Development of Automated Valve train Analysis and Optimization Process

JunWook Jeong

Hyundai motor company

MunSung Kim

Dassault Systemes Korea

Abstract: The valve train system is one of the major component of internal combustion engine because of its influence on the performance, durability and NVH. In this study, a new valve profile design process using B-Spline curve is suggested. Since this new method maintains continuity of valve profiles, it is convenient to optimize the profile using Isight. Goals of the new optimization processes are: 1) Maximizing the area under the valve lift curve, fullness, which related to the engine performance directly. 2) Considering dynamic constraints such as maximum acceleration, contact stress, and etc. Dynamic behaviors of the valve train are predicted by multi-body dynamic analysis using AVL EXCITE Timing Drive, and this is included in the automated process in Isight. From this new process, time required for a valve profile analysis is reduced with improved robustness. Furthermore, a design engineer can achieve optimal design of a valve train system without knowing complex CAE.

Keywords: Valve train, Kinematic Analysis, Dynamic Analysis, Multi-Body Dynamics, Isight, Optimization, Process Automation

1. Introduction

The valve train system is one of the major parts of internal combustion engine, which controls the amount of air-fuel mixture to be drawn into the cylinder and exhaust gas to be discharged. So how to design valve lift profiles and valve train components are the most important regarding to the engine performance, valve train durability, and NVH. Therefore valve train system should be optimally designed so as to avoid an abnormal valve movement, such as valve jumping or bounce up to the maximum engine speed. In order to decrease development time and costs, CAE tools are usually used for the optimization of valve train system from the early design stage. In this study, new processes to design and optimize the valve lift profile have been developed and dynamic analysis procedure of valve train system has been automated by using Isight.

2. Valve train analysis procedure

Valve train analysis procedures are typically divided into kinematic and dynamic analysis step. Kinematic analysis is not only to design a valve lift profile but also to calculate pseudo-static forces and Oil film characteristics, etc. Dynamic analysis is to predict the dynamic movement of valve train component considering the effect of inertia and stiffness. New tools for kinematic analysis based on the Microsoft Excel are developed. For the dynamic analysis, AVL EXCITE Timing Drive (EXCITE TD) software, specialized for the valve train analysis, is used.

2.1 Analysis model

A lumped mass model is applied for the valve train analysis. This model contains the geometry of valve train system, mass, stiffness, and damping of each part. Moreover non-linear characteristics of contact and separation between the cam and follower are taken into consideration. Valve spring model consists of several lumped masses, which can represent coil crash and spring surge phenomenon.
A lot of models for the process automation and optimization should be prepared according to the various valve train types such as direct acting, end pivot, center pivot type, and etc. In this study end pivot type valve train is selected for automation and optimization. The schematic diagram of valve train analysis model is shown in Figure 1.

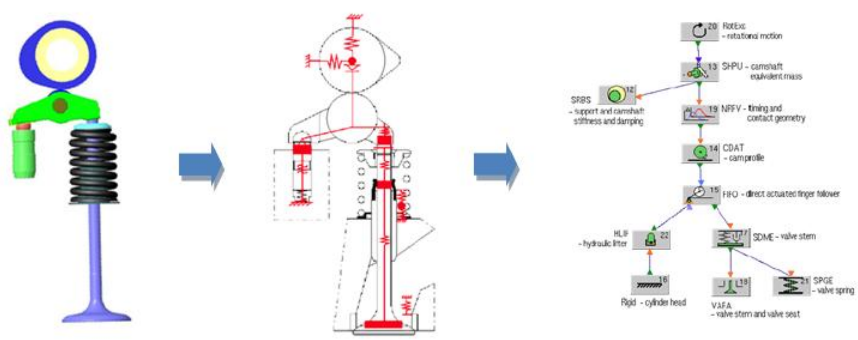

Figure 1. Schematic diagram of end pivot type valve train model.

2.2 Kinematic analysis

In the previous section kinematic analysis is defined as a work to design a valve lift profile and calculate pseudo-static forces. Because valve lift is the major factor to improve the engine performance, the goal of kinematic analysis is to optimize the valve profile so as to maximize the area under the valve lift curve. Generally, the valve has to be opened and closed as quickly as possible in order to allow the maximum amount of charge to be drawn into the cylinders. However the area under the valve lift is limited by certain kinematic constraints, such as the maximum engine speed without abnormal valve movement, ability to manufacture, durability, and NVH. When a new valve lift profile is designed, for instance, we have to evaluate whether the kinematic guidelines are satisfied or not, such as maximum positive acceleration, maximum cam-follower contact stress, minimum radius of curvature and spring cover factor, etc. And then the valve lift should be repeatedly modified until the area below the valve lift is maximized. The manual kinematic optimization processes like this are very laborious and time-consuming jobs.

