Structural optimization of cylinder-crown integrated hydraulic press with hemispherical hydraulic cylinder

Weiwei Zhang, Xiaosong Wang*, Zongren Wang, Shijian Yuan

School of Materials Science and Engineering, Harbin Institute of Technology, Harbin, 150090, China

Abstract

Cylinder-crown integrated hydraulic press is an innovative press. The hemispherical hydraulic cylinder also functions as a main portion of crown. Compared with the conventional hydraulic press in which cylinder mounted in the crown, the thickness of hemispherical hydraulic cylinder could be much thinner and the crown section modulus could be much higher under the same application condition. As a result, the material strength capacity is better utilized. Based on sequential quadratic programming, structural optimization of hemispherical hydraulic cylinder for weight reduction has been carried out within the range of constraints including strength and stiffness conditions. Compared with the initial design, a lighter structure with weight reduction 7% and acceptable stress distribution has been obtained. Considering the advantages of cylinder-crown integrated hydraulic press, according to its optimization design, a 6300KN prototype hydraulic press has been manufactured.

Keywords: Cylinder-crown integrated hydraulic press; Optimization design; Sequential quadratic programming

1. Introduction

Various forming processes are associated with a large variety of forming equipments. ASM Handbook, (1988) classified the forming equipments into three types: load-restricted equipments (hydraulic presses), stroke-restricted equipments (crank and eccentric, or mechanical presses), and energy-restricted equipments (hammers and screw presses). Altan et al. (2004) conducted that the load-carrying capability of the frame has been achieved...
by using various designs such as crown-columns style, cast (or welded) structure pre-stressed by forged tie rods or laminated plates assembled through large transverse pins. In modern presses design, no matter how the press structure changes, the hydraulic cylinder is still cylindrical shape and always assembled inside the press crown which is subjected to the bending moment caused by press loading. The cylinder and press crown could not be reinforced by each other. As a result, the material strength capacity is not fully utilized.

In addition, the damage of hydraulic cylinder caused by incorrect design, machining, or operation, are often located on the connecting flange, where the stress is concentrated severely. To prevent the shortcomings mentioned above, Wang et al. (2010) provided an idea of a cylinder-crown integrated hydraulic press with hemispherical cylinder. During his long-term research on die-less hydro-bulging of spherical shell, Wang et al. (2005) realized that the allowable applied pressure on the shell is the highest for the spherical shell than other shape shells. Thus, he suggested that the hydraulic cylinder should be better designed as a hemispherical shape and also functions as a main portion of the press crown, which is so called cylinder-crown integrated hydraulic press.

### Nomenclature

- $B$: Hesse approximation matrix
- $C_i(x)$: vector of equality or inequality constraints
- $d$: independent variable of the quadratic programming sub-problem and search direction of iteration
- $E$: subscript set of equality constraints
- $E^n$: n-dimensional Euclidean space
- $f$: deflection of hemispherical hydraulic cylinder
- $F(x)$: objective function
- $I$: subscript set of inequality constraints
- $u_i$: penalty parameter
- $W(x)$: penalty-type line search objective function
- $x$: vector of variables
- $\alpha_k$: step size factor
- $\gamma$: gradient difference of the Lagrange functions
- $\sigma_m$: equivalent stress
- $\nabla_x$: the first order partial derivatives

### 2. Structural characteristics

For variable application, as shown in Fig. 1, this kind of press can be designed as column style or straight-side frame style. Compared with the traditional hydraulic press, the characteristic and advantages of cylinder-crown integrated hydraulic press are as following: (1) Hemispherical hydraulic cylinder also functions as a main portion of the press crown, and they are manufactured into a solid part; (2) Compared with cylindrical shell, thick-walled spherical shell can decrease one half wall thickness under the condition of the same internal pressure, internal radius and allowable stress; (3) The section modulus of the hemispherical crown is much larger than that of the rectangle crown because of a higher geometry centroid. Therefore, when the same bending moment is applied, the hemispherical crown has lower tensile bending stress and a higher safety factor from the strength point of view. (4) The cylinder-crown integrated hydraulic press is able to have higher nominal force and larger area of plunger when the contour geometric dimensions are the same; (5) There is lower stress concentration caused by machining and assembly.

### 3. Structure optimization design

The detailed design for cylinder-crown integrated structure is shown in Fig. 2. In order to suit for variable press bed sizes and press capacity, the overall dimensions of cylinder-crown integrated structure can be changed for variable application. However, structural improvement on local region to overcome stress concentration and
reduce total weight is very necessary. So, structural optimization for cylinder-crown integrated structure based on mathematical programming to obtain the lightest weight and acceptable stress distribution within the range of strength and stiffness conditions should be carried out.

Fig. 1. Cylinder-crown integrated hydraulic press: a) Column style; b) Straight-side frame style.

