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Computational Simulation Analysis for Dynamics of Multibody System Coupled with Flexible Deformation of Valve Train

***Abstract**. Rigid and flexible multibody dynamics simulation analysis for the valve train of gasoline engine is conducted on the basis of the different constraints conditions, which among components have been varied in accordance with the kinematic and dynamic characteristics of the system to gradually approximate actual working conditions. Based on Lagrangian equation，absolute Cartesian coordinate and the floating frame of reference formulation for multibody dynamics, the computational dynamic simulation method used in professional simulation approach within computer program of UGNX is employed hereby to compute the displacement curve, velocity curve and acceleration curve of intake valve and exhaust valve, which elaborate the feature of valve motion, dynamic properties of the parts and whole system. Simulation results illustrate that computational dynamics of multibody system is an effective approach to analyze the dynamical characteristic of complex mechanical system in the flexible multibody model on the way of being high fidelity of the real constraints and load conditions of complex mechanical system with the consideration of all nonlinear factors arising from contact and impact constraint, flexible deformation of components and valve spring with designed parameters.*

***Streszczenie.** Analiza i symulacja dynamiki szeregu zaworów w silniku benzynowym zawiera zwykle szereg ograniczeń. Przedstawiono nową metodę analizy bazującą na równaniach Lagrange'a i płynnej zmianie odniesień. Metodę zaimplementowano w oprogramowaniu UGNX. (**Analiza numeryczna właściwości dynamicznych wieloelementowego systemu mechanicznego na przykładzie szeregu zaworów**)*

Keywords. Valve train, Multibody dynamics, Flexible deformation, Computational simulation analysis.
Słowa kluczowe: dynamika systemu mechanicznego, szereg zaworów.

1. Introduction

Valve train, as a critical sub-assembly system of engine, influences air exchange process based on valve timing which determines the magnitude of volumetric efficiency as well as main performance of gasoline engine. Valve train is featured as a complex mechanical system with a number of parts and components, long drive train, weak stiffness, designed gaps among parts and from inaccuracy of manufacturing. With the development of high speed and large power engine, the advent of vibration, fly-off, anti-jump and bad noise of valve train may be generated by impact force in mechanism and thermal load. At the same time the impact and contact between components in mechanism will make great effect on the stability, reliability and working life of valve train. Accordingly, not only the properties of motion of valve train should be studied in designing process, but also the dynamics analysis for high speed and high softness valve system should be conducted, especially on valve opening and closing; they are the feature of velocity, stiffness, vibration frequency and contact stress of valve system [1]. Traditionally, the numerical dynamic analysis for valve train is performed with single lumped mass model or multiple lumped mass model based on underlying assumption on the configuration of actual valve train system and involved with translational joint constraints [2]-[4], which computes the motion characteristics and dynamical properties of valve train in a simplified model, but the effect of inertial forces and impulse force at high speed and the effect of non-linear factors in the system are neglected so that there is a certain departure between simulation result and actual performance of dynamical equation of mechanism.

The fast development of many researches explored on numerical method for dynamic analysis of multibody system and advanced computer algorithms introduce new research approach, that is, computational dynamics of multibody system resulting in better simulation analysis for the dynamics of valve train [5,6]. However, diverse studies in many literatures on simulation analysis for the dynamics of valve train employed more simplified model, including the idealized constraints for contact surfaces between parts, the assumption without position-dependent equivalent mass and the variation of stiffness which influencing the dynamics of mechanism in such a way that more accurate simulation method should be applied to the research on the dynamics of mechanism, where all nonlinear factors playing certain important role should be taken into account in the model and analyzed carefully to illustrate the actual dynamics analysis.

