Exciting Moment Analysis of VR-Type Engine*

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A V-type 6-cylinder engine in a special compact design was developed several years ago by Volkswagen. The bank angle was a 15 degrees narrow angle (cylinders are offset). This engine is located between the straight (single cylinder head, small width and good balancing of the oscillating inertia forces) and V-type (short design) engines and combines both the advantages. This is called a VR-type engine. In this study, the conditions that can change a straight engine into a VR-type design without a cylinder offset as well as the exciting moment which occurs in the VR-type engine are analyzed. Finally, in the case of engines with a set number of cylinders, it examines the feasibility and the limit bank angle of a VR-type design.

Key Words: Reciprocating Engine, Vibration, Dynamical Analysis, Narrow V-Type Engine, Exciting Moment, Bank Angle

1. Introduction

A V-type 6-cylinder engine with a new design was developed several years ago by Volkswagen(1). This newly developed engine has a bank angle that is small (15 degrees) as compared with conventional V-type 6-cylinder engines. This new engine has the characteristics of a conventional straight engine and a V-type engine because the bank angle is small. It is called a VR-type engine.

First in this study, the conditions necessary to make a straight VR-type engine are analyzed. Next, the exciting moment which occurs in a VR-type engine is examined. Then the mechanism of erasing the pitching moment and the balancer mechanism in order to reduce the yawing moment in the exciting moment is discussed. The relationship between the cylinder arrangement and the exciting moment is analyzed by the parameter in the bank angle in reference to a VR-type engine with an even number of cylinders from 4 to 8. In conclusion, the practical limit on the bank angle for VR-type structures is clarified and the reduction effect by the balancer of the first order yawing moment is also examined. Further, the engine discussed in this paper is a 4-stroke cycle with equal interval ignition and cylinders are not offset.

2. Exciting Force and Inertia Torque

2.1 Exciting force

Figure 1 shows the single piston crank mechanism and the coordinate system O-xyz. The origin O of the coordinate system is the center of the crankshaft. The z-axis is the direction of the crankshaft. The x-axis is the direction of movement of the piston. The y-axis is perpendicular to the z and x-axes. The center of the piston and crank pins are given by the points O_p and C. The mass of the piston and the connecting rod are m_p and m_r. Point G(x_G, y_G) is the center of gravity of the connecting rod. L is the length. r is the crank radius. Let $\overline{O_pG}$ be replaced by L_p. Then $\lambda = r/L$ and $c_p = L_p/L$. The rotation angle of the crank is θ. The angle between the x-axis and the centerline of the connecting rod is δ. The signs in the angle make the clockwise direction positive based on the x-axis. Point O_x is the instantaneous center of the piston crank mechanism. This is used to obtain the inertia torque (the exciting moment with respect

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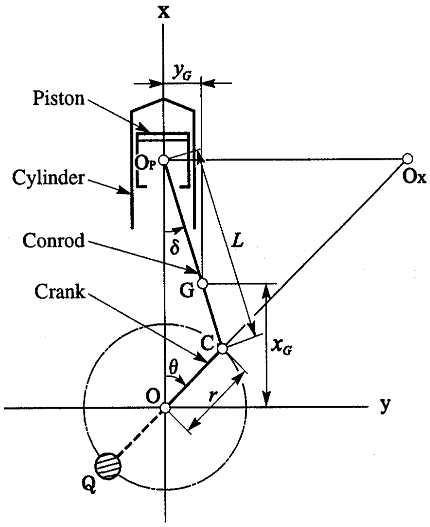


Fig. 1 Single piston crank mechanism

to the z-axis is specifically called the inertia torque) around the crankshaft. Point Q is the symmetrical position of the origin to the crank pin. A balance weight is added to point Q. The exciting force in the direction of the y-axis can be lost due to the balance weight. When the angular acceleration $\ddot{\theta}$ of the crank is negligible as compared to the angular velocity $\omega(=\dot{\theta})$, the exciting force in the direction of the x-axis can be shown by the following equation⁽²⁾.

$$F_x(\theta)=m_{rec}r\omega^2F(\theta) \tag{1}$$

$$m_{rec}=m_p+(1-c_p)m_r \tag{2}$$

$$F(\theta)=\cos\theta+\frac{\lambda\cos2\theta}{\cos\delta}+\frac{\lambda^3\sin^2 2\theta}{4\cos^3\delta} \tag{3}$$

