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Shape Optimization of a Segment Ball Valve Using Metamodels

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Abstract : *This study presents the optimization design process of a segment ball valve that involves the reduction of the flow resistance coefficient and the satisfaction of the strength requirement. Numerical analysis of fluid flow and structural analysis have been performed to predict the flow resistance coefficient and the maximum stress of a segment ball valve. In this study, a segment ball valve incorporating the advantages of a ball valve and a butterfly valve has been devised. In general, ball valves are installed in a pipe system where tight shut off is required. Butterfly valves having smaller end-to-end dimension than ball valve can be installed in narrow spaces in a pipe system. The metamodels for the shape design of a segment ball valve are built by the response surface method and the Kriging interpolation model.*

Key words : *Ball Valve; Shape Optimization; Response Surface Method; Kriging; Metamodel*

1. Introduction

A valve is a device that regulates the flow or the pressure in a fluid flow or pressure system. This regulation may involve the stopping and starting of flow, flow rate control, flow diversion, back flow prevention, pressure control, or pressure relief(Lee et al., 2010; Smith, 2004). A valve should be designed for smooth operation and should satisfy the structural safety requirement under diverse environments. Generally, the flow coefficient C_v is considered as the standard response in selecting a valve. It states the flow capacity of a valve in gal(U.S.)/min of water at a temperature of 60°F for 1lb/in^2 at a specific opening position (Lee et al., 2010; Smith, 2004). The flow resistance coefficient and the flow coefficient are inversely proportional to each other. Thus, for simplicity, the flow resistance coefficient is utilized.

Hydrodynamic characteristics of valves have been investigated. Ogawa(1995) and Kimura(1995) studied the flow coefficient C_v and the torque characteristics of valves. But there have not been many studies on structural optimization design considering hydrodynamic characteristics and structural safety. This study presents the optimization process of a segment ball valve that involves the reduction of the flow resistance coefficient and satisfaction of the strength requirement.

A segment ball valve has the advantages of a ball valve and a butterfly valve. In general, ball valves are installed in a pipe system where tight shut off is required. It consists of a ball placed in the passageway through which fluid flows. The operating principle of a ball valve is similar to that of a butterfly valve. However, the ball valves have relatively long end-to-end dimensions. On the other hand, butterfly valves offer advantages of compact size and lightweight, which result from their smaller end-to-end dimensions(Skousen, 2006).

The optimization problem of a valve is a coupled problem that requires fluid flow analysis and structural analysis. The flow resistance coefficient is calculated by fluid flow analysis for a fully-open valve. The strength performance of a valve cannot be investigated at the fully-open state. In this study, a fixed ball angle is suggested to predict the stress generated in a valve. In this process, the stress is calculated by FSI(Fluid-Structure Interaction).

FSI analysis applies the result(forces or temperature or convection load) from ANSYS CFX(2007) at the fluid-structure interface as a load to the simulation analysis (ANSYS, Inc., 2007). That is, the wall pressure used in fluid flow analysis is applied as a load to the internal surface of a valve. The maximum wall pressure should be found to calculate the maximum stress. The pressure increases as the ball angle ψ decreases. At the fully-open state; the ball angle has 90°.

The wall pressure cannot be made uniformity when the flow area between the valve body and segment ball is changed according to the shape of segment ball. Therefore,

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for relatively uniform wall pressure, angle ψ has been selected to correspond to the angle representing the specific distance between the valve body and the segment ball.

The paper presents a computationally efficient method for determining the optimum shape of a segment ball valve. In general, a gradient based optimization algorithm, which is adopted as the optimizer, can find a mathematically reliable optimum. However, the use of the gradient based algorithm is limited in applying to valve design. The optimum may not be obtained due to the excessive computation time. Furthermore, the gradient based algorithm can find only the local optimum.

To overcome these difficulties, the optimization scheme using metamodel is introduced. First, the RSM (Response Surface Method)(Montgomery, 2005) and the Kriging interpolation method are utilized to surrogate the true responses of the flow resistance coefficient and the maximum stress. The use of the metamodels not only reduces the tedious computing time to obtain an optimum but also facilitates optimization. Then, any optimization algorithm can be utilized to find the optimum shape.

The design variables are set up as the segmenting angle, which decides the shape of the segment ball, and the radius of curvature inside the segment ball. ANSYS CFX 11.0 and ANSYS Workbench 11.0 were used for the numerical analysis of fluid flow and the structural analysis.