This paper based on three-dimensional digital model of valve train established in UGNX in accordance with its actual topological structure in nominal parameters, which are virtually assembled to be the multibody system of valve train in Assembly module then in Motion module of UGNX in such a way that the parameters such as mass, stiffness, damping etc. of all separate bodies in system for dynamics analysis are set completely. In addition, all elements affecting dynamical properties should be discussed and added into the methodology involved in program to solve the kinematic and dynamic characteristic of valve at rated speed of crankshaft. Moreover, as working at high speed with weaker stiffness, push rods are defined as deformable body which makes valve train flexible multibody system, of which the dynamical properties will be computed to obtain more accurate simulation results on mechanism. The computational simulation of the flexible multibody on working condition of valve train system will be used as the basis of studying and verifying the performance of engine, even as the approach for the modification of valve train system and the boundary condition for research on vibration and noise of the mechanism

2. The multibody system of valve train

2.1 Multibody dynamic formulations

Multibody system is a complex mechanical system consisting of a number of components jointed by kinematic pairs, which is non-free particles system. Solution to the dynamical equation of multibody system by Newton's classical mechanics will be very complicated due to a large quantity of unknown constraint forces in all kinematic pairs. With regard to rigid multibody system, Lagrangian equation of the first kind has commonly been utilized for complex spacecraft or satellites, and typical representative contains Roberson-Wittenburg approach which employs body fixed coordinates [7]; while absolute Cartesian coordinate in complex mechanical systems [8]. All applications of above methodology are proved to be effective way to solve dynamics equations with holonomic or non-holonomic constraints system.

The solution to the dynamics of multibody system is based on the study on the solution of differential algebraic equation, where more advent of developing algorithms are involved, for example, there exist different methods for the integration techniques of differential algebraic equation in accordance with different treatment to coordinate matrix and Lagrange multipliers. Moreover, the solution to the compatibility of initial value and to the stiffness of differential algebraic equation caused by system coupling will be significant to the research of multibody system [9,10].

In previous study the elastic deformation of rigid body is neglected in simulation analysis of multibody system, which should be considered in the computation when complex mechanical systems run at high speed, or is constructed with higher accuracy and less weight. In particular, under the analysis of constrained flexible bodies that undergo large displacements coupled with the deformation, which is sufficient to disturb the performance of tis intended function and actual operation, if the coupled terms are neglected, solution to dynamics equation will fail to describe the dynamic characteristics of system [11]-[13].

Elastic body is a deformable object of which the relevant positions of all internal points vary in time domain that floating frame of reference can’t describe their position in inertial coordinate system correctly, accordingly, floating frame of reference is brought to depict displacement deformation of points in flexible body. Because there are relevant movements among points in body, floating frame of reference varying with the deformation of flexible body is used to represent the position vector of arbitrary point with flexible body which can be expressed in Equ.1.

(1) $$\vec{r} = \vec{r_0} + A(\vec{S_p} + \vec{u_p})$$

where: $\vec{r}$ – vector of the point in inertial coordinate, $\vec{r_0}$ – vector of origin of floating coordinate in inertial coordinate, A – direction cosine matrix, $\vec{S_p}$ – vector of flexible body in floating coordinate in non-deformation condition, $\vec{u_p}$ – corresponding deformation vector and is determined by modal coordinate, that is, $u_p = \Phi_p q_f$, where Φ_p – deformation modal matrix, q_f – the generalized coordinate of deformation, as shown in Fig.1.

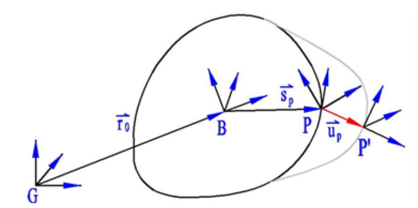

Fig.1. Reference system for flexible body

Dynamics equation of flexible body expressed in the following Lagrangian equation:

(2) $$\begin{cases} \dfrac{d}{dt}\left(\dfrac{\partial L}{\partial \dot{\xi}}\right) - \dfrac{\partial L}{\partial \xi} + \dfrac{\partial \Gamma}{\partial \dot{\xi}} + \left[\dfrac{\partial \Psi}{\partial \xi}\right]^T \lambda - Q = 0 \\ \Psi = 0 \end{cases}$$

where: ψ – constraint equation, λ – lagrange multiplier factor, ξ – generalized coordinate, Q – generalized force, L – kinetic potential of lagrangian, $L=T-U$, T and U are respectively kinetic energy and potential energy, Γ – energy loss function.

