Exciting Moment Analysis of V-Type Engine*
(14-Cylinder V-Type Engine)

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The automobile industry in Japan is moving towards high-performance and high-quality engines, which are high-powered and compact. In Europe and America, this goal has already been achieved and multicylinder high-powered engines have been developed. The maximum number of cylinders in an engine for a motorcar in these countries is 16 cylinders in a V-type and this engine is used in sports and racing cars. The next largest engine size below the 16 cylinders is the V-type 12-cylinder engine which is widely used in many luxury vehicles. In Japan, however, although the V-type 12-cylinder engine is the largest, it is loaded only into one type of car. In this paper, we analyze the exciting moment of the V-type 14-cylinder engine which is positioned between the V-type 16-cylinder and 12-cylinder engines, but does not yet have a practical use as a motorcar engine. Here, we consider the characteristics and evaluate the V-type 14-cylinder engine for use in a motorcar.

Key Words: Reciprocating Engine, V-Type Engine, Vibration, Exciting Moment, Bank Angle, 14-Cylinder V-Type Engine, Dynamic Balancer

1. Introduction

The motorcar market is moving towards world-wide maturity and the competition among countries is becoming extremely keen. The high-performance and the low-weight of engines have become pressing requirements to secure competitive strength, and the fabrication of large displacement engines with improved specific power is being attempted. Multicylinder V-type engines are required for this purpose. Currently, the V-type 12-cylinder engine is the largest used in domestic motorcar though it is used only for one type of car. This type of engine is also used for trucks and buses, but in these cases the design concept of engine displacement[1] is different. Overseas, the V-type 12-cylinder engine is often used in luxury motorcars, while the V-type 16-cylinder is used in sports cars[2].

The V-type 14-cylinder engine, (hereafter abbreviated as the V-14 engine along with the other V-type engines) which was selected as the subject of our study, is positioned between the V-12 engine and the V-16 engine. Although the V-14 engine has not yet been used in automobile, many types of V-14 engines has been put into practical use as engines for land and marine use. However, these engines cannot be considered identical to motorcar engines, because they are fundamentally different in size, weight and design concept. In this study, we consider the V-14 engine for use in a motorcar.

One of the authors has previously studied the exciting moments of V-6, V-8 and V-10 engines for motorcars[3]–[6]. The results of analyses of the exciting power and exciting moments of V-type engines and in-line engines have previously been reported[7]. However, the analyses given in this paper are different from those used previously. We analyze the various types of cylinder arrangements (order of injection) with the V-angle as an unknown quantity which can possibly be composed for practical use. We have selected a V-angle which can eliminate the first-order exciting moment and at the same time is effective for the second-order moments. By this analytical method, new information has been revealed concerning the above engines. The study of the V-14 engine is an extension of these studies. Generally, as the number of cylinders increases, the engine

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vibration is reduced. It is said that when the cylinder number of one bank is an odd number such as that in the V-14 engine it is more disadvantageous than for the case of even numbers. However, since V-6 engines are more widely used than in-line 6-cylinder engines because of space efficiency and stiffness improvement of the cylinder block and crankshaft, we believe that further studies are required on V-14 engine as well. The V-14 engine described in this paper is a four stroke-cycle engine with equal interval ignition.

2. Nomenclature

The main nomenclatures used in this paper are as follows.

r : crank radius
θ : rotation angle of crank
ω : angular velocity ($\dot{\theta}$)
δ : inclination angle of connecting rod
s : center distance of cylinders
m_p : piston mass
m_r : connecting rod mass
L : length of connecting rod
L_p : distance between piston pin and center of gravity of connecting rod
L_c : distance between crank pin and center of gravity of connecting rod
λ : r/L
C_p : L_p/L
m_{rec} : $m_p+(1-C_p)m_r$
α_0 : V-angle (bank angle)
α_1,α_2 : inclination angles of the two banks of V-type ($\alpha_0=\alpha_2-\alpha_1$)

