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(1985) 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 $\psi$ decreases. At the fully-open state; the ball angle $\psi$ 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 \( \psi \) 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 \( y(x) \) is represented as

\[
y(x) = \beta + v(x)
\]

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

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

\[
\hat{y}(x) = \beta + r^T(x)R^{-1}(y - \beta q)
\]

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

The unknown correlation parameters of \( \theta_1, \theta_2, \cdots, \theta_k \) defined in \( R \) are calculated from the model as follows:

\[
\text{maximize} \quad \frac{\ln(\sigma^2) + \ln|R|}{2}
\]

where \( \theta_i \) \( (i = 1, 2, \cdots, n) > 0 \). 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

\[
\text{Average error} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\hat{y}_i - y_i}{y_i} \right| \times 100
\]

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2}
\]

where \( n_i \) 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\(^\circ\), a flow field was structured by a CFX-mesh at \( \psi = 90^\circ \), as shown in Fig. 2. The value of \( \psi \) ranged from 0\(^\circ\) to 90\(^\circ\). The segment ball valve was fully closed at \( \psi = 0^\circ \) and fully-open at \( \psi = 90^\circ \). 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 \( L_e/D = 4.4(R_{chest})^{1/6} \)}
The flow resistance coefficient \( \zeta \) 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)

\[
\Delta P = \frac{\zeta v^2 \rho}{2}
\]

\[
\zeta = \frac{\Delta P}{(1/2)v^2 \rho}
\]

\[
\Delta P = P_1 - P_2
\]

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 \( \rho \) 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).

### 4.3 Fluid-structure interaction analysis

An on-off valve does not work at \( 0^\circ < \psi < 90^\circ \) generally. But, for the investigation of structural safety, the FSI model sets the angle \( \psi \) of the segment ball to be \( 0^\circ < \psi < 90^\circ \). The flow field is structured at \( t = 3 \text{ mm} \) 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.
The boundary condition for the structural analysis is shown in Fig. 7. The area of the valve flange was set as the fixed support. The wall pressure was applied as a load to the internal surface of the segment valve. The maximum stress was observed by the von-Mises stress.

![Fig. 7 Boundary conditions for static structural analysis](image)

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:

\[
\begin{align*}
\text{Minimize} & \quad \zeta(x_1, x_2) \\
\text{Subject to} & \quad \sigma_{\text{max}} - \sigma_{\text{y}}/1.5 \leq 0 \\
& \quad 56^\circ \leq x_1 \leq 64.5^\circ \\
& \quad 80\text{mm} \leq x_2 \leq 100\text{mm}
\end{align*}
\]

where \( \zeta \) is the flow resistance coefficient, \( \sigma_{\text{max}} \) is the maximum stress and \( \sigma_{\text{y}}/1.5 \) 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 metamodels 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

<table>
<thead>
<tr>
<th>No.</th>
<th>$x_1$ (°)</th>
<th>$x_2$ (mm)</th>
<th>$\zeta$</th>
<th>$\sigma_{\text{max}}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>58.151</td>
<td>94.676</td>
<td>0.172</td>
<td>101.260</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>33</td>
<td>60.614</td>
<td>82.730</td>
<td>0.194</td>
<td>106.140</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>50</td>
<td>60.101</td>
<td>99.918</td>
<td>0.183</td>
<td>88.233</td>
</tr>
</tbody>
</table>

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 $\beta$ and $\theta$

<table>
<thead>
<tr>
<th></th>
<th>$\beta$</th>
<th>$\theta_1$</th>
<th>$\theta_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\zeta$</td>
<td>0.2031</td>
<td>1.92146</td>
<td>12.48807</td>
</tr>
<tr>
<td>$\sigma_{\text{max}}$</td>
<td>99.7852</td>
<td>43.56414</td>
<td>100.0</td>
</tr>
</tbody>
</table>

\[
y = 3.644 - 0.128 x_1 + 0.337 \times 10^{-2} x_2 + 0.117 \times 10^{-2} x_1^2 \\
- 0.406 \times 10^{-4} x_1 x_2 - 0.720 \times 10^{-5} x_2^2
\]  
(10)

\[
\hat{y} = 82.936 - 3.083 x_1 + 3.034 x_2 + 0.295 \times 10^{-1} x_1^2 \\
- 0.113 \times 10^{-1} x_1 x_2 - 0.143 \times 10^{-1} x_2^2
\]  
(11)

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

<table>
<thead>
<tr>
<th>No.</th>
<th>$\zeta$</th>
<th>$\hat{\zeta}$</th>
<th>$\sigma_{\text{max}}$</th>
<th>$\hat{\sigma}_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RSM</td>
<td>Kriging</td>
<td>RSM</td>
<td>Kriging</td>
</tr>
<tr>
<td>1</td>
<td>0.1796</td>
<td>0.1759</td>
<td>100.58</td>
<td>100.27</td>
</tr>
<tr>
<td>2</td>
<td>0.1864</td>
<td>0.1808</td>
<td>101.26</td>
<td>97.00</td>
</tr>
<tr>
<td>3</td>
<td>0.1748</td>
<td>0.1720</td>
<td>102.67</td>
<td>103.87</td>
</tr>
<tr>
<td>4</td>
<td>0.2047</td>
<td>0.1985</td>
<td>104.62</td>
<td>100.80</td>
</tr>
<tr>
<td>5</td>
<td>0.2485</td>
<td>0.2517</td>
<td>99.33</td>
<td>99.55</td>
</tr>
<tr>
<td>6</td>
<td>0.2076</td>
<td>0.2019</td>
<td>102.99</td>
<td>98.33</td>
</tr>
<tr>
<td>7</td>
<td>0.1788</td>
<td>0.1740</td>
<td>106.79</td>
<td>102.84</td>
</tr>
<tr>
<td>8</td>
<td>0.1834</td>
<td>0.1800</td>
<td>104.07</td>
<td>101.38</td>
</tr>
<tr>
<td>9</td>
<td>0.2184</td>
<td>0.2149</td>
<td>94.21</td>
<td>99.49</td>
</tr>
<tr>
<td>10</td>
<td>0.2320</td>
<td>0.2290</td>
<td>96.94</td>
<td>95.77</td>
</tr>
</tbody>
</table>

#### Table 5 Validation of metamodels

<table>
<thead>
<tr>
<th></th>
<th>$\zeta$</th>
<th>$\sigma_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RSM</td>
<td>Kriging</td>
</tr>
<tr>
<td>RSME</td>
<td>0.0043</td>
<td>0.0072</td>
</tr>
<tr>
<td>Average%Error</td>
<td>2.07%</td>
<td>2.54%</td>
</tr>
</tbody>
</table>

#### Table 6 Optimization results

<table>
<thead>
<tr>
<th></th>
<th>$\zeta$</th>
<th>$\sigma_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RSM</td>
<td>Kriging</td>
</tr>
<tr>
<td>design variables</td>
<td>flow resistance coefficient</td>
<td>Maximum stress</td>
</tr>
<tr>
<td>$x_1$ (°)</td>
<td>$x_2$ (mm)</td>
<td>$\zeta$</td>
</tr>
<tr>
<td>RSM</td>
<td>56.465</td>
<td>100.0</td>
</tr>
<tr>
<td>Kriging</td>
<td>57.668</td>
<td>93.340</td>
</tr>
</tbody>
</table>

The optimum values of the optimization problem are shown in Table 6, where the $\hat{}$ means the predicted value and $\hat{\zeta}$, $\hat{\sigma}$ 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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