The mathematical model of flexible multibody can be computed in the same way used in rigid multibody system. Computational dynamics of multibody system has developed rapidly with the application of professional simulation by computer and is proposed to calculate dynamics of complex mechanical system by the software, which involves appropriate methods for solving differential algebraic equation of mechanism effectively to obtain a stable algebraic solution, which helps promote the efficiency of designation and analysis of mechanical system.

2.2 Computational model

In this paper, the valve train system of some gasoline engine with single cylinder is studied, where complex transmission train exists. The structural configuration of valve train is shown in Fig.2, ten bodies including frame, cam, intake valve, intake valve bottom rocker, intake valve push rod, intake valve head rocker, exhaust valve, exhaust valve bottom rocker, exhaust valve push rod, exhaust valve head rockers.

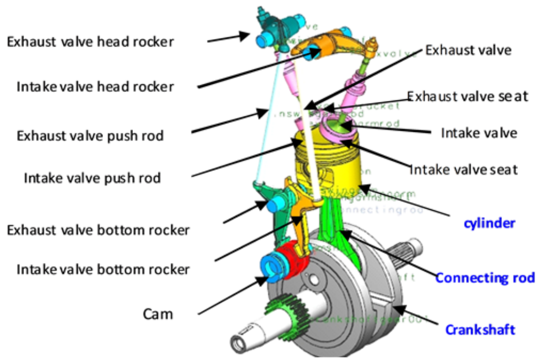

Fig.2. The configuration of valve train

In this section, the rigid-multi-body physical model of valve train established in accordance with components dimension is composed of 3D digital parts designed in UGNX with the dynamic parameters used for simulation such as Young’s modulus, Poisson’s ratio, moment of inertia, mass, stiffness, damping etc. which are the same as the actual components in spatial configuration without any simplified assumption, and upon which the simulation analysis of system should be more accurate than traditional approaches; then assembled in Assembly module to check interference between parts and physical model in Motion module to form topological multibody system with rigid bodies, joint constraints, force element and external forces. All dynamic characteristics are defined according to the law of motion and joint constraints among components. All joints are shown in table1.

Table 1. List of joint constraints among components

Components	Joint constraints(1)	Joint constraints(2)
Cam and frame	Revolute joint	/
Cam and bottom rockers	Curve to curve connector	3 dimensional contact
Bottom rockers and push rod	Spherical joint	/
Push rod and head rockers	Spherical joint	/
Bottom push rod and frame	Revolute joint	/
Head rockers and valves	Curve to curve connector	3 dimensional contact
Valves and frame	Cylindrical joint	/
Head rockers and frame	Revolute joint	/

3. Multibody dynamics analysis for valve train

3.1 Dynamics analysis on idealized constraints

Assumption: (1) parts are rigid bodies; (2) no friction and internal clearance among parts and in joints; (3) no clearance between valve tips and head rockers; no clearance between cam and bottom rockers; (4) the constraints between cam and bottom rocker and between head rocker and valve are Curve to curve connector; (5) the stiffness and parameter of valve spring given by calculation from designed parts.

Cam profile is a very significant parameter in dynamics analysis, of which the displacement and the one-order differential coefficient affect the motion of cam follower and valve. In the simulation model the constraints between cam and bottom rocker as well as valve tip and head rocker are curve to curve connector which is a type of idealized constraint in calculation to ensure no impact force generated between cam and bottom rocker as well as valve tip and head rocker, but rocker ratio varies by time, which makes the contact points also varying in certain contact area. Furthermore, because the acceleration of bottom cam often changes sharply, valves are inclined to jounce or vibrate by the impact stress during motion procedure, which increases the noise and abrasion on the contact area. Let crankshaft running at the speed of 2500rpm, 4500 rpm and 6000 rpm, see the displacement, velocity and acceleration of intake valve and exhaust valve in virtual multibody mechanism in different working conditions calculated.