2. Kriging interpolation method

Kriging is a method of interpolation named after a South African mining engineer named D. G. Krige, who developed the technique while trying to increase the accuracy in predicting ore reserves. In Kriging model, the global approximation model for a response $y(\mathbf{x})$ is represented as

$$y(\mathbf{x}) = \beta + v(\mathbf{x}) \tag{1}$$

where $\mathbf{x}$ is the design variable vector, β is a constant, and $v(\mathbf{x})$ is the realization of a stochastic process. In Eq. (1), $v(\mathbf{x})$ has the mean zero, variance σ^2, and non-zero covariance. The flow resistance coefficient ζ is replaced by $y(\mathbf{x})$ to make a surrogate approximation model.

Let $y(\mathbf{x})$ be an approximation model Hereafter, ^ means the estimator. When the mean squared error between $y(\mathbf{x})$ and $\hat{y}(\mathbf{x})$ is minimized, $\hat{y}(\mathbf{x})$ becomes

$$\hat{y}(\mathbf{x}) = \hat{\beta} + \mathbf{r}^T(\mathbf{x})\mathbf{R}^{-1}(\mathbf{y} - \hat{\beta}\mathbf{q}) \tag{2}$$

where $\mathbf{r}$ is the correlation vector, $\mathbf{R}$ is the correlation matrix, $\mathbf{y}$ is the observed data and $\mathbf{q}$ is the unit vector. The definition of $\mathbf{R}$ and $\mathbf{r}$ are well explained in Refs. Guinta et al.(1998), Lee et al.(2006) and Leary et al.(2004).

The unknown correlation parameters of Θ_1, $\Theta_2, \cdots$, Θ_n defined in $\mathbf{R}$ are calculated from the model as follows:

$$maximize\ -\frac{[n_s ln(\hat{\sigma}^2) + ln|\mathbf{R}|}{2} \tag{3}$$

where Θ_i $(i = 1, 2, \cdots, n) > 0$. In this study, the method of modified feasible direction is utilized to determine the optimum parameters. To assess the Kriging model, the error in surrogate model can be measured by

$$Average\%error = \frac{1}{n}\sum_{i=1}^{n_t}\left|\frac{\hat{y}_i - y_i}{y_i}\right| \times 100 \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n_t}\sum_{i=1}^{n_t}(y_i - \hat{y}_i)^2} \tag{5}$$

where n_t is the number of sample points for validation, which is set to 10 in this study.

3. Segment ball valve

A segment ball valve (Lee and Lee, 2009) consists of partial ball, body, stem and seat as shown Fig. 1. Because a segment ball valve has small end-to-end dimensions, it can be installed in narrow spaces in a pipe system. When a segment ball is in fully-open position, it is fully out of the passageway through which the fluid flows. In general, a butterfly valve has flow resistance coefficient of 0.2 – 1.5 in turbulent flow, and a ball valve 0.1(Smith, 2004; Skousen, 2006). In this study, we investigate the on-off segment ball valve.

4. Optimization of a segment ball valve

4.1 Fluid analysis

Numerical analysis of fluid flow was carried out to obtain flow resistance coefficients according to the shape of the segment ball. For fluid analysis of a segment ball angle of 90°, a flow field was structured by a CFX-mesh at ψ = 90°, as shown in Fig. 2 The value of ψ ranged from 0° to 90°. The segment ball valve was fully closed at ψ = 0° and fully-open at ψ = 90°. A velocity profile develops before the fluid reaches the valve. Thus, the distance required for the flow to develop may be estimated by using an empirical formula for entry length L_e given by L_e/D = $4.4(R_{eD})^{1/6}$