Next, consider an example where an n piston crank mechanism is arranged on one line along the z-axis. When the interval of the explosion is equal, the phase difference of the crank is $2\pi/n$. Then, the rotation angle of the ith crank can be represented by $\theta_i=\theta+(i-1)(2\pi/n)$, $i=1, 2,\cdots, n$. The exciting force which acts the ith piston crank mechanism is, $F_{xi}(\theta_i)$. $F^*_{xi}(\theta_i)$ shows the dimensionless exciting force. The sum total $F^*_x(\theta)$ of the exciting force that acts on the n-cylinder engine is shown by the following equation.

$$F^*_x(\theta)=\sum_{i=1}^{n}F^*_{xi}(\theta_i) \tag{4}$$

Equation (4) shows the characteristics of the change pattern of the exciting force.

2.2 Inertia torque

Assuming that the radius of gyration of the connecting rod is k, an inertia torque $T_z(\theta)$ around the crankshaft which occurs on the single piston crank mechanism is found from Fig. 1 as follows⁽³⁾.

$$T_z(\theta)=r^2\omega^2\left\{m_{rec}F(\theta)G(\theta)+\frac{m_r a^2\nu\sin2\theta}{\cos^4\delta}\right\} \tag{5}$$

Here

$$\left.\begin{aligned}G(\theta)&=\frac{\sin(\theta-\delta)}{\cos\delta}\\ a^2&=\frac{k}{L^2}-c_p(1-c_p)\\ \nu&=\frac{1-\lambda^2}{2}\end{aligned}\right\} \tag{6}$$

The dimensionless inertia torque $T^*_z(\theta)$ is shown by the following equation from Eq.(5).

$$T^*_z(\theta)=F(\theta)G(\theta)+\frac{m_r}{m_{rec}}a^2\nu\frac{\sin2\theta}{\cos^4\delta} \tag{7}$$

A change pattern with the inertia torque of the single cylinder is obtained from Eq.(7).

The inertia torque which occurs on the straight n-cylinder engine is a summation with the inertia torque that acts on each cylinder. Dimensionless inertia torque $T^*_{zi}(\theta)$ which acts on the ith cylinder is obtained by replacing θ in Eq.(7) with θ_i. The sum total $M^*_{zn}(\theta)$ of $T^*_{zi}(\theta)$ is shown as follows.

$$M^*_{zn}(\theta)=\sum_{i=1}^{n}\left\{F(\theta_i)G(\theta_i)+\frac{m_r}{m_{rec}}a^2\nu\frac{\sin2\theta_i}{\cos^4\delta}\right\} \tag{8}$$

Next, a V-type engine with an even number of cylinders $2n$ will be examined. The bank angle is α. Here it is assumed that the two lines of straight engines are symmetrically arranged on either side of the x-axis. The rotation angle of the crank is measured with respect to the x-axis. Inertia torque $M^*_z(\theta)$ which acts on the V-type engine at this point is shown as follows.

$$M^*_z(\theta)=M^*_{zn}\left(\theta+\frac{\alpha}{2}\right)+M^*_{zn}\left(\theta-\frac{\alpha}{2}\right) \tag{9}$$

A change pattern with the inertia torque of the V-type engine is obtained from this.

3. Analysis of a VR-Type Engine

3.1 The construction of a VR-type engine

The VR-type engine is fundamentaly the same as a V-type engine except for the fact that the bank angle of the former is small.

Figure 2 shows the design and the coordinate system O$-xyz$ of a VR-type engine. Origin O is assumed to be at the center of the crankshaft. The x-axis is the direction of the bisector in the bank angle. The z-axis is in the direction of the crankshaft. The y-axis is perpendicular to the x and z-axes. Points O_{P1} and O_{P2} are the centers of the piston pins of the two straight engines which make up a VR-type engine. Points C_1 and C_2 are the centers of the crank pins. Points Q_1 and Q_2 show the centers of the balance weight. Now, the pitching moment which occurs in one of the two straight n-cylinder engines which make up a V-type engine can be represented as $M_{ny}(\theta)$. The pitching moment of the straight n-cylinder engine of the other engine that has a different cylinder arrangement can be represented as $M'_{ny}(\theta)$.