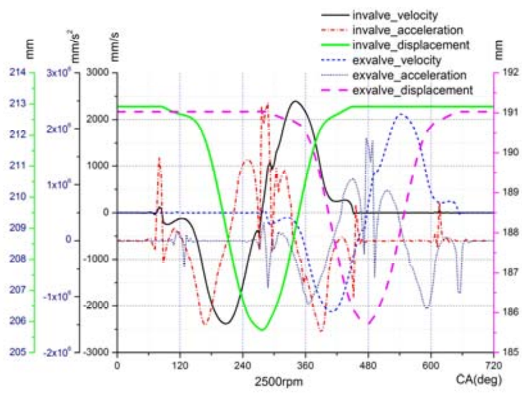

Fig.3. The law of motion of valves at 2500rpm in ideal joints

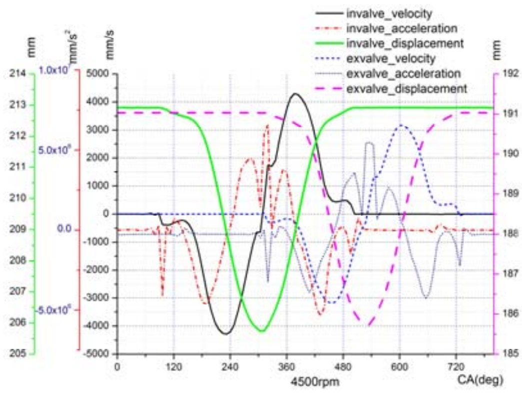

Fig.4. The law of motion of valves at 4500rpm in ideal joints

Viewing simulation curve in Fig.3 to Fig.5, the conclusion is that the velocity and acceleration of valves increases with the speed runs from 2500rpm to 6000rpm, the velocity of valve at the valve closing to the seat changes within the range of ±0.3m/s in simulation working conditions, which satisfies the requirement of the velocity of valve at the valve closing to the seat (≤0.6m /s) for steel alloy valve to ensure there is no excessive impact and abrasion at the contact area between valve and seat. In fact, acceleration curve determines the magnitude and the variation of inertial force of the mechanical components so as to affect applied forces of whole mechanism greatly [14]. Simulation curve obtained shows the acceleration under working condition keeps almost continuous except for several abrupt variation and its dynamic properties well enough to ensure the normal working of whole mechanism. But simulation shows there is motion wave in acceleration curve at the time of valve opening and closing, which is caused by the impact from between valve tip and head rocker and between valve and seat. Especially there is a big wave at maximum displacement of valve, which is caused by maximum contact stress at the minimum curvature of cam. Simulation results coincide with the actual working condition and structure configuration properties of valve train. In addition, at idle speed 2500rpm, the contact stress and spring force affect contact condition between cam and bottom rockers, which strengthen acceleration vibration of valve. Such situation also complies with the actual working condition of engine.