3. Exciting Moment and Cylinder Arrangement

3.1 Exciting moment

We consider that n single-cylinder engines are connected in line in the phase difference $2\pi/n$ of the crank with balance weight. The exciting force $F_x(\theta)$ that acts in the direction (x-axis) of the piston movement and $F_y(\theta)$ that acts in the direction perpendicular (y-axis) to it, in the in-line n-cylinder engine are given as follows, assuming that the exciting forces acting in ith cylinder are $F_{xi}(\theta_i)$ and $F_{yi}(\theta_i)$.

$$\left.\begin{aligned} F_x(\theta)&=\sum_{i=1}^{n}F_{xi}(\theta_i)\\ F_y(\theta)&=\sum_{i=1}^{n}F_{yi}(\theta_i)\end{aligned}\right\} \qquad (1)$$

Here,

$$\left.\begin{aligned} F_{xi}(\theta_i)&=m_{rec}r\{\ddot{\theta}G(\theta_i)+\omega^2F(\theta_i)\}\\ F_{yi}(\theta_i)&=0\end{aligned}\right\} \qquad (2)$$

$$\left.\begin{aligned} G(\theta_i)&=\frac{\sin(\theta_i-\delta_i)}{\cos\delta_i}\\ F(\theta_i)&=\cos\theta_i+\frac{\lambda\cos 2\theta_i}{\cos\delta_i}+\frac{\lambda^3\sin 2\theta_i}{4\cos^3\delta_i}\end{aligned}\right\} \qquad (3)$$

Assuming that the distance from the center of the engine to each cylinder is s_i, the exciting moments M_{y0} and M_{x0} around the y- and x-axes, which occur within the engines are given by the following equations.

$$\left.\begin{aligned} M_{y0}&=\sum_{i=1}^{n}F_{xi}(\theta_i)\cdot s_i\\ M_{x0}&=\sum_{i=1}^{n}F_{yi}(\theta_i)\cdot s_i=0\end{aligned}\right\} \qquad (4)$$

Figure 1 shows that the two in-line engines R_1 and R_2 are arranged in the V-type at an angle α_0. The directions of the two piston movements are represented by x_1- and x_2-axes and the crankpins and balance weights are represented by C_1, C_2 and Q_1, Q_2, respectively. When the exciting moments, which are shown by Eq. (4), of in-line engines R_1 and R_2 are represented by M_{y01} and M_{y02}, the pitching moment M_y and the yawing moment M_x around the x- and y-axes which occur due to their V-type setup are represented as follows.

$$\left.\begin{aligned} M_y&=M_{y01}\cos\alpha_1+M_{y02}\cos\alpha_2\\ M_x&=-(M_{y01}\sin\alpha_1+M_{y02}\sin\alpha_2)\end{aligned}\right\} \qquad (5)$$

Here, the signs of α_1 and α_2 in the clockwise direction about the z-axis are positive.

Next, we consider the V-14 engine. The V-14 engine studied in this paper has a structure where the cylinders of a 14-cylinder in-line engine (hereafter abbreviated as the L-14 engine, similar to other in-line engines) tilt alternately and the two L-7 engines are compactly arranged as a V-type. The phase difference of the crankpin of the L-7 engine is $2\pi/7$ and the crankpins are in equiangular arrangement. The exciting force $F_x(\theta)$ in the direction of the x-axis, is represented by Eq. (1), due to the reciprocating mass of the L-7 engine does not cause either the first- or second-order moments. We number the

