

A Study Concerning Booming Noise of a Multi-link Type Variable Compression Ratio Engine

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ABSTRACT

There was concern that a variable compression ratio engine fitted with a multi-link mechanism might produce louder booming noise due to the inertial forces caused by the lateral swing of the links. Accordingly, a relational expression between the inherent characteristics of the links was found to counterbalance those forces.

As a result, it was found that a multi-link VCR engine designed on the basis of this link concept showed lower levels of horizontal excitation forces similar to the reduction of vertical forces. This suggests that, even without any add-on devices like a balance shaft, the engine can achieve the same level of booming noise performance as conventional engines. In addition, this new link concept obtained as a result of this study is expected to be effective in reducing higher-order interior noise as well.

INTRODUCTION

In a multi-link type variable compression ratio (VCR) engine, the 2nd-order displacement of the pistons can be reduced through the design of the link geometry. As a result, it is possible to reduce the 2nd-order vertical displacement, which is one of the basic vibration orders of an inline 4-cylinder engine.⁽¹⁻³⁾ On the negative side, because the multi-link mechanism newly generates horizontal excitation forces that are not present in a conventional piston-crankshaft system, there is concern

that such forces might have an adverse impact on increasing booming noise.

The aim of this study was to develop a multi-link mechanism for substantially reducing such horizontal excitation forces. The specific approach taken in this effort was first to make clear the mechanism causing these excitation forces. That was done by dividing link displacement between the basic orders of engine revolution and the higher-order phenomena above them and formulating equations for the engine excitation forces at each order. In the process of doing that, a relational expression was found for the inherent characteristics of the links. That expression was then used to make clear the conditions of the link geometry for markedly reducing 2nd-order horizontal excitation forces.

FEATURES OF MULTI-LINK VCR ENGINE

CONFIGURATION OF MULTI-LINK VCR ENGINE - Figure 1 shows the configuration of a prototype multi-link VCR engine that has been described in detail elsewhere.⁽²⁾ This engine system consists of the four-bar mechanism inside the dashed lines and the piston mechanism. The four-bar mechanism comprises a lower link (L-link) connecting the upper pin (U-pin), crankpin and control pin (C-pin), a control link connecting the C-pin and control shaft (C-shaft), and the crankshaft. As the crankpin rotates, the C-pin pivots. The piston mechanism consists of the piston and an upper link (U-link) connecting the piston pin and the U-pin.

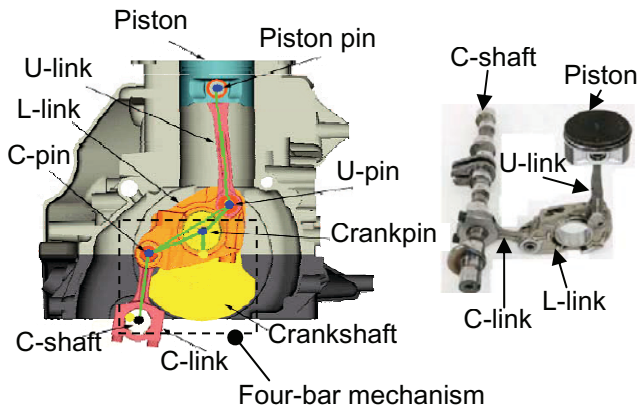


Fig. 1 Basic Configuration of the Multi-link VCR Engine

The C-shaft has a journal with a specific degree of eccentricity in the same direction. The C-link that pivots freely is supported by this journal. The rotation of the C-shaft changes the support position of the eccentric journal of the C-link, with the result that the piston's top dead center position moves vertically in tandem with the inclination of the L-link. In this way, the multi-link mechanism functions to variably control the compression ratio of the engine.⁽⁴⁾

EXCITATION FORCES OF MULTI-LINK VCR ENGINE -

The engine excitation forces that have a large impact on booming noise are the summation of the inertial forces of the moving parts that are displaced in the vertical and horizontal directions. Figure 2(a) compares the 2nd-order vertical excitation force of an inline 4-cylinder engine fitted with a conventional piston-crankshaft system without a balance shaft and that of the multi-link VCR engine (Fig. 1). This excitation force in the conventional system is produced by the piston's 2nd-order displacement, thereby giving rise to booming noise.

