Optimization of mechanical design problems using advanced optimization technique

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Abstract. In design of mechanical elements, designers usually consider certain objectives that are related with cost, time, quality and reliability of product depending on the requirements. In this paper, parametric optimization of spring design problem and pressure vessel design problem has been carried out using Amended Differential Evolution Algorithm (ADEA). ADEA is modified DE that can handle constraint and complex problems effectively. In spring design problem, parameters are optimized to reduce volume of compression and in pressure vessel design problem, parameters are optimized to reduce total cost. The results obtained using ADEA are compared with the results reported by other researchers. The comparison of results shows that ADEA provides better results for both spring and pressure vessel design problems.

1. Introduction

For the competitive market, industries always look for solutions that reduces cost of a component without compromising quality and time to manufacture a component. One of the ways to reduce the cost of a component is improvement in design. Optimization of design problems consists of certain objective function, viable solution and optimization technique. The viable solutions are the set of all designs that are distinguished by all feasible values of the design parameters. Optimization methods search for the optimum design from all available viable solutions.

As optimization of mechanical assembly leads to a complex objective function with many design parameters, individual components or intermediate assemblies are optimized in practice. Appropriate selection of design parameters is necessary to reduce cost, improve productivity and quality, increase reliability, etc. For the complex real life problems, Evolutionary Optimization Techniques are preferred than Conventional Optimization Techniques (COTs) (Savsani and Savsani, 2014).

In this work, ADEA is used to optimize two design problems, namely, spring design that has three design parameters (two continuous and one integer) and eight constraints and pressure vessel design that has four design parameters and four constraints.
2. Amended differential evolution algorithm

Unconstraint problem can be solved by using DE algorithm. Rana and Lalwani (2017) made some modifications to improve the performance of Differential Evolution (DE) and added constrained handling technique to solve real life complex problems. The modified DE algorithm is named as ADEA. They made following modifications in DE (Rana and Lalwani, 2017):

1) Initialization of random population
2) Selection of scale factor ($F$) and crossover rate ($CR$) based on rank ($R$)
3) Selection of mutant vector
4) Condition for crossover vector.
5) Constraint handling technique

The detailed description of all modifications is available in Rana and Lalwani (2017).

3. Formulation of design problems

Two design problems viz., spring design problem and pressure vessel design problem are discussed below with objective function and constraints.

3.1. Spring design problem

Spring design problem involves integer and continuous design variables. The spring design problem, investigated by He et al., (2004), is taken to optimize design parameters. In this problem, material used for spring is music wire spring steel ASTM A228 and three design parameters, such as, the wire diameter ($d$), the mean coil diameter ($D$) and number of active coils ($N$) are optimized to minimize the volume of compression spring.

The problem with objective function and constraints is given below (He et al., 2004).

Minimize, $f = \frac{x^2 + x^2(x + 2)}{4}$

Subject to constraints:

Subject to constraints:

$g_1 X = \left(\frac{x^2}{\pi x^3} + S\right) - S \leq 0, g_2 X = 4 - f \leq 0$

$g_3 X = d_{\text{min}} - x_3 \leq 0, g_4 X = x_2 - D_{\text{max}} \leq 0$

$g_5 X = 3.0 - x_1 \leq 0, g_6 X = -\sigma \leq 0$

$g_7 X = \sigma_{\text{p}} + \frac{(F_{\text{max}} - f)}{K} + 1.05 x_3 + 2 x_1 - l_f \leq 0$ and $g_8 X = \sigma_{\text{w}} - \frac{(F_{\text{max}} - f)}{K} \leq 0$

where,

$K = \frac{6x + 1}{8x^3} \frac{4}{2x^2} K = \frac{6x + 1}{8x^3} \frac{4}{2x^2} K = \frac{6x + 1}{8x^3} \frac{4}{2x^2} K = \frac{6x + 1}{8x^3} \frac{4}{2x^2} K = \frac{6x + 1}{8x^3} \frac{4}{2x^2} K = \frac{6x + 1}{8x^3} \frac{4}{2x^2} K = \frac{6x + 1}{8x^3} \frac{4}{2x^2}$
Table 1 Design parameters and its ranges

| Design parameters       | Range       |
|-------------------------|-------------|
| \( x_1 \)              | 0.2-1       |
| \( x_2 \)              | 0.6-3       |
| \( x_3 \)              | 1.0-70      |
| Other parameters        |             |
| The maximum load \( F_{\text{max}} \) | 1000 lb.   |
| The maximum free length \( l_{\text{max}} \) | 14 in.     |
| The minimum wire diameter \( d_{\text{min}} \) | 0.2 in.    |
| The allowable maximum shear stress \( S \) | 189000 psi  |
| The maximum outside diameter of the spring \( D_{\text{max}} \) | 3 in.       |
| The preload compression force \( F_p \) | 300 lb      |
| The allowable maximum deflection under preload \( \sigma_{pm} \) | 6 in        |
| The deflection from preload to maximum load positon \( \sigma_w \) | 1.25 in     |
| Shear modulus \( G \)  | 11.5 \times 10^6 psi |

3.2. Pressure vessel design problem

The pressure vessel design problem (Fig. 3) was investigated by He et al., (2004). In this problem, the material used for pressure vessel is carbon steel ASME SA 203 grade B and the design parameters such as, the shell thickness \( T_s \), the thickness of the head \( T_h \) and the inner radius \( R \) are optimized to minimize the total cost.