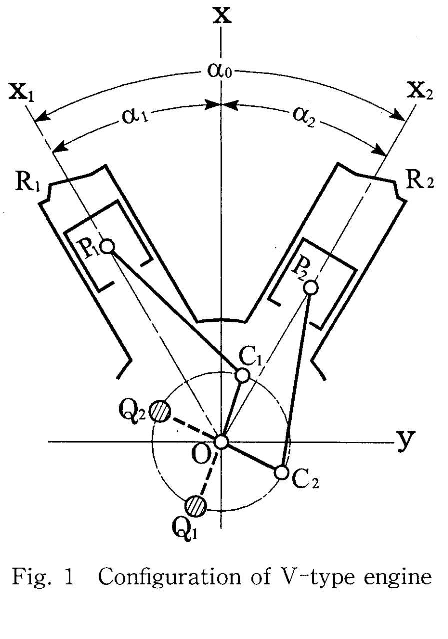
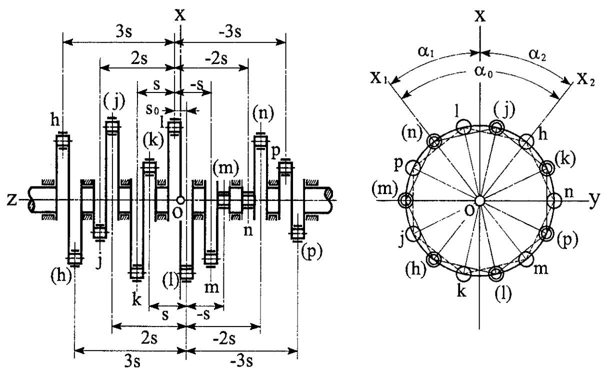


Fig. 1 Configuration of V-type engine



(a) Construction of crankshaft (b) Crankpin phase and V-angle

Fig. 2 Cylinder arrangement example of V-14 engine

cylinders 1, 2, ⋯, 7 according to their order and which has a crank phase of $2\pi/7$ from the positive side of the z-axis showing the direction of the crankshaft of the L-7 engine. Then, $F(\theta_i)$ of Eq. (2) are represented as $F_1, F_2, \cdots, F_7$ by the phase number of the cylinder. That is, $F_1=F(\theta)$, $F_2=F(\theta+2\pi/7), \cdots, F_7=F(\theta-2\pi/7)$. Moreover, because the value of $\ddot{\theta}$ in Eq. (2) is much smaller than that of ω^2 in this study, we hereafter deal only with ω^2.

Figure 2 shows an example of crankshaft construction and the phase of the V-14 engine and its coordinate system. Figure 2(a) shows a crankshaft plane and Fig. 2(b) shows a crankpin phase and the V-angle. The terms h, j, k, l, m, n, and p indicate phase numbers 1～7 of one of the two banks of the V-type, while the other bank is distinguished by the mark ( ). In the construction example shown in Fig. 2, the exciting moments M_{y01} and M_{y02}, which occur on the first bank and second bank of the two L-7 engines, are expressed as follows.

$$\left.\begin{aligned} M_{y01}&=m_{rec}rs\omega^2\{3(F_h-F_p)+2(F_j-F_n)\\ &\quad+(F_k-F_m)\}\\ M_{y02}&=m_{rec}rs\omega^2\{3(F_{(h)}-F_{(p)})\\ &\quad+2(F_{(j)}-F_{(n)})+(F_{(k)}-F_{(m)})\}\end{aligned}\right\} \quad (6)$$

Note that the centers of the two in-line engines of the V-type engine cause a difference of s_0, as shown in Fig. 2. However, this can be neglected because the exciting force of each bank has only a very small influence.

3.1.1 First-order exciting moment Generally, it is desirable that the exciting moment which occurs in the V- type engine becomes extinct for both the first- and second-order by the cylinder arrangement, the V-angle and the balancer. We will first consider the reduction of the first-order exciting moment by the practical balancer. By expanding and arranging Eq. (6) for the first-order, the following equations are obtained. However, this assumes that the subscripts in parentheses are ordered.

$$\left.\begin{aligned}(M_{y01})_1&=a_1\cos\theta+a_2\sin\theta\\(M_{y02})_1&=b_1\cos\theta+b_2\sin\theta\end{aligned}\right\} \quad (7)$$

where a_1, a_2, b_1, and b_2 are constants determined by the cylinder arrangement method. When the two L-7 engines compose a V-type engine, the following equations are obtained from Eq. (5).