Figure 3 illustrates the mechanism causing the 2nd-order displacement of the piston in the conventional system. Piston displacement in the conventional system is the summation of the displacement produced by the vertical displacement of the crankpin and the displacement resulting from the oscillating motion of the connecting rod due to the crankpin's lateral displacement.⁽¹⁾ This 2nd-order displacement goes up and down twice with each revolution of the crankshaft and stems from the mechanism induced by the oscillating motion of the connecting rod.

In contrast, the geometry of the multi-link mechanism can be selected⁽¹⁾ such that the oscillating motion of each link works to cancel the piston's 2nd-order displacement produced by the oscillating motion of the U-link, similar to the connecting rod. As a result, the 2nd-order vertical excitation force can be markedly reduced without using a balance shaft, as is seen in Fig. 2(a) and was previously reported elsewhere.⁽²⁾

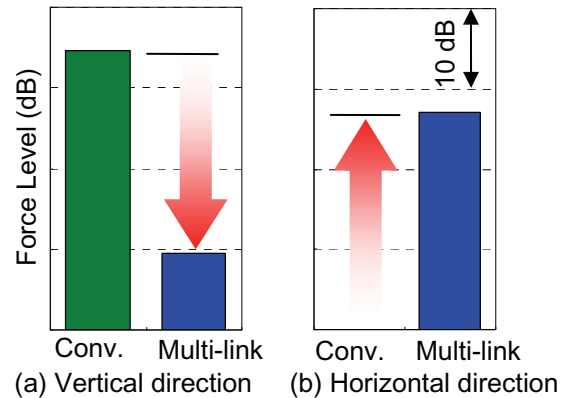


Fig. 2 2nd-order of Excitation Forces at 3500 rpm

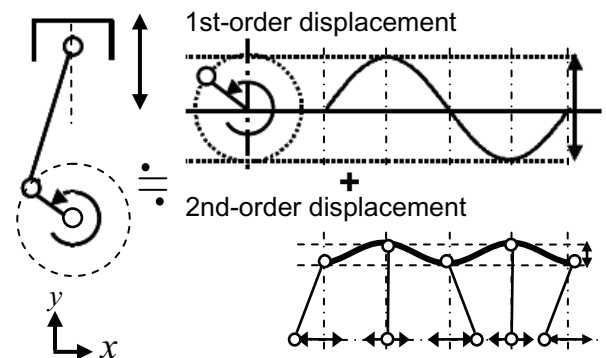


Fig. 3 Mechanism of 2nd-order Displacement

The present study focused on the horizontal excitation forces. As shown in Fig. 2(b), the 2nd-order horizontal excitation forces occurring in the multi-link VCR engine might have an impact on increasing booming noise, even if the vertical vibration is reduced.

Accordingly, the conditions generating these horizontal excitation forces were investigated in detail in this study as described below. In the conventional system, the horizontal displacements of the connecting rod and crankshaft have only 1st-order components as shown in Fig. 4(a), and 2nd-order horizontal excitation forces do not occur. In contrast, it is seen in Fig. 4(b) that the inertial force of the U-link, which undergoes horizontal displacement in the multi-link VCR engine, has a 2nd-order component. Similarly, the inertial forces of the C-link and L-link also have 2nd-order components as shown in Fig. 4(c). These results indicate that the inertial forces of these links in the multi-link VCR engine give rise to the 2nd-order horizontal excitation forces.

Installing a balance shaft would work to reduce the horizontal excitation forces, but that would increase the engine weight and cost and also lead to lower fuel economy. Therefore, the aim of this study was to reduce the 2nd-order horizontal excitation forces without requiring any add-on devices, which is the same approach as that adopted for dealing with vertical vibration.