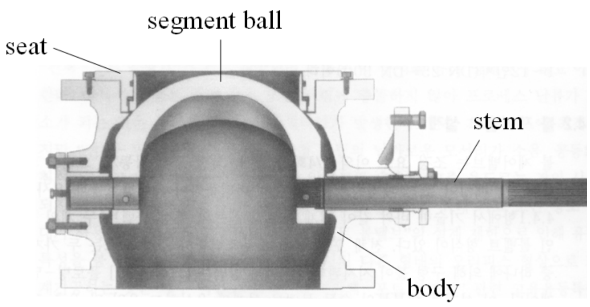

Fig. 1 Segment ball valve

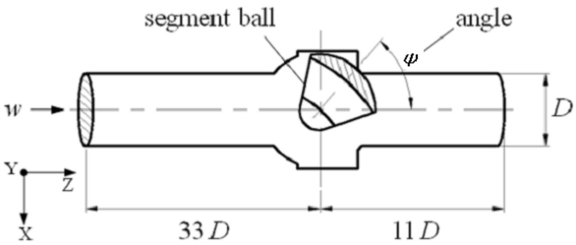

Fig. 2 Simplified numerical model of segment ball valve and coordinate system

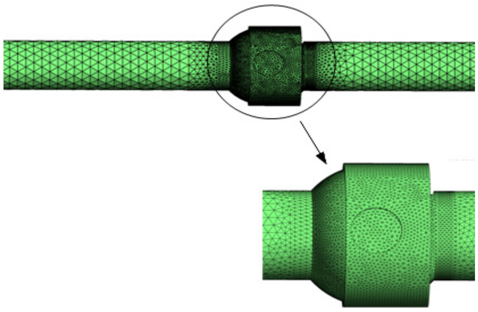

Fig. 3 Flow field for fluid flow analysis

(Henderson et al., 2007). This correlation predicts lengths of approximately 33*D*. The length of the upstream is 33*D* and that of the downstream is 11*D* in Fig. 2. The length is the distance from the shaft of the segment ball to upstream or downstream. The flow field of about 95,000 nodes and 307,000 elements is shown in Fig. 3. The diameter *D* of pipe was 50 mm. The fluid passing the valve is water. Its incoming velocity w is 3 m/s and density ρ is 997.4 kg/m^3, and dynamics viscosity μ is 0.8899×10^{-3} kg/ms. In this study, assumptions for fluid analysis are as follows (Huang and Kim, 1996):

- The flow is steady-state and three-dimensional.
- The fluid is Newtonian and incompressible.
- The walls of the pipe and valve are smooth.

The Boundary conditions were as follows :

- The uniform inlet velocity w is 3 m/s, and the outlet condition is 0.1013 MPa (1 atm).
- Turbulence model is k-ε.
- The wall condition of valve and pipes is No-slip and Smoothing.
- For the rest of boundary conditions, the default values in CFX are utilized.

4.2 Calculation of the flow resistance coefficient

The flow resistance coefficient ζ defines the friction loss attributable to a valve in a pipeline in terms of velocity head or velocity pressure, as expressed by Eq. (6) – (8)

$$\Delta P = \zeta \frac{v^2 \rho}{2} \tag{6}$$

$$\zeta = \frac{\Delta P}{(1/2) v^2 \rho} \tag{7}$$

$$\Delta P = P_1 - P_2 \tag{8}$$

where, P_1 and P_2 are the static pressures taken at upstream and downstream, respectively, v is average velocities (m/s) in a pipe line, and ρ is density (kg/m^3) of fluid. The length of P_1 is 2*D* and that of P_2 is 6*D* from the shaft of the segment ball in Fig. 4(Smith, 2004; IEC, 1997).

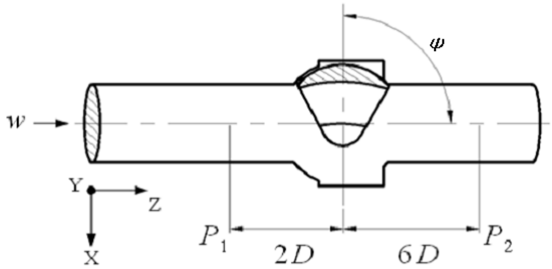

Fig. 4 Position of the P_1 and the P_2 for calculating ζ

4.3 Fluid-structure interaction analysis

An on-off valve does not work at 0° < ψ < 90° generally. But, for the investigation of structural safety, the FSI model sets the angle (ψ) of the segment ball to be 0° < ψ < 90°. The flow field is structured at t = 3 mm in Fig. 5. The length t is the distance between the valve body and the segment ball. The FSI model consists of the body, stem, segment ball and seat in Fig. 6. The FE model was meshed with tetrahedron elements of ANSYS workbench.