$$\left.\begin{aligned}(M_y)_1&=(M_{y01})_1\cos\alpha_1+(M_{y02})_1\cos\alpha_2\\(M_x)_1&=-(M_{y01})_1\sin\alpha_1-(M_{y02})_1\sin\alpha_2\end{aligned}\right\} \quad (8)$$

Equation (8) can be arranged for $\sin\theta$ and $\cos\theta$. The V-angle α_0 is obtained using the conditions for producing a circular precession motion[5]. If Eq. (8) shows the precession motion of normal rotation (the same direction of rotation as in an engine) when $\alpha_0/2$ is divided equally on either side of the x-axis, the first-order exciting moment can be eliminated by a balance weight. To obtain $(M_y)_1$ and $(M_x)_1$ as dimensionless quantities, we denote $(M_y^*)_1=(M_y)_1/M_0$ and $(M_x^*)_1=(M_x)_1/M_0$ using $M_0=m_{rec}rs\omega^2$.

3.1.2 Second-order exciting moment With regard to the second-order exciting moment, when $F(\theta_i)$ in Eq. (3) is represented by a traditional expansion, it can be given as follows.

$$F(\theta_i)=\cos\theta_i+\sum_{n=1}^{\infty}(2n)^2A_{2n}\cos 2n\theta_i \quad (9)$$

$$\left.\begin{aligned}A_2&=\frac{\lambda}{4}+\frac{\lambda^3}{16}+\frac{15\lambda^5}{512}+\cdots\cdots\\A_4&=-\frac{\lambda^3}{64}-\frac{3\lambda^5}{256}-\cdots\cdots\\&\cdots\cdots\cdots\cdots\cdots\cdots\end{aligned}\right\} \quad (10)$$

As a very small quantity higher than λ^3 can be omitted, it is given as the following equation.

$$F(\theta_i)=\cos\theta_i+\lambda\cos 2\theta_i \quad (11)$$

The second term on the right-hand side in Eq. (11) influences the second-order exciting moments $(M_x^*)_2$ and $(M_y^*)_2$. In a similar manner to the first-order exciting moment, when $(M_y^*)_2$ and $(M_x^*)_2$ are arranged by $\sin 2\theta$ and $\cos 2\theta$, it is necessary that they produce a circular precession motion of the second order. However, it is generally difficult for them to satisfy such a condition. Although a precession motion is circular or nearly circular, because a balance shaft is required to eliminate the exciting moment, it is difficult for practical application.

3.2 Cylinder arrangement method

We consider the cylinder arrangement method of the V-14 engine. The combination number of the order of injections of the L-7 engine is 7! = 5 040. In these arrangements, the combination number of the order of injections of the L-7 engine that ignite alternatively across the central cylinder or on the opposite side through the central cylinder is 504. Because the V-14 engine has two L-7 engines in two banks, the number of combinations of cylinder arrangement becomes 504×504=254 016. Because the two banks of the V-type ignite alternately, it is considered that an unsuitable order of injection is contained in the combinations, so we will examine the exciting moments for all combinations here.

To obtain a V-angle for the reduction of the first-order exciting moment, we rearrange $(M_y)_1$ and $(M_x)_1$ of Eq.(8) and change the equations for cos θ and sin θ. When the coefficients of cos θ and sin θ satisfy the condition of composition of a trigonometric function and the exciting moment occurs in circular precession with normal rotation, the V-angle is determined[5]. As a result of this computation it is found that the effective cylinder arrangements which satisfy these conditions are limited to 7 682. Table 1 lists the V-angles from 0° to 180° which are obtained by effective arrangements.

V-angle α_0 takes positive and negative values by the sign of $\alpha_2-\alpha_1$. Table 1 lists only the positive values of V-angles. The V-angle marked by ☆ in Table 1 is related to multiple angles of the phase difference $2\pi/7$ of a crankpin. These angles have different arrangements of about 250 types. Therefore, we consider that an engine which has the same wave of exciting moment and the same V-angle belongs to the same group. Consequently, it is determined that there are a total of 806 groups.