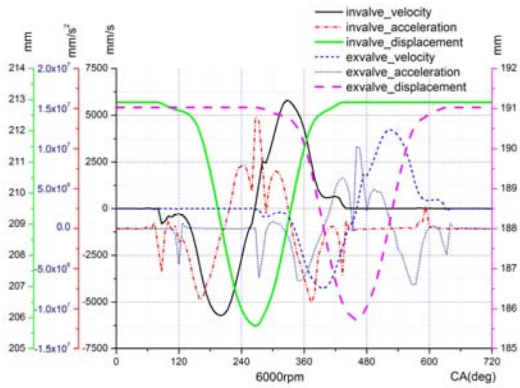

Fig.5. The law of motion of valves at 6000rpm in ideal joints

3.2 Dynamic characteristics of valve train under contact constraints

Valve train is considered as rigid multiple bodies in above section, in fact, as with gasoline engine running at high speed or with higher softness, the deformable bodies and the clearance between parts must be added into simulation, especially in the working condition of cam and bottom rocker as well as valve and head rockers, the contact area introduces complicated pressure caused from valve spring forces, inertial forces of valve train and additional inertial forces from vibration. In order to approximate actual working condition, three dimensional contact constraints are set to the joint between cam and bottom rockers as well as valve tips and head rockers, which is a kind of contact between solids of components in computer methodology [15,16]. Computational simulation establishes dynamic equation in program to calculate the impact stress of components, which is equivalent to non-linear spring and damping model based on penetration depth, where contact stress contains elastic division and damping division, the latter utilize two order step function to define damping value, which applies cubic polynomial to approximate Hessian function of which first order derivative is continuous, while second-order derivative is not continuous.

Simulation analysis is set in three working condition at the speed of 2500rpm, 4500 rpm and 6000 rpm respectively, as the variation of the displacement curve, the velocity curve and the acceleration curve of intake valve and exhaust valve shown in Fig.6. to Fig.8.

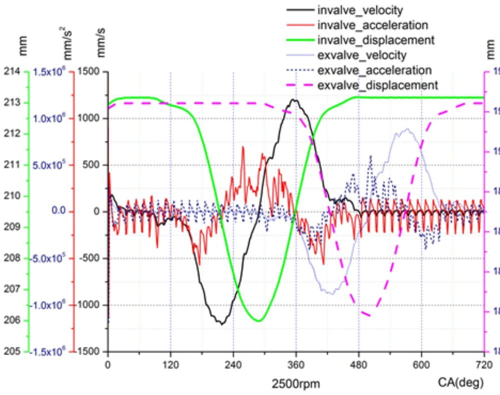

Fig.6. The law of motion of valves at 2500rpm in contact

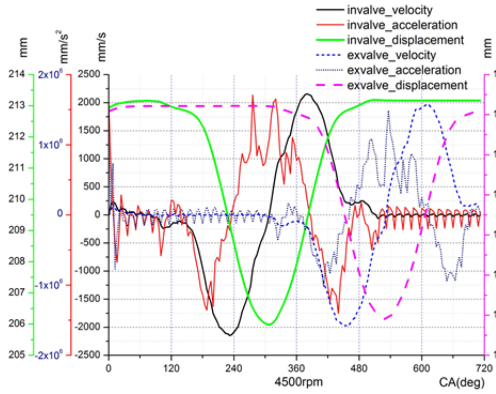

Fig.7. The law of motion of valves at 4500rpm in contact

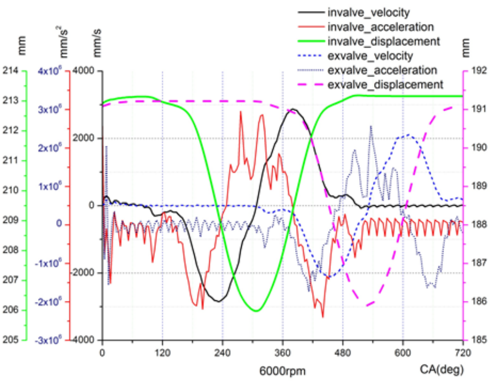

Fig.8. The law of motion of valves at 6000rpm in contact

In this section, simulation result shows that the value of the velocity and acceleration of valve are all less than those in curve to curve constraint where assuming no impact action among components. These results illustrate clearly that the stiffness coefficient and the damping coefficient in system can't be neglected, which exert important effect on hindering the action of inertial force and impact force so that simulation results are more accurately approximation to the actual working condition of valve. In addition, the acceleration curves keep continuous but wave in time domain obviously, which represents that the system undergo alternate load from the impact action and the kinetic momentum of valves. As a matter of fact, the contact between cam and bottom rocker as well as valve tip and head rocker is cylindrical face contact swinging around the joint, which causes contact area varing. The motion contains not only rolling but also skipping by varying rocker ratios so that the contact points are altered in certain area, which makes motion equation time-dependent and the solution to dynamics analysis become complicated, especially kinematic and dynamic characteristics between components [17]-[20]. In the initial stage of motion, acceleration value is 5 times more than those in motion process because there is huge impact force at that time. It is also read that the velocity value and acceleration value of intake valve is much bigger than those of exhaust valve, which shows that there is combustion pressure effectively working on the exhaust valve during running. All results depict the dynamic properties of valve train in actual working condition in more accurate way.