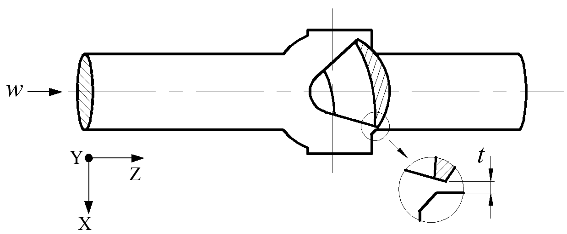

Fig. 5 The t for FSI analysis

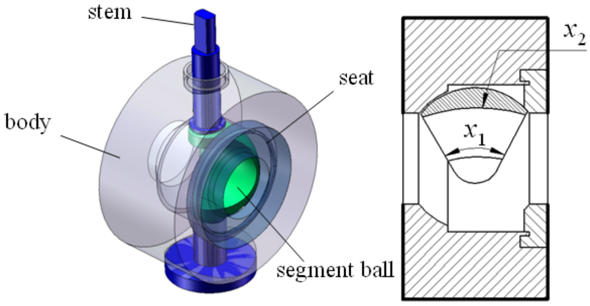

Fig. 6 Design variables for optimization of segment ball valve

The boundary condition for the structural analysis is shown in Fig. 7. The area of the valve flange was set the fixed support. The wall pressure was applied as a load to internal surface of the segment valve. The maximum stress was observed by the von-Mises stress.

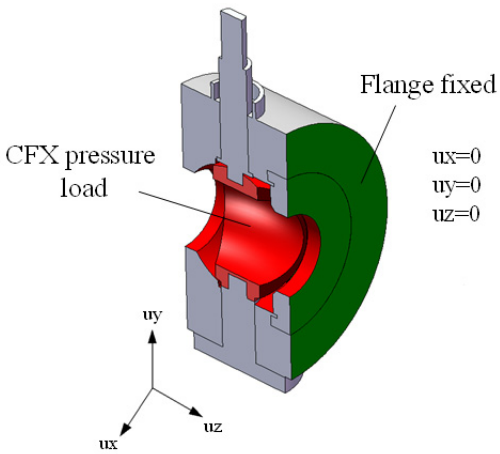

Fig. 7 Boundary conditions for static structural analysis

4.4 Process of the optimum design using metamodels

An optimization problem that minimizes the flow resistance coefficient and satisfies the strength requirement is defined to find the optimum shape of a segment ball valve. The flow resistance coefficient is related to the shape of the segment ball. The design variables are x_1 and x_2, which are the segmenting angle and the radius of curvature inside the segment ball, respectively, in Fig. 6.

The optimization formulation of the segment ball valve can be defined as follows:

$$\begin{aligned} &\text{Minimize} \quad \zeta(x_1, x_2) \\ &\text{Subject to} \quad \sigma_{max} - \sigma_y/1.5 \le 0 \\ &56^\circ \le x_1 \le 64.5^\circ \\ &80mm \le x_2 \le 100mm \end{aligned} \tag{9}$$

where ζ is the flow resistance coefficient, $\sigma_{\max}$ is the maximum stress and $\sigma_y/1.5$ is the allowance stress considering safety factor 1.5 which was obtained by repeated experiments. The material of body, stem and ball is ASTM A351. Its yield strength is 205MPa. The lower bound of x_1 represents the minimum value that can seal the valve in Eq. (9). The lower and upper values of x_2 are set to maintain the strength of the segment ball in Eq. (9).

The design process of a segment ball valve using the RSM and the Kriging interpolation method is as follows:

Step 1: DOE strategy

First, sample points should be set up to obtain the metamedels of flow resistance coefficient and maximum stress. DOE strategies can be used to sample the design space. In this study, the Latin hypercube design is introduced to sample the design space.

Step 2: Matrix experiment

The responses of flow resistance coefficient and maximum stress are calculated for each row of matrix experiments. The number of experiments is identical to the number of rows in the matrix; that is, an experiment means one fluid flow analysis and one finite element analysis. The computation time for one fluid flow analysis and one finite element analysis is about 2 hours on the workstation using 8 CPUs. CFX and ANSYS are used to solve the fluid-structure interactions.

Step 3: Building and validation of metamodels

Based on the responses calculated from Step 2, the RSM and the Kriging models are constructed. To assess the metamodels, the error in the surrogate model is characterized by using a few metrics.

Step 4: Calculation of optimum

Once an approximate formulation for optimization is obtained based on the metamodels, any optimization method can be used. Since all the true functions of the optimization formulation are replaced by simple mathematical expressions, the computational cost of the optimization process is very low. In this study, the GRG(Generalized Reduced Gradient) algorithm is adopted.