4. V-14 Engine

The V-14 engine is evaluated by comparing its pitching and yawing moments to the V-6 engine which is presently in practical use. As a result of examining about 806 groups, it is determined that four groups of $\pm 9.13°$ and $\pm 170.87°$ V-angles are superior to those of the V-6 engine. However, these V-angles are the angles which approached the in-line type ($\alpha_0=0°$) and horizontally opposed type ($\alpha_0=180°$) in which the exciting moment does not occur. Therefore, problems of obtaining a compact engine still remain. The case of 9.13° engine is similar to the VR-type[8].

Figure 3 shows one of the crank structures of V-angle 170.87° for reference. Figure 3(a) shows a crank composition and Fig. 3(b) shows a crank phase. Figure 4 shows the changing patterns of the exciting moments of the engine. Figure 4(a) shows the pitching moment and Fig. 4(b) shows the yawing moment. M_{yb}^* and M_{xb}^* are the pitching and yawing moments of the balancer. These results show that by installing a balancer onto the crankshaft, the remaining pitching and yawing moments are smaller than those for the V-6 engine. When the remaining moment is small, the remaining exciting moment higher than the second-order is also small. However, according to the results of the calculation, the amplitude coefficients of the vibration of $(M_x^*)_2$ and $(M_y^*)_2$ do not agree in each V-angle. Therefore, each V-angle does not occur in the circular precession motion.

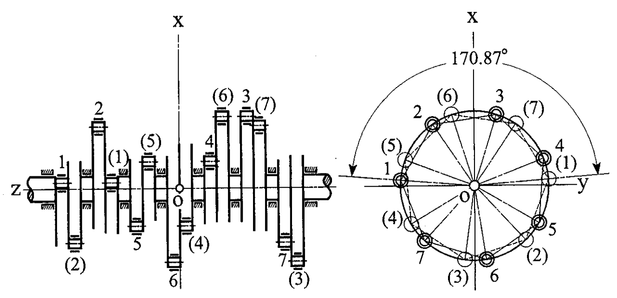
Next, we demonstrate concrete engine examples, where the V-angle is practical and the remaining exciting moment higher than the second-order, is comparatively small.

4.1 49.54° V-14 engine

One of the cylinder arrangements in this case is as follows.

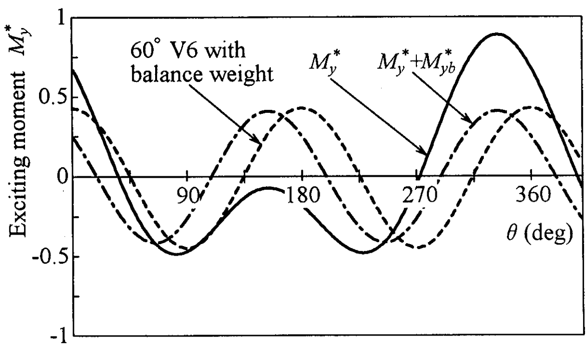
The first bank	1	4	5	2	6	3	7
The second bank	(3)	(7)	(6)	(2)	(5)	(1)	(4)

The exciting moments M_{01}^* and M_{02}^* which occur in the two L-7 engines are obtained by the following equations from Eq.(6).