Fig. 2. Dimension of the 6300KN hemispherical hydraulic cylinder.

3.1. Sequential quadratic programming method

Sequential quadratic programming is one of the most successful general methods for solving nonlinear constrained optimization problems (Michael, 2008). It possesses fast convergence speed and good robustness. Supported by solid theoretical foundation, sequential quadratic programming has been developed and used to solve many important practical problems. A nonlinear constrained optimization problem can be expressed as

\[
\begin{align*}
\text{minimize} \quad & F(x) \quad x \in E^n \\
\text{subject to} \quad & C_i(x) = 0 \quad (i \in E) \\
& C_j(x) > 0 \quad (j \in I)
\end{align*}
\]

where \( F(x) \) is the objective function, \( x \) is the vector of variables, \( E^n \) is n-dimensional Euclidean space. When \( i \in E \), \( C_i(x) \) is the vector of equality constraints. When \( i \in I \), \( C_j(x) \) is the vector of inequality constraints. \( E \) is the subscript set of equality constraints, \( I \) is the subscript set of inequality constraints.
Sequential quadratic programming converts a nonlinear programming problem into a sequence of quadratic programming sub-problems. An application of sequential quadratic programming requires that one iteratively solve the quadratic programming sub-problem of the form

$$\begin{align*}
\minimize & \quad S(d) = \nabla_x F(x) d + \frac{1}{2} d^T B d / 2, \quad x, d \in \mathbb{R}^n \\
\text{subject to} & \quad C_i(x) + \nabla_x C_i(x)^T d = 0 \quad (i \in E) \\
& \quad C_j(x) + \nabla_x C_j(x)^T d > 0 \quad (i \in I)
\end{align*}$$

where $\nabla_x$ is the first order partial derivatives with respect to $x$, $d$ is the independent variable of the quadratic programming sub-problem and search direction of iteration, $B$ is the Hesse approximation matrix modified by the Newton method.

At each iteration, the search direction and the input for next iteration are calculated. And the Hesse matrix is updated by the Broyden–Fletcher–Goldfarb–Shanno (BFGS) formula.

$$B_{k+1} = B_k - \frac{\delta d \delta^T B_k}{\delta^T B_k \delta} + \frac{\gamma \gamma^T}{\delta^T \gamma},$$

where $\delta = x_{k+1} - x_k$, $\gamma$ is the gradient difference of the Lagrange functions, and $B_k \delta = \gamma$

A penalty-type line search objective function is built for the determination of step size factor $\alpha_k$

$$W(x) = F(x) + \sum_{i \in E} \alpha_i |C_i(x)| - \sum_{i \in E} \min(0, C_i(x)),$$

where $W(x)$ is a penalty-type line search objective function, $\alpha_i$ is a penalty parameter, $i \in E \cup I$

To guarantee descent in the objective function, the step size factor $\alpha_k$ must satisfy the following equation

$$W(x + \alpha_k d) \leq W(x) + 0.1 W'(x) \quad 0 \leq \alpha_k \leq 1.$$  (5)

If Eq.(5) is satisfied, the step size factor $\alpha_k$ determined by Eq. (4) is substituted into

$$x_{k+1} = x_k + \alpha_k d_k.$$  (6)

Then a new approximate minimum point has been obtained.

### 3.2. Problem proposed and optimization objectives

The design variables of cylinder-crown integrated structure are sketched in blue colour in Fig.3. The designed catapult mainly consists of two parts: outer structure located on the connecting flange and inner structure located on the special liquid vessel. The objective function is the total weight which is obtained by CAD system, and the whole cylinder-crown integrated structure must satisfy some constraints including strength and stiffness conditions at any deformation stage. To summarize all design requirements, the objective function is defined as below:

$$\begin{align*}
\minimize & \quad F(x, R_j) \quad (i = 1, 2, \ldots, 5, \ j = 1, 2, 3) \\
\text{subject to} & \quad \sigma_{ae}(x, R_j) \leq \sigma (i = 1, 2, \ldots, 5, \ j = 1, 2, 3) \\
& \quad f(x, R_j) \leq f (i = 1, 2, \ldots, 5, \ j = 1, 2, 3)
\end{align*}$$

where $\sigma_{ae}$ is the equivalent stress, $f$ is the deflection of hemispherical hydraulic cylinder, $[\sigma]$ is the allowable stress, and $[f]$ is the allowable deflection.

The finite element analysis software ABAQUS was used for stress and deformation analysis, and the multidisciplinary optimization software ISIGHT was used for integrating sequential quadratic programming and dynamic analysis to search the optimal design variables among the feasible regions. The detailed optimization flow chart was shown in Fig.4.