2.3 Dynamic analysis

Dynamic analysis is a kind of multi-body dynamic analysis to predict the dynamic behavior considering stiffness and damping between the parts of valve train system. From the dynamic analysis, we can determine dynamic valve motion, dynamic forces between cam and follower, spring surge vibration. Besides, valve seating force, camshaft driving torque, camshaft bearing load, valve jump and bounce, and engine's dynamic limiting speed also can be calculated. The objective of dynamic analysis is to maximize dynamic limiting speed within constraint guidelines of dynamic analysis such as valve seating velocity, valve jump and bounce. In order to achieve the objectives, it's necessary to optimize the valve spring load and reduce the weight of each component. Sometimes even the valve lift should be redesigned.

The forces from dynamic analysis can be used as an input load for fatigue analysis, which predicts durability of the valve train components. Dynamic analysis is commonly divided into two steps, single cylinder analysis and multi-cylinder analysis for the purpose of analysis.

3. Cam profile design and optimization

Kinematic analysis is defined as the process to design a valve lift and optimize it in the previous section. This process is quite laborious and dependent on the engineer's hands-on experience of the valve train analysis. In addition, it is difficult to maintain consistency of the valve lift because the engineers who perform the analysis have different design strategy. To resolve these problems, the automation and optimization processes for valve train kinematic analysis have been developed by using Isight.

3.1 Cam profile design with B-Spline curve

A valve profile design process generally begins with defining the shape of valve acceleration curve. Several different definition methods of the acceleration curve have been introduced in the last few decades. However these definition methods are not suitable for the optimization because of less flexibility and discontinuity troubles.

In this study a new representation with B-Splines was applied to the valve acceleration definition. The advantages of this representation are the fact that the change in the design point is displayed graphically and the numbers of control points could be increased easily. Furthermore, the B-Spline curve is always smooth and continuous at any point inside the design space and it is possible to modify the acceleration curve in part without any influence on the other section. Because of these advantages new method is well suited for the optimization process.

However It is quite difficult to control all design points of B-Spline curve for the kinematic optimization. So seven design parameters to modify the shape of the acceleration curve was selected. That parameters define the relationship between design points and can directly and intuitively adjust the shape of the curve within the design range. The design parameters and acceleration curve shape are shown in Fig 2.

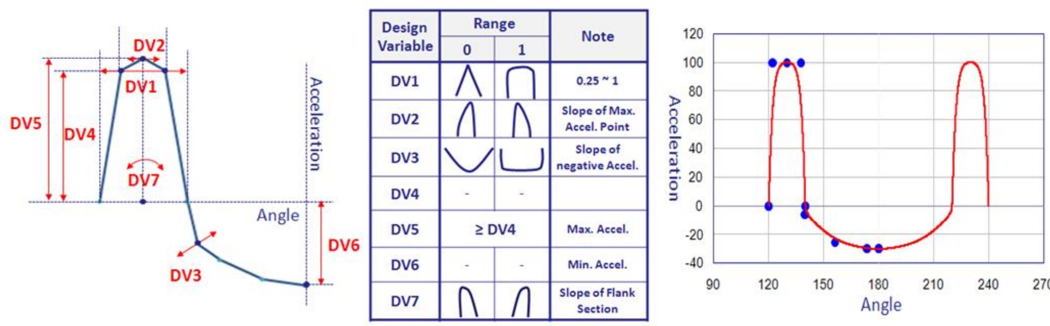

Figure 2. Design parameters and shape of acceleration curve using B-Spline.

New tool for the kinematic analysis based on the Microsoft EXCEL is developed with the curve design method using B-Spline. This tool is composed of four parts, valve acceleration shape design, ramp definition, the kinematic analysis results display, and the graph of the designed valve lift profile. The kinematic optimization process using Isght can be run automatically by clicking the button in this tool. This new tool is shown in Fig 3.

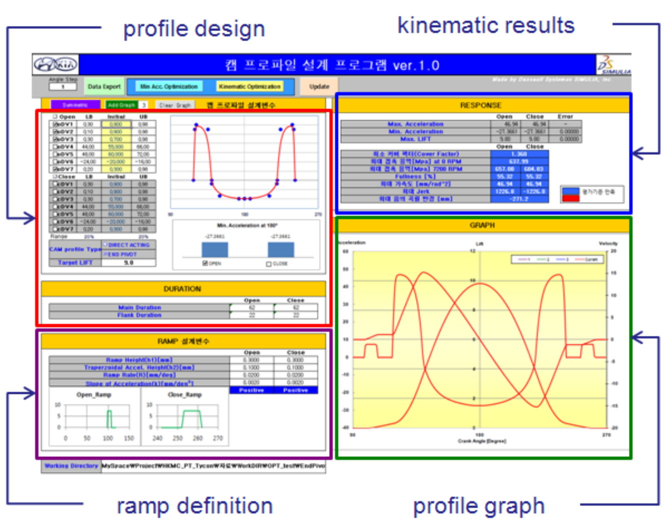

Figure 3. New tool for the kinematic analysis.