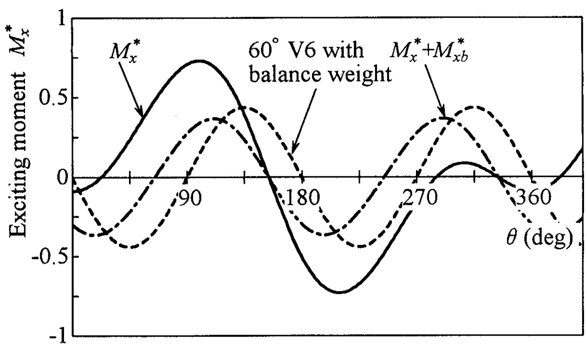


(a) Construction of crankshaft (b) Crankpin phase and V-angle

Fig. 3 170.87° V-14 engine

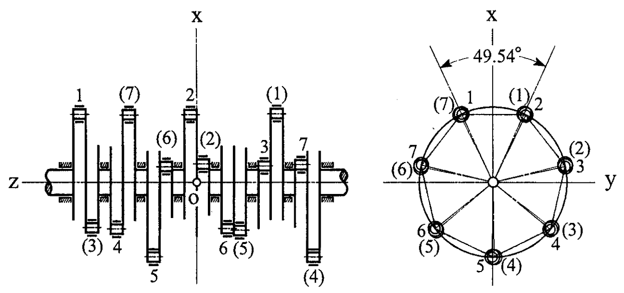


(a) Pitching moment



(b) Yawing moment

Fig. 4 Exciting moment of 170.87° V-14 engine



(a) Construction of crankshaft　(b) Crankpin phase and V-angle

Fig. 5　49.54° V-14 engine

$$\left.\begin{aligned}M_{01}^{*}&=3(F_1-F_7)+2(F_4-F_3)+(F_5-F_6)\\M_{02}^{*}&=3(F_{(3)}-F_{(4)})+2(F_{(7)}-F_{(1)})+(F_{(6)}-F_{(5)})\end{aligned}\right\}\quad(12)$$

Each first-order coefficient of the right-hand side of Eq.(7) is obtained as follows.

$a_1=-0.9058$, $a_2=-1.8045$
$b_1=1.9608$, $b_2=0.4816$

The V-angle α_0 which can erase the first-order exciting moment is obtained as ±49.54°. The first-order exciting moment of the balancer of normal rotation is given by the following equations.

$$\left.\begin{aligned}(M_y^*)_1&=M_0\cos(\theta+\theta_0)\\(M_x^*)_1&=-M_0\sin(\theta+\theta_0)\end{aligned}\right\}\quad(13)$$

Where, M_0 is the amplitude coefficient and θ_0 is the initial phase. The results of calculations are obtained as 1.5363 and 51.43°, respectively. Figure 5 shows the crank structure of the V-14 engine with a V-angle of 49.54°. Figures 5(a) and 5(b) are drawn similar to Figs. 3(a) and 3(b). Figure 6 shows the exciting moment of the engine and Figs. 6(a) and 6(b) show the pitching and yawing moments, respectively. In comparison with the exciting moment of the V-6 engine, it is found that the remaining pitching moment is slightly smaller, but the remaining yawing moment is larger than that of the V-6 engine. Examining the second-order in this case, there is no great difference in the amplitude coefficient of vibration of $(M_y^*)_2$ with 9.13° and 170.87°, but $(M_x^*)_2$ shows about 6-fold larger values. Therefore, it is impossible to install the second-order balancer for the circular precession motion.

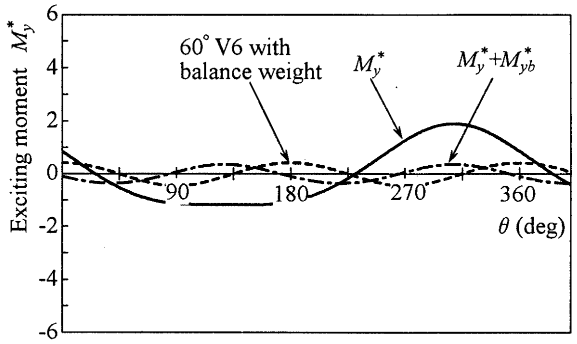
4.2　63.03° V-14 engine

One of the cylinder arrangements in this case is as follows.