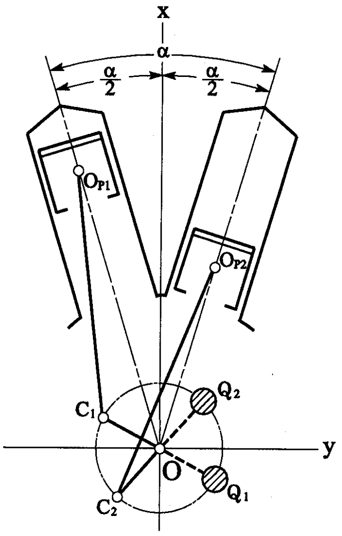


Fig. 2 Configuration of VR-type engine

Then, the pitching and yawing moments $M_{2ny}(\theta)$, $M_{2nx}(\theta)$ which occur on the V-type engine can be shown, respectively, by the following equations.

$$M_{2ny}(\theta)=M_{ny}(\theta)\cos\left(-\frac{\alpha}{2}\right)+M'_{ny}(\theta)\cos\left(\frac{\alpha}{2}\right) \tag{10}$$

$$M_{2nx}(\theta)=-\left\{M_{ny}(\theta)\sin\left(-\frac{\alpha}{2}\right)+M'_{ny}(\theta)\sin\left(\frac{\alpha}{2}\right)\right\} \tag{11}$$

Therefore, if pitching moments $M_{ny}(\theta)$ and $M'_{ny}(\theta)$ which occur in the two straight engines satisfy the following equation, the pitching moment in the VR-type engine is eliminated.

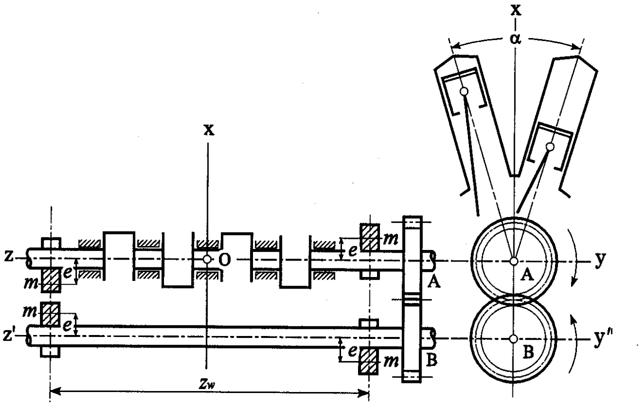
$$M_{ny}(\theta)+M'_{ny}(\theta)=0 \tag{12}$$

In order to satisfy Eq. (12), the cylinders in the two straight engines should be opposite each other.

On the other hand, Eq. (11) of the yawing moment $M_{2nx}(\theta)$ contains $\sin(-\alpha/2)$ and $\sin(\alpha/2)$. Therefore, when α becomes large, the amplitude of the change pattern of $M_{2nx}(\theta)$ increases. The value of α must be small in order that the change in $M_{2nx}(\theta)$ is small. However, the value of α is limited by the structure of the V-type engine. The value of α must be determined in order to limit the vibration in the VR-type engine so that it is less than that in the conventional V-type engine. It is possible to eliminate the yawing moment by using a balancer. The mechanism of the balancer will be analyzed next.

3.2 The balancer for yawing moment

In general, a change in the pitching moment has a more significant impact on the engine as compared with the change in the yawing moment. In a V-type engine, a V-type 8-cylinder engine that is at 90 degrees eliminates the pitching and yawing moments and for the V-type 6-cylinder engine which is at 60 degrees only the pitching and yawing moments that are above the second order component remain. The yawing moment must be reduced using the balancer because the pitching moment is completely eliminated in the VR-type engine.



(a) Crank structure

(b) Side view

Fig. 3 Mechanism of the balancer for yawing moment

Figure 3 shows a model of the balancer that can eliminate the first order yawing moment of a VR-type engine. The coordinate system is an O-xyz coordinate system, which makes the center of the crankshaft the origin as in Fig. 2. Figure 3(a) shows a section of the crankshaft. Figure 3(b) shows an outline of the side. As shown in Fig. 3(a), a balancer axis z' is installed parallel to the bottom of the z-axis and it is reversed by two gears A and B. Weights with mass m are installed near both edges of the crankshaft and the balancer axis which is an equal distance from the origin O. Two weights which are on the same axis have phase difference π, as is shown in Fig. 3(a). In addition, two weights which are placed opposite between the two axes have the same phase difference of π. The distance between the centers of gravity of weights and the centerline of the axis is e. The distance of the two weights on the same axis is z_w. The yawing moment $M_{xb}(\theta)$ which occurs with these four balancers is given by the following equation.

$$M_{xb}(\theta)=2mez_w\omega^2\sin\theta \tag{13}$$

Therefore, if m, z_w and e are used to satisfy the following equation, the first order yawing moment which occurs in the VR-type engine is completely eliminated. Only that equal to or more than the second order moment is left.

$$M_{2nx}(\theta)+M_{xb}(\theta)=0 \tag{14}$$

Then, it is possible for the bank angle of the VR-type engine to be changed arbitrarily.