Table 1 Upper bound and lower bound of design variables

	x_1 (°)	x_2 (mm)
upper bound	64.5	100
lower bound	56	80

4.5 Results

Table 2 Results of the sample points from analysis

No.	x_1 (°)	x_2 (mm)	ζ	σ_{max} (MPa)
1	58.151	94.676	0.172	101.260
…	…	…	…	…
33	60.614	82.730	0.194	106.140
…	…	…	…	…
50	60.101	99.918	0.183	88.233

The number of sample points $n_s = 50$ were obtained by latin hypercube design (LHD). The sample points are created within a design domain in Eq.(9). In Table 1, the flow resistance coefficient and the maximum stress were computed by fluid analysis and FSI analysis. In Eq.(9), the metamodels for the flow resistance coefficient and the maximum stress are built based on the data in Table 2 The approximate model of the RSM for the flow resistance coefficient and the maximum stress are shown in Eq. (10) – (11), respectively.

Table 3 Optimum parameters β and Θ

	β	Θ_1	Θ_2
ζ	0.2031	1.92146	12.48807
σ_{max}	99.7852	43.56414	100.0

$$\hat{y} = 3.644 - 0.128x_1 + 0.337\times10^{-2}x_2 + 0.117\times10^{-2}x_1^2 - 0.406\times10^{-4}x_1x_2 - 0.720\times10^{-5}x_2^2 \quad (10)$$

$$\hat{y} = 82.936 - 3.083x_1 + 3.034x_2 + 0.295\times10^{-1}x_1^2 - 0.113\times10^{-1}x_1x_2 - 0.143\times10^{-1}x_2^2 \quad (11)$$

Table 4 Results of 10 sample points for validation of the metamodels

No.	ζ	$\hat{\zeta}$		σ_{max}	$\hat{\sigma}_{max}$	
		RSM	Kriging		RSM	Kriging
1	0.1796	0.1759	0.1695	100.58	100.27	100.89
2	0.1864	0.1808	0.1805	101.26	97.00	94.86
3	0.1748	0.1720	0.1741	99.97	102.67	103.87
4	0.2047	0.1985	0.2048	104.62	100.80	99.51
5	0.2495	0.2517	0.2330	99.33	99.55	99.82
6	0.2076	0.2019	0.1996	102.99	98.33	97.59
7	0.1788	0.1740	0.1743	105.79	102.84	100.88
8	0.1834	0.1800	0.1795	104.07	101.38	104.50
9	0.2184	0.2149	0.2162	94.21	99.49	96.16
10	0.2320	0.2290	0.2322	96.94	95.77	98.19

For the Kriging interpolation method, the optimum parameters of Θ_1 and Θ_2 are determined by solving Eq. (3). Then, the estimator β is calculated. The optimum estimators are shown as Table 3.

Table 5 Validation of metamodels

	$\hat{\zeta}$		$\hat{\sigma}_{max}$	
	RSM	Kriging	RSM	Kriging
RSME	0.0043	0.0072	3.271	3.761
Average%Error	2.07%	2.54%	2.78%	2.96%

The validity of the approximate model is investigated for error about 10 sample points within the design domain in Eq.(9). Its results are shown in Table 4 – 5. With respect to the approximation of the flow resistance coefficient, the RSM model is slightly better than the Kriging model. The coefficient of determination (R^2) is 0.9731. On other hand, the approximate model of the maximum stress by the RSM and the Kriging were similar to each other. The maximum stress ranged from 88.23MPa to 106.14MPa. The difference of the maximum stress was negligible in the engineering sense.

Table 6 Optimization results

	design variables		flow resistance coefficient		Maximum stress	
	x_1 (°)	x_2 (mm)	ζ	$\hat{\zeta}$	σ_{max} (MPa)	$\hat{\sigma}_{max}$ (MPa)
RSM	56.465	100.0	0.1695	0.1692	103.05	99.33
Kriging	57.668	93.340	0.1715	0.1675	105.31	100.33

The optimum values of the optimization problem are shown in Table 6, where the ˆ means the predicted value and ζ, σ are the results from the analysis. Each optimum value of an approximate model was calculated by the GRG algorithm in EXCEL. Particularly, the developed EXCEL-Kriging program computed the optimum value of Kriging approximate model(Song et al., 2009).

4. Conclusion

The present study proposed the shape optimization process for the design of a segment ball valve. The optimization methods adopted at the study is the RSM and the Kriging interpolation. We proposed the most suitable optimization method after comparing the two optimization methods for an optimization design problem involving fluid analysis and structural analysis.

The response of the flow resistance coefficient is a highly nonlinear function with noises. Thus, the RSM model was slightly more suitable than the Kriging interpolation model for obtaining the flow resistance coefficient. The predictions of the maximum stress by the RSM and the Kriging models, respectively, were similar in the engineering sense.

This study did not consider noise, vibration and cavitation etc. However, these factors need to be considered for valves design.

Acknowledgements

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