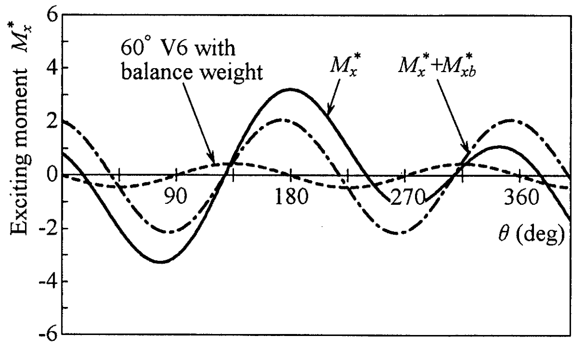
The first bank	1	2	5	6	7	4	3
The second bank	(4)	(3)	(7)	(1)	(2)	(5)	(6)

The V-angle α_0 is obtained as ±63.03° using a similar computation as for the former example. The exciting moment with normal rotation is obtained by the following equations.

$$\left.\begin{aligned}(M_y^*)_1&=4.9216\cos(\theta+38.57°)\\(M_x^*)_1&=-4.9216\sin(\theta+38.57°)\end{aligned}\right\}\quad(14)$$

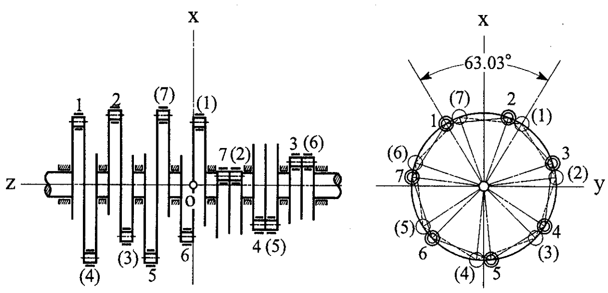


(a) Pitching moment



(b) Yawing moment

Fig. 6　Exciting moment of 49.54° V-14 engine



(a) Construction of crankshaft　(b) Crankpin phase and V-angle

Fig. 7　63.03° V-14 engine

Figures 7(a) and 7(b) show the structure of the crank of V-angle 63.03° and Figs. 8(a) and 8(b) show the changing patterns of the pitching and yawing moments of the engine. In this case, the pitching and yawing moments are large in comparison to those of the V-6 engine. Examining the remaining second-order exciting moment, the amplitude coefficients of $(M_y^*)_2$ and $(M_x^*)_2$ are large, but the difference is comparatively small.

4.3　Evaluation of the V-14 engine

As is evident from Table 1, the V-angles of the V-14 engine which enable the reduction of the first-order exciting moment are of 216 types between 0°～180°. These angles scatter approximately in the entire range of 0°～180°, but the smallest neighboring