3.3 Dynamics analysis of flexible multibody system

Because multi-rigid-body dynamics can't present the dynamic properties of mechanism undergoing large displacement or abrupt excitation, a flexible multibody system has been employed in simulation analysis recently, which consisting of elastic and rigid components connected by joints and/or force elements [21].Hereinafter the study on the impact of elastic deformation on the motion of mechanism will be discussed to approximate the actual dynamics of valve train, in the multibody system push rods with less stiffness are flexible body so that establishing finite elemental formulation of the rods jointed with other bodies in system to form flexible multibody system. The paper applies Advanced Simulation module in UGNX to calculate the modal shape and properties of the rods which is constituted into flexible multibody system and is in seamless connection with other components. The kinematic and dynamic simulation of flexible multibody system is performed with pushrods in its finite element formulation where the modal properties （first 6 rigid modal shape not included in simulation）is applied to simulation analysis, as shown in Fig.9. as follows.

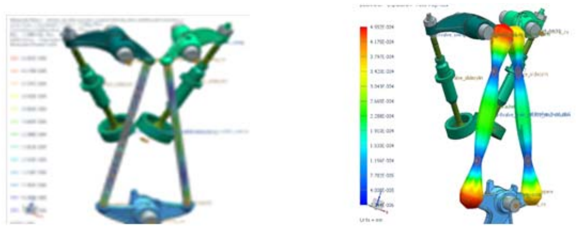

Fig.9. Diagraph of the flexible multibody system of valve train in simulation analysis

The basic difference between multi-rigid-body and flexible multibody system exists in that the stiffness and damping elements are exerted on the constraint nodes in multi-rigid-bodies while the linear deformation and stiffness property of all nodes is represented by modal superposition of deformable bodies in flexible multibody system, the latter doesn't contain dynamic parameters, where modal truncation is ultilized to express the first 12 order modal shapes of the system so that more accurate solution to computational dynamics of flexible multibody system will be obtained on the dynamic characteristics and stress of system interested for study on performance of engine.

In this section, simulation result in Fig.10. to Fig.12. shows that in working condition at speed of 2500rpm, the velocity value and the acceleration value of valve in flexible multibody system are much less than those in rigid - multi - body system wherever in the same trend, but almost the same as those in contact constraint condition, while at the speed of 4500rpm and 6000rpm, the values mentioned above are almost same in rigid or in flexible multibody system. The results show that flexible multibody system is of similar trend of dynamic characteristics with the model with contact constraints.

Table 2. 7 to12 order of modal frequency of intake push rod and exvalve push rod

Modal frequency [Hz]	Intake push rod	Exvalve push rod
7 order	1.5E+3	1.496E+3
8 order	4.092E+3	4.081E+3
9 order	7.905E+3	7.885E+3
10 order	1.252E+4	1.251E+4
11 order	1.283E+4	1.28E+4
12 order	1.876E+4	1.87E+4