4. Evaluation of a VR-Type Engine

Here, the exciting moment and bank angle of a VR-type engine with a set number of cylinders are examined. All the design specifications of the engines such as the pistons and the connecting rods used in the concrete examples are identical. Also, the exciting moments are related to the second order component for analysis. As for the first order component, the conditions and the effects of the balancer which eliminates it are considered. In addition, in the following analysis, the number of cylinders in the two lines of the straight engines which make up a VR-type engine is n.

4.1 VR-type 4-cylinder engine (VR 4 engine)

A VR 4 engine has few practical advantages for an automobile. Here, applications to other fields are examined.

Table 1 shows combinations of the cylinder arrangements that make up the two lines of the straight engine of a VR 4 engine. There are two kinds of cases, 1 and 2. In Table 1, the figure in the top section and the figure in the brackets in the bottom section show the first and second lines of the cylinder arrangements, respectively. The figures of the arrangements represent the phase number of the crank. With the arrangement in section 3, the first and second lines are opposite arrangements. Dimensionless pitching moments $M^*_{2y1}(\theta)$ and $M^*_{2y2}(\theta)$ of the two lines of the straight engine in Case 1 are shown by the following equations.

$$\left.\begin{aligned} M^*_{2y1}(\theta)&=\frac{1}{2}\{F_2(1)-F_2(2)\}\\ M^*_{2y2}(\theta)&=\frac{1}{2}\{F_2(2)-F_2(1)\}\end{aligned}\right\} \qquad (15)$$

Here, $F_2(1)$ and $F_2(2)$ show the θ of $F(\theta)$ at the phase number. The pitching and yawing moments $M^*_{4y}(\theta)$ and $M^*_{4x}(\theta)$ which occur in the VR 4 engine due to the above are shown by the following equations.

$$\left.\begin{aligned} M^*_{4y}(\theta)&=M^*_{2y1}(\theta)\cos\left(-\frac{\alpha}{2}\right)+M^*_{2y2}(\theta)\cos\left(\frac{\alpha}{2}\right)\\ M^*_{4x}(\theta)&=-\left\{M^*_{2y1}(\theta)\sin\left(-\frac{\alpha}{2}\right)+M^*_{2y2}(\theta)\sin\left(\frac{\alpha}{2}\right)\right\}\end{aligned}\right\} \qquad (16)$$

The pitching moment becomes zero due to the arrangement. The remaining yawing moment is arranged by the following equation.

$$M^*_{4x}(\theta)=2\cos\theta\sin\frac{\alpha}{2} \qquad (17)$$

The value for the balancer of the first order yawing moment is shown by Eq. (14). The pitching and yawing moments in Case 2 are the same as when $M^*_{2y1}(\theta)$ and $M^*_{2y2}(\theta)$ are exchanged in Eq. (16) from Table 1. Therefore, the yawing moment is obtained as follows.

$$M^*_{4x}(\theta)=-2\cos\theta\sin\frac{\alpha}{2} \qquad (18)$$

Table 1 Combinations of cylinder arrangement of VR 4 engine

Case	Arrangement
1	1 2 (2) (1)
2	2 1 (1) (2)

Figure 4 shows the change patterns for the yawing moments when the bank angle changes from 10 to 90 degrees as in Case 1. The change pattern of the exciting moment of a V-type 6-cylinder engine at 60 degrees (60° V 6 engine) with a balancer mechanism which is presently in use is shown in Fig. 4 by a chain line. The range where the VR 4 engine does not exceed the change pattern of the 60° V 6 engine is the standard latitude for the bank angle α. Figure 4 shows that a VR 4 engine can be used without a balancer if the bank angle α is 20 degrees. Case 2 is obtained by only reversing the phases in Case 1 and has the same results as Case 1.

Figure 5 shows the balancer effect of the VR 4 engine. Here, the exciting moment of a 60° V 6 engine is shown for comparison. When the balancer that eliminates the first order yawing moment is installed, the second and higher order yawing moments can be disregarded regardless of the value of the bank angle α.