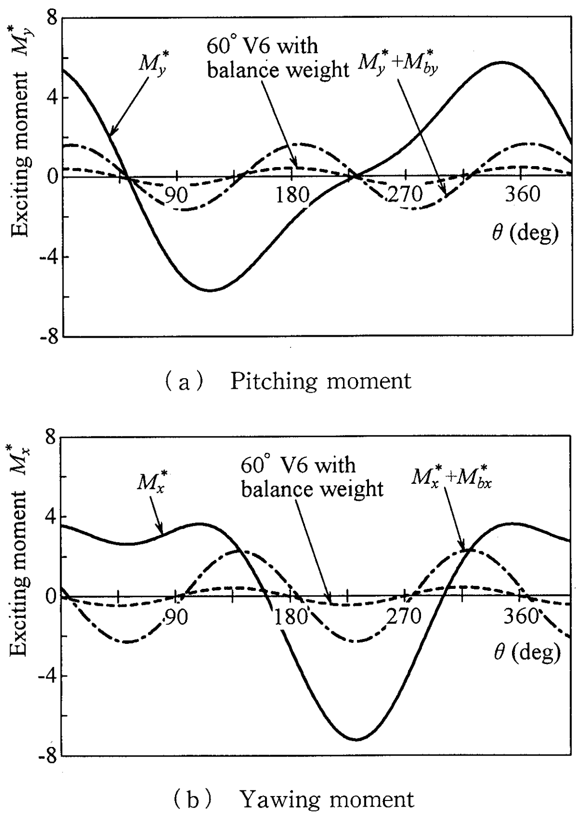


Fig. 8 Exciting moment of 63.03° V-14 engine

angle difference is about 10′ and the maximum is about 224′. Therefore, if the V-angle of the V-14 engine is formed carefully in the cylinder arrangement, it is possible to design it using the arbitrary angle to some extent. Also, the smoothing of vibrations using multicylinders increases the V-angle according to the increase in the number of cylinders. This tendency shows that the number of V-angle in the V-14 engine increases rapidly, compared to the changes in V-6 to V-10 engines. As expected initially, it is found that the exciting moment of the V-14 engine is larger than that of the V-6 engine on the whole, because the second-order remaining exciting moment is large. We have attempted a detailed examination of the second-order exciting moment and have determined that some combinations in the amplitude of the second-order were small at the V-angle for the first-order extinction, and that the amplitude coefficients of $(M_y^*)_2$ and $(M_x^*)_2$ were approximately the same. However, such an example could be accidental.

5. Conclusion

(1) Many combinations of cylinder arrangements of the V-14 engine are possible. There are about 7600 kinds of cylinder arrangements which can reduce the first-order exciting moment.

(2) There are 216 kinds of V-angles which can possibly reduce the first-order exciting moment. Considering the difference of the vibration wave of the exciting moment, they are divided into 806 groups.

(3) The V-angles of the V-14 engine which can possibly reduce the first-order exciting moment, scatter approximately in the entire range of 0°∼180°. Therefore, it is considered that the V-angle does not have practical limitations of design.

(4) Compared to the V-6 engine for practical use, the V-angles of the V-14 engine, which has the same efficiency as the V-6 engine, exist as two kinds and are similar to the in-line type or the horizontally opposed type engine. The reduction of the second-order exciting moment was investigated.

Table 1 V-angles of V-14 engine

(deg)

	1	2	3	4	5	6
1	☆ 0	28.92	60.56	89.09	119.44	151.08
2	1.41	29.77	60.91	91.26	120.23	152.06
3	1.74	30.87	61.45	91.92	123.17	152.40
4	1.88	31.12	62.37	92.84	123.42	152.55
5	2.22	34.06	63.03	93.37	124.51	☆154.29
6	3.21	34.84	63.37	93.73	125.36	155.70
7	4.06	35.20	65.20	94.52	126.35	156.02
8	5.15	35.73	65.54	97.46	126.69	156.17
9	5.40	36.65	66.21	97.70	126.84	156.51
10	8.34	37.31	67.12	98.80	127.16	157.49
11	9.13	37.66	67.66	99.65	☆128.57	158.34
12	9.49	39.49	68.01	100.63	129.99	159.44
13	10.02	39.83	68.80	100.97	130.31	159.69
14	10.94	40.49	71.74	101.12	130.46	162.63
15	11.60	41.41	71.99	101.44	130.80	163.42
16	11.94	41.94	73.08	☆102.86	131.78	163.77
17	13.77	42.30	73.93	104.27	132.63	164.30
18	14.11	43.09	74.92	104.59	133.72	165.22
19	14.78	46.03	75.26	104.74	133.97	165.89
20	15.70	46.28	75.41	105.08	136.91	166.23
21	16.23	47.37	75.73	106.07	137.70	168.06
22	16.58	48.22	☆ 77.14	106.92	138.06	168.40
23	17.37	49.20	78.56	108.01	138.59	169.06
24	20.31	49.54	78.88	108.26	139.51	169.98
25	20.56	49.69	79.03	111.20	140.17	170.51
26	21.66	50.01	79.37	111.99	140.51	170.87
27	22.51	☆ 51.43	80.35	112.34	142.34	171.66
28	23.49	52.84	81.20	112.88	142.69	174.60
29	23.83	53.16	82.30	113.79	143.35	174.85
30	23.98	53.31	82.54	114.46	144.27	175.94
31	24.30	53.65	85.48	114.80	144.80	176.79
32	☆ 25.71	54.64	86.27	116.63	145.16	177.78
33	27.13	55.49	86.63	116.97	145.94	178.12
34	27.45	56.58	87.16	117.63	148.88	178.26
35	27.60	56.83	88.08	118.55	149.13	178.58
36	27.94	59.77	88.74	119.09	150.23	☆180

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