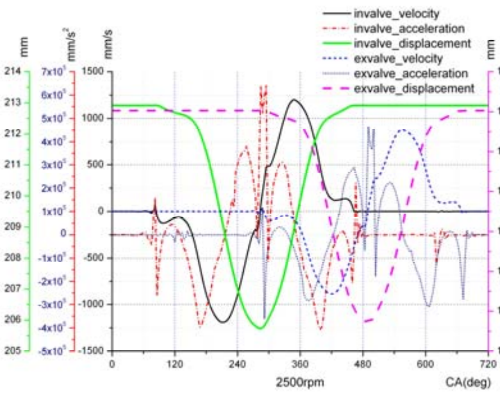

Fig.10. The law of motion of valves at 2500rpm in flexible system

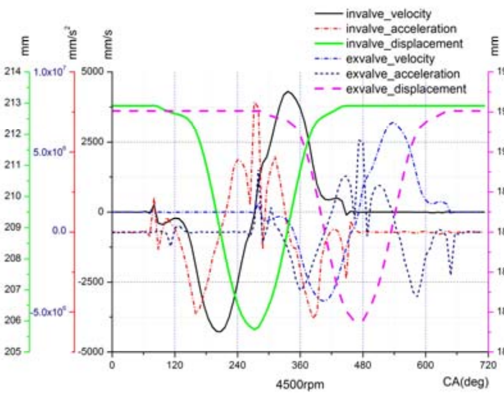

Fig.11. The law of motion of valves at 4500rpm in flexible system

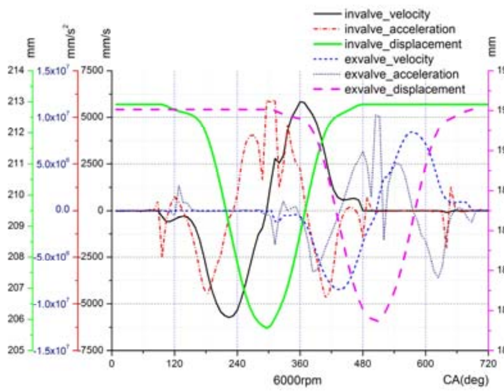

Fig.12. The law of motion of valves at 6000rpm in flexible system

When the deformation of system has been computed in simulation analysis, especially at the lower speed of 2500rpm, those results reflect the actual working condition of system. But at much higher speed such as 4500rpm and 6000rpm, the dynamic stiffing will affect the dynamic characteristics of the valve train so that the velocity value and the acceleration value of valves are similar to those of multi-rigid-body of system. It is concluded that flexible multibody system is the most accurate simulation formulation to analyze the complex mechanical system under the consideration of all those nonlinear elements in model which are neglected in traditional approaches.

4. Conclusion

In this paper, the dynamic properties of multibody system of valve train is studied based on computational dynamics of multibody system, of which the three dimensional digital model is established in professional software UGNX according to the actual subassembly mechanism of valve train. In order to obtain the solution to the dynamical equation in simulation analysis, the dynamics model of multibody system should be established as well as the boundary condition almost the same as the actual working condition, so that the conclusion can be obtained as follows:

(1) Simulation results show that multibody system is an much more effective way to depict the dynamical characteristics of complex mechanism of valve train. In addition, the simulation curves of the displacement, the velocity and the acceleration of valves analyzed from the multibody system reflect the actual working condition, which can be utilized for the further study on the vibration and noise analysis of the gasoline engine Moreover, computational dynamics analysis in UGNX is feasible method to study the dynamic properties of multibody system;

(2) At specified speed, the dynamic performance of the valve train system comply to the requirement of design for components, especially the velocity curve and the acceleration curve of valves keep continuous so as to ensure the minimum ending speed of valve closing to the valve seat, which produces impact stress as little as possible, and to realize stable running of valve train, which eliminates the problem of jump-off and fly-off of the valves;

(3) In companion with the simulation in multi-rigid-body system and flexible multibody system, obtaining more accurate simulation of the dynamical characteristics of the mechanism is based on more actual boundary condition including the computation of the clearance among components, elastic characteristics and the damping elements in constraints;

(4) Flexible multibody system is an much effective formulation to simulate the dynamical characteristics of valve train on the basis of using modal truncation to depict the deformation of flexible body in complex mechanical system.

Acknowledgements
Authors wish to express their gratitude to Internal Combustion Engine Research Institute for providing instrumentations and program.

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