Figure 6 shows the inertia torque $M^*_{4z}(\theta)$ of a VR 4 engine when the bank angle α is 15 degrees. $M^*_{2z1}(\theta)$

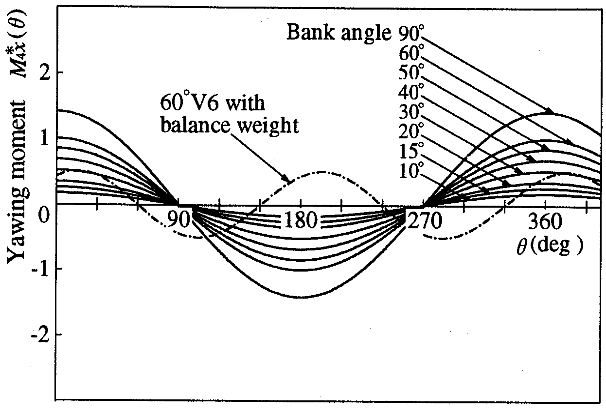


Fig. 4 Yawing moment of VR 4 engine (Case 1)

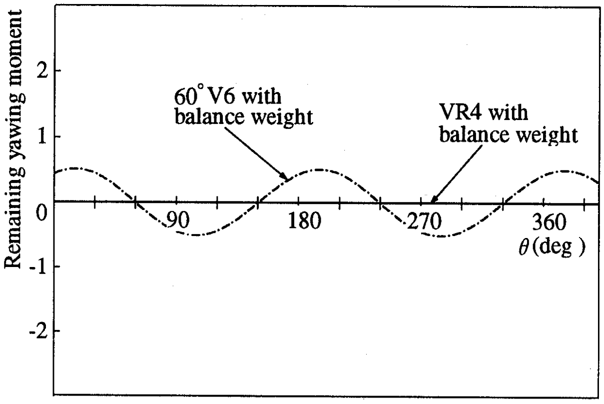


Fig. 5 Balancer effect of VR 4 engine

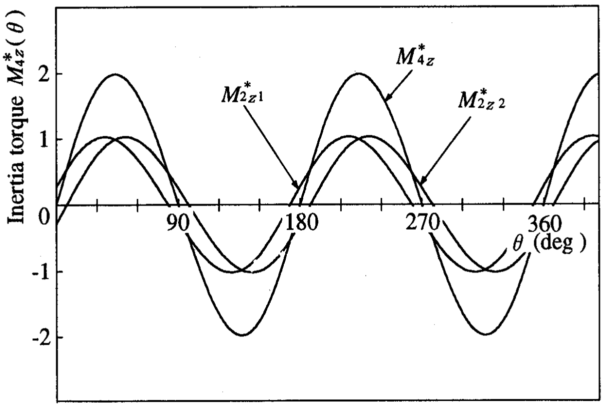


Fig. 6 Inertia torque of VR 4 engine (α=15°)

and $M^*_{2z2}(\theta)$ show the inertia torque of the two straight 2-cylinder engine of a VR-type. The inertia torque of the VR-type engine becomes a summation with the inertia torque of the straight engines with two lines. Change patterns $M^*_{4z}(\theta)$ in Cases 1 and 2 become equal. The bank angle affects the phase difference of $M^*_{2z1}(\theta)$ and $M^*_{2z2}(\theta)$ and it directly influences the amplitude of $M^*_{4z}(\theta)$. A V-type engine becomes a straight one when its bank angle α is zero and the inertia torque of the VR 4 engine is smaller only for the phase difference of the bank angle as compared to the straight 4-cylinder engine. As described above, a VR 4 engine can eliminate the first order yawing moment by means of a balancer. However, like the conventional straight 4-cylinder engine, there is still a second order inertia force in the direction of the x-axis. Therefore, a VR 4 engine has few practical advantages.

4.2 VR-type 6-cylinder engine (VR 6 engine)

The cylinders of the straight 6-cylinder engine are arranged symmetrically in the same phase on either side in two straight 3-cylinder engines. This prevents pitching and yawing moments(4). A VR 6 engine however has two straight 3-cylinder engines which are arranged opposite each other as in the V-type.

Table 2 shows the combinations of cylinder arrangements of the VR 6 engine. It is three kinds of arrangements from Cases 1 to 3. Here, this is an analysis of Case 1. In Case 1, pitching moments $M^*_{3y1}(\theta)$ and $M^*_{3y2}(\theta)$ of the two straight 3-cylinder engines which make up a VR 6 engine are shown by the following equations.

$$\left.\begin{aligned} M^*_{3y1}(\theta)&=\{F_3(1)-F_3(3)\} \\ M^*_{3y2}(\theta)&=\{F_3(3)-F_3(1)\} \end{aligned}\right\} \tag{19}$$

Exciting moments $M^*_{6y}(\theta)$ and $M^*_{6x}(\theta)$ which occur in VR 6 engine are shown by the following equations.