3.2 Optimization problem

A constrained optimization problem is formulated to improve the engine performance regarding the kinematic constraints.

The objectives of kinematic optimization are to maximize the area under the valve lift curve, which is related to the engine performance.

Design variables for the optimization could be all seven design parameters (eg. DV1 ~ DV7).

The opening section and closing section of the valve acceleration curve could be independently defined by the new tool. Also symmetrical type of the curve can be defined. Unsymmetrical curves have been considered in this study. At first feasible parameters should be set, and then these parameters are constrained to a certain range around that point. The range of the parameters are set to 20%. In general, maximum valve lift and duration are determined by the engine's thermodynamic performance requirement. Therefore, these parameters are not included in the optimization variables.

The constraints of this optimization are maximum acceleration, spring cover factor, cam-follower contact stress and minimum radius of curvature.

In order to optimize this problem, Isight model is used with the kinematic calculation tool as shown in Fig 4. NLPQL-Sequential quadratic program strategy, well-suited for highly non-linear design space is applied for the optimization.

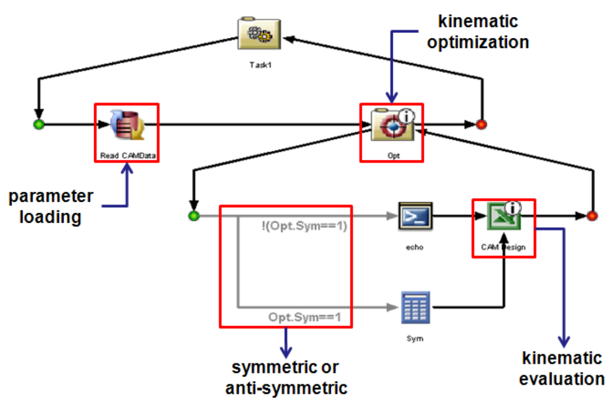

Figure 4. Isight model for kinematic optimization.

3.3 Results

The objective of this optimization is to maximize the area under the valve lift while satisfying the kinematic boundary conditions. The original and the optimized curves are shown in Fig 5. The area under the valve lift has increased even though the maximum acceleration has decreased. Also the spring cover factor has improved.

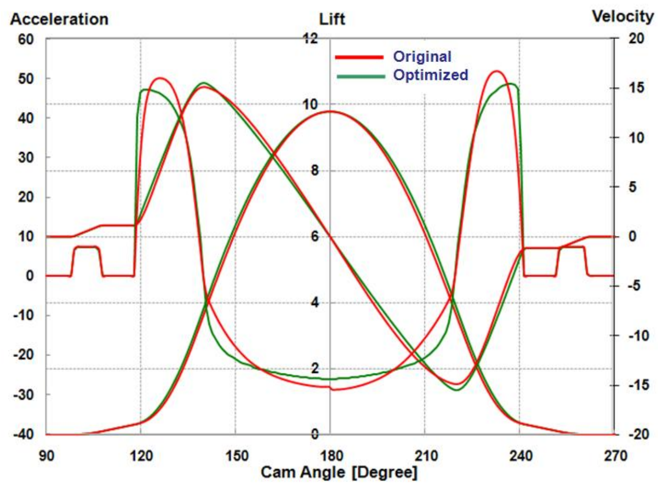

Figure 5. Kinematic valve lift, velocity, and acceleration curves.

4. Automated dynamic analysis process and optimization

In order to perform a valve train dynamic analysis such as model configuration, analysis execution and analyzing the result, it's necessary to have an experienced operational capability and skill to manage the software. These difficulties have been a major obstacle for design engineers to use the CAE. In this chapter, automated processes of dynamic analysis are presented in order that design engineers who are not familiar with CAE can easily perform the valve train dynamic analysis.

