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An enhanced flexible dynamic model and experimental verification for a valve train with clearance and multi-directional deformations

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ABSTRACT

An enhanced flexible dynamic model for a valve train with clearance and multi-directional deformations is proposed based on finite element method (FEM), and verified by experiment. According to the measured cam profile, the available internal excitations in numerical solution to the model are achieved by using piecewise cubic Hermite interpolating polynomial. The comparative analysis demonstrates that the bending deformation of the rocker arm is much larger than the radial deformation, signifying the necessities of multi-directional deformations in dynamic analysis for the valve train. The effects of valve clearance and cam rotation speed on contact force, acceleration and dynamic transmission error (DTE) are investigated. Both theoretical predictions and experimental measurements show that the amplitudes and fluctuations of contact force, acceleration and DTE become larger, when the valve clearance or cam speed increases. It is found that including the elasticity and the damping will weaken the impact between the rocker arm and the valve on the components (not adjacent to the valve) at either unseating or seating scenario. Additionally, as valve clearance or cam rotation speed becomes larger, the valve lift and the working phase decrease, which eventually leads to inlet air reduction. Furthermore, our study shows that the combustion rate improvement, input torque, and components durability can be improved by tuning valve clearance or adjustment the cam profile.

1. Introduction

The valve opening and closing are the major features for a valve train, and the valve lift curve has a significant influence on engine power, output torque, fuel consumption rate and idling stability. However, the slender tappet, pushrod, rocker arm and valve with lower stiffness are prone to deformation, which introduces irregularities to the valve lift curve. Additionally, impact force caused by valve clearance between the rocker arm and the valve can induce valve jump-free and component durability reduction. In the development of the high speed and precision, a flexible dynamic model for a valve train in consideration of components deformations and valve clearance is necessary to be developed, and its dynamic characteristics are paid more attentions to maintain the accurate lift curve and long-life components durability.

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Nomenclature

h	Cam lift
ω_c	Rotation angular speed of the cam
$\mathbf{U}$	The vector of 20 DOF
u_i	Degree of freedom of the dynamic model
$\mathbf{Q}$	The vector of the local coordinates
qi	Local degree of freedom of the beam element i
Li	Length of element
di	Diameter of element
$\mathbf{m}_i$, $\mathbf{k}_i$	The mass and stiffness matrices of beam element i in local coordinates
$\mathbf{R}_i$	The matrix of coordinate transformation
$\mathbf{D}$	Corresponding relationship matrix between beam element and the dynamic model element
$\mathbf{B}_i$	Coordinate connection matrix between the beam element and the dynamic model element
$\mathbf{M}_i^e, \mathbf{K}_i^e, \mathbf{C}_i^e$	The mass, stiffness and damping matrices of dynamic model element
$\mathbf{M}$, $\mathbf{K}$, $\mathbf{C}$	The global matrices of mass, stiffness and damping in dynamic model
$\mathbf{F}$	The force vector of dynamic model
f_{12}	The contact force between the cam and the tappet
K_{12}, C_{12}	Contact stiffness and damping between the cam and the tappet
h_c	Contact deformation of the cam
h_t	Contact deformation of the tappet
R_c	Radius of curvature of the cam
a	Half-width of Hertz contact
l	The length of contact line between the cam and the tappet
υ_c,υ_t	Poisson ratio of the cam and the tappet, respectively
E_c,E_t	Young's modulus of the cam and the tappet, respectively
f_{23}	The contact force between the tappet and the pushrod
K_{23}, C_{23}	Contact stiffness and damping between the tappet and the pushrod
f_{34}	The contact force between the pushrod and the rocker arm
K_{34}, C_{34}	Contact stiffness and damping between the pushrod and the rocker arm
f_{45}	The contact force between the rocker arm and the valve
K_{45}, C_{45}	Contact stiffness and damping between the rocker arm and the valve
f_{4x}, f_{4y}	The contact force between the rocker arm and bearing along the x, y axis, respectively
K_{4x}, C_{4x}	Contact stiffness and damping between the rocker arm and the bearing along x axis, respectively
K_{4y}, C_{4y}	Contact stiffness and damping between the rocker arm and the bearing along y axis, respectively
f_s	The valve spring force
f_{57}	The contact force between the valve and valve seat
K_{57}, C_{57}	Contact stiffness and damping between the valve and the valve seat
W, V	The radial and axial displacement of beam element
E_k, E_p	Kinetic energy and deformation energy of beam element
E_W, E_V	The radial and axial kinetic energy of beam element
b	Valve clearance
ρ	Material density
l_0	Pre-compression length of valve spring
K_s	Valve spring stiffness
E	Young's modulus
δ	Dynamic transmission error
σ	Predicted stress of the pushrod
n	Rotation speed of the cam shaft

To date, significant efforts have been put on the dynamic analysis of a cam drive and a valve train. The early dynamic solution to cam-driven system was obtained by Hrones [1]. His theoretical results demonstrated that the dynamic characteristics of the cam follower with constant acceleration were worst at high speed, which was later verified experimentally by Mitchell [2]. Thereafter, the dynamic characteristics of valve train dynamics have attracted increasing attention. Eiss [3] established a dynamic model for the cam mechanism with two degrees of freedom. Chen et al. extended this model by considering residual shock [4] and nonlinearity [5]. However, these dynamics models were simplified by lumped parameters and elastic deformations were not included. A lumped parameter dynamic model does not adequately predict the dynamic behavior of valve train, which was seen in the experiments reported by Pisano et al. [6]. The dynamic models with distributed