Table 2 Combinations of cylinder arrangement of VR 6 engine

Case	Arrangement
1	1 2 3 (3) (2) (1)
2	1 3 2 (2) (3) (1)
3	2 1 3 (3) (1) (2)

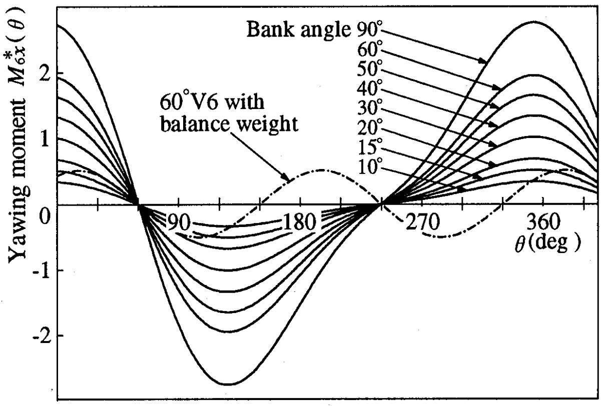


Fig. 7 Yawing moment of VR 6 engine (Case 1)

$$\left.\begin{aligned} M^*_{6y}(\theta)&=M^*_{3y1}\cos\left(-\frac{\alpha}{2}\right)+M^*_{3y2}\cos\left(\frac{\alpha}{2}\right) \\ M^*_{6x}(\theta)&=-\left\{M^*_{3y1}\sin\left(-\frac{\alpha}{2}\right)+M^*_{3y2}\sin\left(\frac{\alpha}{2}\right)\right\} \end{aligned}\right\} \tag{20}$$

$M^*_{6y}(\theta)$ becomes zero and $M^*_{6x}(\theta)$ can be arranged as shown in the following equation.

$$M^*_{6x}(\theta)=2\sqrt{3}\sin\frac{\alpha}{2}\{\cos(\theta-30°)+\lambda\cos(2\theta+30°)\} \tag{21}$$

Figure 7 shows the change pattern of the yawing moment $M^*_{6x}(\theta)$ of Case 1. Similar to Fig. 4, the bank angle α changes from 10 to 90 degrees. As the bank angle α becomes large, the amplitude of the change pattern also becomes large. Here, the exciting moment of a practical 60° V 6 engine is shown in Fig. 7 for comparison. In Case 1, Fig. 7 shows that a bank angle from 10 to 15 degrees is sufficient.

Figure 8 shows the effects of the balancer for Case 1. The bank angle α is 15 degrees. By installing a balancer, only a change pattern larger than the second order one of the exciting moment of a VR 6 engine remains. The change pattern becomes large with an increase in α. When the bank angle α is 40 degrees, the change pattern is near the value of a 60° V 6 engine. However, it is advisable to make it as close to the straight type of the bank angle at 15 degrees as possible rather than to widen the bank angle from 30 to 40 degrees by installing a balancer.

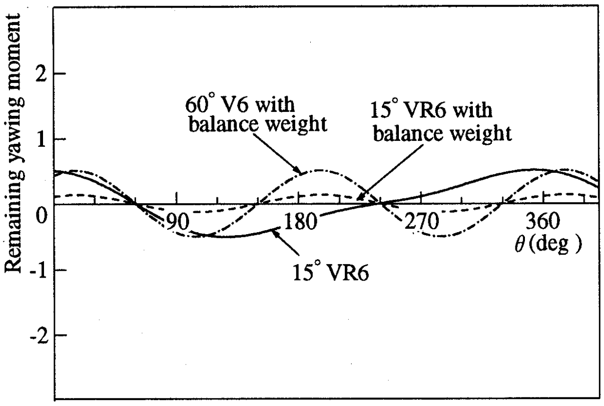


Fig. 8 Balancer effect of VR 6 engine ($\alpha=15°$)

A change pattern with inertia torque shows a similar tendency as Fig. 6 for the VR 4 engine. As compared with the straight 6-cylinder engine, the amplitude of the change pattern decreases slightly in size. At the 60° V 6 engine, because the inertia torque of straight engines with two lines have a 60 degrees phase difference, they cancel each other and the inertia torque becomes zero.