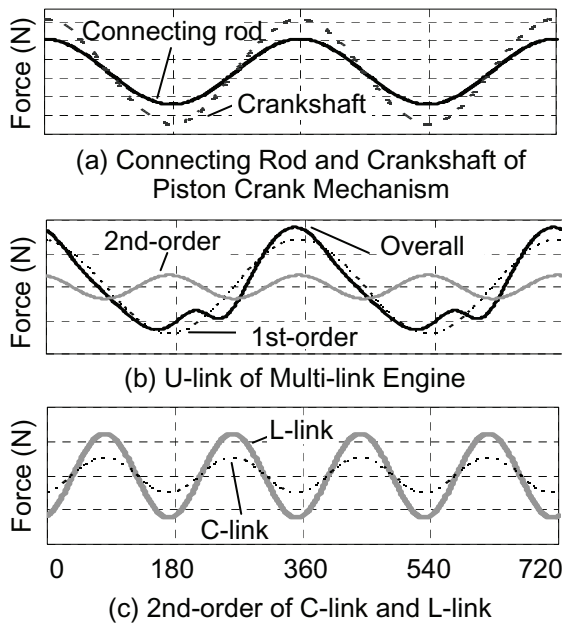


Fig. 4 Horizontal Inertial Forces at 3500 rpm

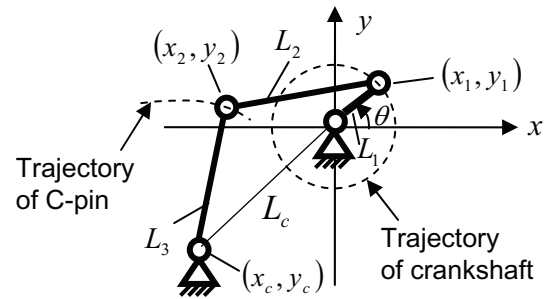


Fig. 5 Coordinates of the Four-bar Mechanism

VIBRATION ORDER FORMULATION USING THE TAYLOR EXPANSION - It is possible to formulate an equation for the temporal characteristics of each pin's displacement and inertial force based on the link geometry and inertial specification values of the multi-link VCR engine.⁽¹⁾ However, under a condition where the temporal characteristics show the mixed presence of multiple orders as seen in Fig. 4(b), it would be difficult to find a method for balancing the 2nd-order inertial forces.

Therefore, an attempt was made to formulate an equation for the vibration order characteristics with respect to the horizontal displacement of the C-pin in the four-bar mechanism. The result is shown in Eq. (3.1), which was obtained with the Taylor expansion,⁽⁵⁾ similar to the equation for the conventional system. The details are given in the appendix.

$$x_2 = a_0 + a_1 \sin \theta + b_1 \cos \theta + a_2 \sin 2\theta + b_2 \cos 2\theta + \dots + a_n \sin n\theta + b_n \cos n\theta \quad (3.1)$$

As a result, it was found that the expression was exceptionally complicated unlike that for the conventional system, inasmuch as the terms $a_0 \sim a_n$ and $b_1 \sim b_n$ in Eq. (3.1) consist of the variables $L_1, L_2, L_3, L_c, x_c, y_c$ and their higher orders. Therefore, it would be very difficult to use this equation to study a method for balancing the inertial forces. That meant the equation had to be greatly simplified in order to formulate an expression for the vibration order characteristics of the four-bar mechanism.

FORMULATION OF AN EXPRESSION FOR HORIZONTAL EXCITATION FORCES - An effort was made to simplify Eq. (3.1) from the three perspectives noted below in order to formulate an expression for the horizontal excitation forces. As a result, a simplified expression was obtained for the horizontal excitation forces F_{xH} of the 2nd and higher orders as shown in Eq. (3.2). It should be noted that it is not necessary to examine the 1st and lower orders because they are cancelled out in an inline 4-cylinder engine. The subscript H signifies the 2nd and higher orders. The link geometry of the multi-link VCR engine is shown in Fig. 5.

FORMULATIONS FOR HORIZONTAL EXCITATION FORCES OF MULTI-LINK VCR ENGINE

2ND-ORDER HORIZONTAL DISPLACEMENT OF FOUR-BAR MECHANISM - An investigation was made of the 2nd-order horizontal displacement of the pins in the four-bar mechanism inside the dashed lines in Fig. 1. The geometry of the four-bar mechanism is shown in Fig. 5, where the trajectories of the crankpin and C-pin are indicated by the dashed lines.

It is seen from the pin trajectories that the C-pin's vertical displacement is sufficiently smaller than that of the crankpin. Accordingly, the 1st-order component of the C-pin's horizontal displacement is produced by the crankpin's horizontal displacement. The vertical displacement of the crankpin induces the pivoting motion of the L-link, which creates the mechanism that causes the 2nd-order component in the same way as the oscillating motion of the connecting rod (Fig. 3).

Accordingly, in the prototype multi-link VCR engine that incorporates this four-bar mechanism, it is impossible to reduce the 2nd-order horizontal displacement to zero because the L-link necessarily undergoes pivoting motion. Therefore, as described below, a method was investigated for balancing the inertial forces of each link that are produced by the 2nd-order displacement of the pins.