### 3.3. Optimization example and discussion

The optimization model can be used for any structures corresponded to variable press capacity. Suppose that the press capacity is 6300 kN, and the optimization process is shown in Table 1. Within the range of constraints, a group of optimal parameters is obtained. Compared with the initial design, the total weight was decreased 7%, and the value of equivalent stress was decreased 12.1%.
Fig. 3. Design variables of cylinder-crown integrated structure.

Fig. 4. Optimization flow chart based on sequential quadratic programming.

Table 1. Optimization process and results.

| Scale | Initial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---------|---|---|---|---|---|---|---|---|---|
| $x_1$ | 102     | 102 | 91 | 86.9 | 83.4 | 82.1 | 70 | 70.5 | 70 | 70 |
| $x_2$ | 235     | 235 | 233.3 | 231.9 | 235.5 | 236.8 | 225 | 250 | 248.3 | 225 |
| $x_3$ | 110     | 140 | 143.4 | 140.3 | 142.2 | 143.0 | 122.4 | 150 | 150 | 150 |
| $x_4$ | 390     | 390 | 368.4 | 360.3 | 351.7 | 348.5 | 320 | 348.7 | 320 | 323.9 |
| $x_5$ | 165     | 165 | 169.8 | 172.2 | 161.7 | 160.3 | 182 | 182 | 155 | 182 |
| $R_1$ | 30      | 30  | 30   | 40  | 35  | 35   | 50  | 50  | 30  | 30  |
| $R_2$ | 15      | 15  | 20.2 | 40  | 15.4 | 14.4 | 50  | 50  | 5  | 30  |
| $R_3$ | 50      | 50  | 50   | 125 | 54.5 | 55.0 | 124 | 125 | 60 | 56.2 |
| $\sigma_m$ | 0.16 | 0.16 | 0.17 | 0.17 | 0.18 | 0.18 | 0.16 | 0.17 | 0.20 | 0.20 |
| $f$ | 4.99 | 4.87 | 4.74 | 4.71 | 4.67 | 4.64 | 4.60 | 4.55 | 4.51 | 4.48 |
| $F$ | 109 | 109 | 128 | 125 | 111 | 111 | 141 | 159 | 135 | 157 |
3.4. Finite element analysis of 6300KN cylinder-crown integrated hydraulic press

Based on the optimization design for cylinder-crown integrated structure, a lightest weight and acceptable stress distribution has been obtained. Subsequently, a 6300KN cylinder-crown integrated hydraulic press with hemispherical hydraulic cylinder has been manufactured, and the detailed structure parameters have been introduced by Zhang, et al (2014). In addition, finite element analysis of the cylinder-crown integrated hydraulic press was carried out, and the displacements distribution along horizontal direction and vertical direction are shown in Fig.5b and Fig.5c respectively, which are within an acceptable range.

![Fig.5. Finite element analysis of cylinder-crown integrated hydraulic press: a) Model; b) Displacement (U3); c) Displacements (U3, U2)](image)

4. Conclusion

1. For cylinder-crown integrated hydraulic press, hemispherical hydraulic cylinder also functions as a main portion of the press crown, they are manufactured into a solid part. The thickness of hemispherical hydraulic cylinder can be much thinner and the section modules can be much higher than that in the conventional hydraulic press under the same application condition. So, material strength capacity has been better utilized.

2. Based on sequential quadratic programming, 7% weight reduction has been achieved by structural optimization, and the stress distribution is also within an acceptable range compared with the initial design.

3. An optimized 6300 kN cylinder-crown integrated hydraulic press has been manufactured, and the finite element analysis for the whole press has also been conducted. The results show that both the stress and deformation are reasonable.

Acknowledgments

This paper was financially supported by the High-end CNC Machine Tools and Basic Manufacturing Equipment Technology Major Project (No.2011ZX04001-011).

Reference

ASM Handbook. Forging and forming, Volume 14, ASM International, Ohio, 1988.
Altan. T, Ngaile. G and Shen. G. S., 2004. Cold and Hot Forging - Fundamentals and Applications. ASM International, Ohio.
Michael. B.B., 2008. Nonlinear Optimization with Engineering Applications, Springer, New York.
Wang. Z. R, Yuan. S. J, Wang. X. S, et al., 2010. Hydraulic press with unity of cylinder and crown. Patent Number:20100502688.5, China.
Wang. Z. R, Liu. G, Yuan. S. J, et al., 2005. Progress in shell hydroforming. J. Mater. Process. Tech. 2005, 167, 230-236
Zhang. W. W, Wang. X. S, Wang. Z. R, et al. Mechanical Analysis on the Cylinder-Crown Integrated Hydraulic Press with a Hemispherical Cylinder. Proc. IMechE, Part C: Journal of mechanical engineering science. 2014, DOI: 10.1177/0954406214537800