The change patterns of the exciting moments in Cases 2 and 3 change as in Case 1 and the maximum amplitude becomes equal. Therefore, a VR 6 engine is superior with regard to eliminating the pitching moment of the 60° and 90° V 6 engines, but this does not include straight 6-cylinder engine. In order to make it similar to a straight engine, a balancer is necessary and, therefore the limit value of the bank angle becomes 15 degrees.

4.3 VR-type 8-cylinder engine (VR 8 engine)

The phase difference of the crank of the straight 4-cylinder engine needed for a VR 8 engine is $\pi/2$, which is different from the practical phase difference π at present. Table 3 shows combinations with eight effective kinds of cylinder arrangements in a VR 8 engine. Here, Case 1 will be analyzed. Pitching moments $M^*_{4y1}(\theta)$ and $M^*_{4y2}(\theta)$ of two straight 4-cylinder engines which make up the VR-type are shown by the following equations.

$$\left.\begin{aligned} M^*_{4y1}(\theta)&=\frac{3}{2}\{F_4(1)-F_4(3)\}+\frac{1}{2}\{F_4(2)-F_4(4)\}\\ M^*_{4y2}(\theta)&=\frac{3}{2}\{F_4(3)-F_4(1)\}+\frac{1}{2}\{F_4(4)-F_4(2)\}\end{aligned}\right\} \tag{22}$$

The pitching and yawing moments $M^*_{8y}(\theta)$ and $M^*_{8x}(\theta)$ which occur in a VR 8 engine are shown by the following equations.

$$\left.\begin{aligned} M^*_{8y}(\theta)&=M^*_{4y1}\cos\left(-\frac{\alpha}{2}\right)+M^*_{4y2}\cos\left(\frac{\alpha}{2}\right)\\ M^*_{8x}(\theta)&=-\left\{M^*_{4y1}\sin\left(-\frac{\alpha}{2}\right)+M^*_{4y2}\sin\left(\frac{\alpha}{2}\right)\right\}\end{aligned}\right\} \tag{23}$$

$M^*_{8y}(\theta)$ becomes zero and $M^*_{8x}(\theta)$ is similar to the following equation.

Table 3 Combinations of cylinder arrangement of VR 8 engine

Case	Arrangement	Case	Arrangement
1	1 2 4 3 (3) (4) (2) (1)	5	2 1 3 4 (4) (3) (1) (2)
2	3 2 4 1 (1) (4) (2) (3)	6	4 1 3 2 (2) (3) (1) (4)
3	1 4 2 3 (3) (2) (4) (1)	7	2 3 1 4 (4) (1) (3) (2)
4	3 4 2 1 (1) (2) (4) (3)	8	4 3 1 2 (2) (1) (3) (4)

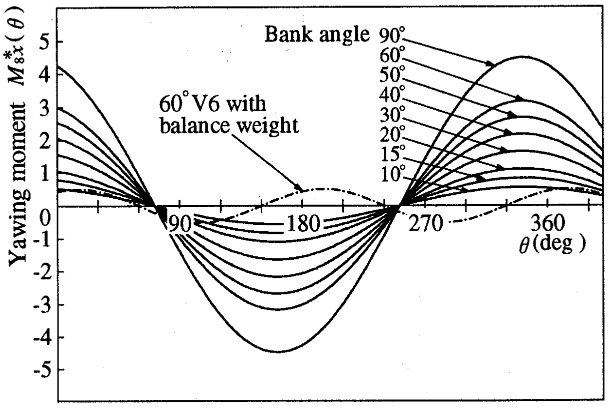


Fig. 9 Yawing moment of VR 8 engine (Case 1)

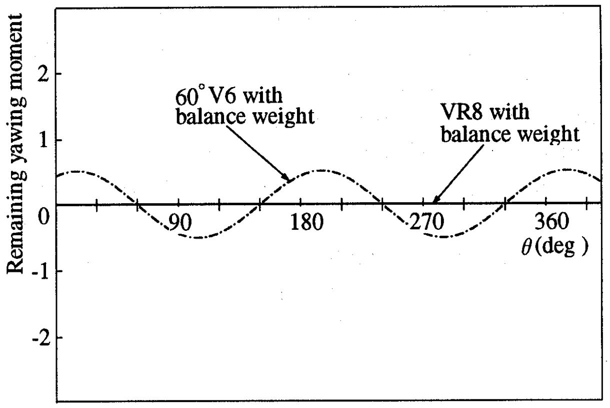


Fig. 10 Balancer effect of VR 8 engine (Case 1)

$$M^*_{8x}(\theta)=2\sqrt{10}\sin\frac{\alpha}{2}\cos(\theta-18.434\,948°) \tag{24}$$

Figure 9 shows the change pattern of $M^*_{8x}(\theta)$. Similarly, the bank angle α changes from 10 to 90 degrees. As compared with a 60° V 6 engine which has a balancer mechanism, it is believed that the limit bank angle is about 10 degrees.