4.1 Automated process using Isight

After the optimal valve profile has been selected by the kinematic analysis, Dynamic analysis is performed with the selected lift curve. Dynamic analysis is divided into single cylinder and multi cylinder dynamic analysis. The Single cylinder dynamic analysis is to determine dynamic valve motion, dynamic forces considering only one cylinder of the valve train. If the design guidelines are not satisfied, the kinematic analysis will be performed again by modifying the maximum valve lift, duration, and valve spring load. Otherwise optimum mass and stiffness of valve train components will be found by dynamic optimization process. After the design guidelines are satisfied by the optimization, finally multi cylinder dynamic analysis is performed in order to determine the effect of adjacent cylinder, cam shaft driving torque, and bearing load are determined. The dynamic loads calculated by these dynamic analysis are used as a boundary condition for durability analysis. Figure 6. shows the whole valve train analysis procedure.

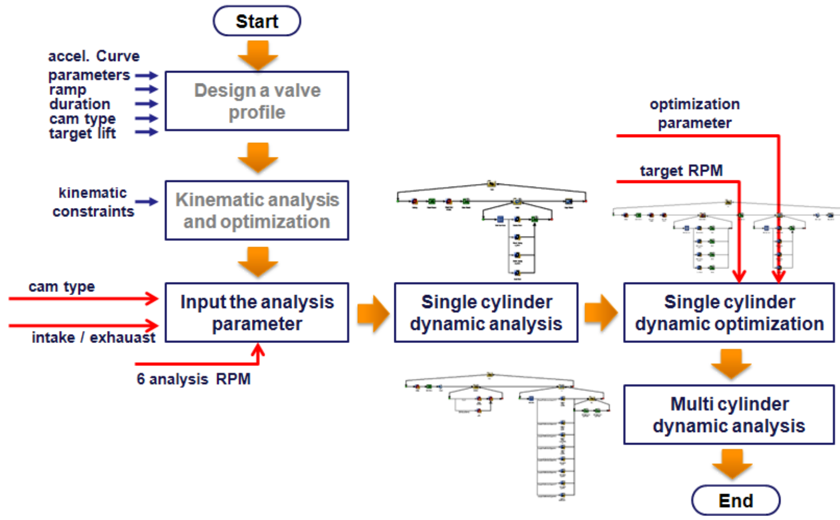

Figure 6. Valve train analysis procedure using Isight.

Various types of analysis model have to be prepared for the dynamic analysis depending on the different valve train and engine types. In this automated dynamic analysis process, four kinds of single cylinder models and eight kinds of multi cylinder models are included in the form of template models. These dynamic analysis procedures are integrated and automated by Isight process, which is consist of data loading part, dynamic simulation executing part consistent with the valve train type, and results summary part. All input parameters and types of valve train could be defined at the main operating tool made by Excel. Isight model for the automated analysis process is shown in Fig. 7

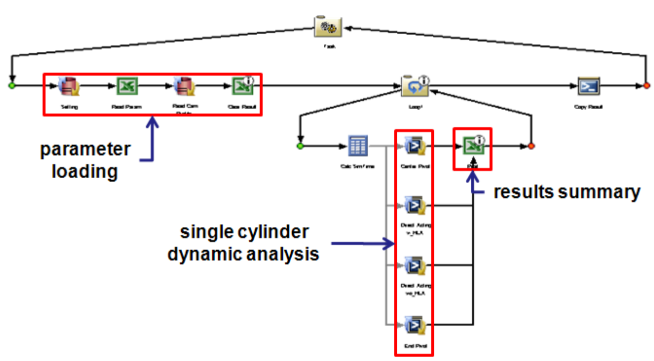

Figure 7. Isight model for automated analysis process.

5. Conclusion

In this work, a new valve profile design process using B-Spline curve is suggested. Also kinematic optimization and dynamic analysis processes are integrated and automated using Isight. The benefits of these optimization and automation are :

1. Time required for valve profile design is reduced and the kinematic optimization process is automated with improved robustness.
2. Dynamic analysis processes are automated. So a design engineer can easily perform a dynamic analysis and summarize the analysis results without knowing complex CAE.
3. Standardization of analysis process ensures the reliability of analysis results regardless of designer's experience.
4. New tool for kinematic and dynamic analysis based on the MS Excel can enhance user's convenience.

6. References

1. Norton, R.L. "Cam design and manufacturing handbook," Industrial press Inc., 2002.
2. Scheucher,R., and Hellinger, W., "Using Bezier splines for design optimization of cams regarding valve train dynamics," Proc. IMechE, vol. 221, J. Multi-body Dynamics, 2007.
3. Montazersadgh, Farzin H., "Development of an Automated Cam Profile Designer and Optimizer," SAE Technical paper 2010-01-1108, 2010
4. Beloiu, Dumitru M., "Modeling and Analysis of Valve Train, Part I – Conventional Systems," SAE Technical paper 2010-01-1198, 2010