cylinders of the DO are shown in Figure 2 using the simulation software which is developed in LabView by authors.

Figure 2(a) shows that when using the maxima VA of the TVS, the pairs of state classes: (D_0 and D_4), (D_2 and D_4), and (D_6 and D_2) couldn't be separated fully in new two-dimensional VN_A (VN_{Ax}, VN_{Ay}). However, Figure 2(b) shows that using the minima VB of the TVS, the pairs of state classes are very well separated in the new two-dimensional VN_B (VN_{Bx}, VN_{By})

4. Conclusions

Using the new method for building two-dimensional VDS has the advantages in classifying R technical states of MDE. The authors applied the new approach for diagnosing the technical sates in the two -axes Descartes (VN_x and VN_y) using the maxima and minima VDS of the shaft-line TVS. The results show that the minima VDS produces the better classification performance than the maxima VDS.

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Abbreviation list

CF	Vector of firing coefficients
DO	Diagnostic object
DoE	Design of Experiments
DWT	Dead weigh tonnage
MDE	Marine diesel engine
MPP	Main propulsion plant
MV	Motor vessel
SATVC	Software for automatic torsional vibration calculation
TV	Torsional vibration
TVS	Torsional vibration signal
VDS	Vector of diagnostic signs
VN	New vector of two equivalent elements

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