Figure 10 shows what happens, when the first order yawing moment is eliminated by the balancer. The remaining second order and higher values become very small. A V-type 8-cylinder engine at 90 degrees (90° V 8 engine), however which has a practical balancer mechanism at present has very good features in regard to vibration. The pitching and yawing moments due to inertia force rarely occur. By using a balancer, similar to the V 8 engine, the yawing moment of the VR 8 engine rarely occurs. However, the purpose of the VR-type engine is to have a small bank angle without using a balancer mechanism. Therefore, by comparing the pitching and yawing moments with a 90° V 8 engine which can be eliminated approximately by using a balancer mechanism, it is clear that a VR 8 engine has few advantages.

A change pattern with the inertia torque shows a similar tendency as the former case. The amplitude becomes quite small as compared with the VR 4 and V 6 engines. Vibration restraint effects due to the use of a multi-cylinder is clear in the inertia torque due to the above.

The shape of the crank can be divided into two sets, Cases 1, 4, 6, 7 and Cases 2, 3, 5, 8 from the arrangements of each case in Table 3. The former set is obtained by turning a crank every 90 degrees based on Case 1 and the latter set is obtained by turning a crank every 90 degrees based on Case 3. Therefore, the vibration wave of those exciting moments shifts only for the turn phase difference. In addition, Cases 1 and 3 are arrangements by which the two symmetrical cylinders were exchanged in the two straight 4-cylinder engines which make up the V-type engine. Therefore, the difference in those exciting moments is only a phase of the vibration wave. The vibration wave of the exciting moment of the VR 8 engine has results similar to Case 1 due to this phenomenon.

As described above, the permitted limit value of the bank angle of the VR 8 engine is about 10 degrees. When a balancer is added, the VR-type with a bank angle from 15 to 20 degrees is as efficient as a the 90° V 8 engine. It is clear that it is superior to the VR 6 engine.

5. Conclusion

The V-type 6-cylinder engine with a narrow bank angle has been used as a compact engine in a straight 6-cylinder engine. In this study the exciting moment and the balancer mechanism which causes problems particularly in regard to the design and the efficiency of these engines were analyzed. Furthermore, the problems of VR-type engines with a set number of cylinders were examined. As a result, the following conclusions were obtained.

(1) The basic cylinder arrangement which a VR-type design needs was clarified.

(2) The limit value of the bank angle of the VR 4 engine is 15 degrees. The VR 4 engine can be used as a practical engine because the yowing moment is smaller than that of the V 6 engine. If a balancer is added, the bank angle can be selected arbitrarily and is as efficient as a straight 4-cylinder engine.

(3) As for a VR 6 engine, when it is compared with a straight 6-cylinder engine, pitching moment due to inertia force does not occur. However, the yawing moment is slightly larger than the second order exciting moment which occurs in a 60° V 6 engine. Also, by using a balancer to eliminate the first order yawing moment, efficiency that is equal to a straight 6-cylinder engine can be obtained.

(4) As for a VR 8 engine, the permitted limit value of the bank angle is 10 degrees. When a balancer mechanism is used, even if the bank angle is from 15 to 20 degrees, efficiency which is the same as that of a 90° V 8 engine can be obtained. Also, the inertia torque decreases substantially and the effects of vibration restraint by using a multi-cylinder is significant.

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References

(1) Krueger, H., Der Massenausgleich des VR6-Motors, Motortech. Z., Vol. 54, No. 2 (1993), p. 96-101.

(2) Ito, N., Takahashi, Y., Tominari, T., Ando, K. and Takahashi, K., Exciting Moment Analysis of V-type Engine (1st Report), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 59, No. 563, C(1993), p. 2026-2034.

(3) Takahashi, K., Oda, T., Ito, N., Takahashi, Y. and Yamamoto, H., Dynamic Relationships of Reciprocating Engines, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 55, No. 512, C(1989), p. 925-930.

(4) JSME Mechanical Engineers Handbook, (in Japanese), (1979), p. 14-31, JSME.