The problem with objective function and constraints is given below (He et al., 2004).

Minimize, \( X = 0.6224x_1x_2x_3 + 1.7781x_2x_4^2 + 3.1661x_3^2x_4 + 19.84x_1^2x_3 \)

Subject to constraints:

\( g_1 = 0.0193x_3 - x_1 \leq 0 \), \( g_2 X = 0.00954x_3 - x_2 \leq 0 \),

\( g_3 X = 1296000 - \pi x_3^4 \frac{4}{3} \pi x_3^2 \leq 0 \) and \( g_4 X = x_4 - 240 \leq 0 \)
Table 2 Design parameters and its ranges

| Design parameters | Range       |
|-------------------|-------------|
| $x_1$             | 0.0625-6.1875 |
| $x_2$             | 0.0625-6.1875 |
| $x_3$             | 10-200      |
| $x_4$             | 10-200      |

4. Results and discussion

The above two problems are solved using ADEA with following parameters:
Population size ($PS = 25$, number of iteration ($G = 1000$, number of runs = 5, control parameters i.e., $F (0.5 - 0.8)$ and $CR (0.85 - 0.95)$. The results are reported by writing the program in MATLAB®.

4.1. Spring design problem

The spring design problem was optimized by many researchers, such as He et al. (2004), Sandgren (1990), Deb and Goyal (1997), and Lampinen and Zelinka (1999) using different optimization techniques. Comparison of results obtained using ADEA with other researchers’ work is shown in Table 3.

Table 3 Comparison of results obtained using ADEA with other researchers’ work for spring design

| Design Variables | ADEA | PSO He et al. (2004) | NLPA Sandgren (1990) | GA Deb (1997) | DE Lampinen (1999) |
|------------------|------|----------------------|----------------------|--------------|-------------------|
| $x_1$            | 0.29162 | 0.283       | 0.283            | 0.283       | 0.283             |
| $x_2$            | 1.38421 | 1.22304101 | 1.180701        | 1.226       | 1.22304101        |
| $x_3$            | 7     | 9         | 10               | 9           | 9                 |

Constraints

- $g_1$: -1.2584 -1008.8114 -54309 -713.51 -1008.8114
- $g_2$: -9.4584 -8.9456 -8.8187 -8.933 -8.9456
- $g_3$: -0.09162 -0.083 -0.08298 -0.083 -0.083
- $g_4$: -1.6158 -1.777 -1.8193 -1.491 -1.777
- $g_5$: -1.7466 -1.3217 -1.1723 -1.337 -1.3217
- $g_6$: -5.4643 -5.4643 -5.4643 -5.461 -5.4643
- $g_7$: 0     | 0     | 0         | 0               | 0           | 0                 |
- $g_8$: -4.2997E-5 | 0     | 0         | 0               | 0           | 0                 |

Objective Function

$fx = 2.6141$  2.65856  2.7995  2.665  2.65856

* NLPA-Nonlinear programming algorithm, * PSO- Particle Swarm Optimization, *GA-Genetic Algorithm, * DE-Differential Evolution

The comparison of results shows that ADEA gives the $f(x)$ value as 2.6141 that is superior to results reported by other researchers. ADEA provides 1.67% enhancement in the results compared with best value reported by Heet. al. (2004).

4.2. Pressure vessel design problem

The pressure vessel design problem was optimized by many researchers, such as Rao (2011), He et al. (2004), CoelloCoello (2001) and Deb (1997) using different optimization techniques. Comparison of results obtained using ADEA with other researchers’ work is shown in Table 4.

Table 4 Comparison of results obtained using ADEA with other researchers’ work for pressure vessel design

| Design Variables | ADEA | TLBO Rao (2011) | PSO He et al. (2004) | GA Coello (2001) | GA Deb (1997) |
|------------------|------|-----------------|----------------------|------------------|--------------|
| $x_1$            | 0.778168641 | NA       | 0.8125            | 0.8125           | 0.9345       |
| $x_2$            | 0.384649163 | NA       | 0.4375           | 0.4375           | 0.5          |
| $x_3$            | 40.31961872 | NA      | 40.0984456       | 40.097398        | 48.329       |
| $x_4$            | 200       | NA       | 176.6365         | 176.654047       | 112.679      |

Constraints

- $g_1$: 0 | NA | 0 | -0.00002 | -0.00475
- $g_2$: -5.55E-17 | NA | -0.03588083 | -0.035891 | -0.038941
- $g_3$: 0 | NA | 0 | -27.886075 | -3652.87684
- $g_4$: -40 | NA | -63.36340416 | -63.349593 | -127.321
Objective Function

| fx          | 5885.872354 | 6059.7143   | 6059.7143   | 6059.946341 | 6410.3811 |
|-------------|-------------|-------------|-------------|-------------|-----------|

*NA-Not Available, *TLBO-Teaching Learning Based Optimization, *GA-Genetic Algorithm

The comparison of results shows that ADEA gives the objective function $f(x)$ value as 5885.872354 that is superior to the results reported by other researchers. ADEA provides 2.87% enhancement in the results compared with the best value reported by Rao (2011).

5. Conclusions

Optimization of spring design and pressure vessel design problems have been carried out using ADEA and the results obtained using ADEA are compared with the results reported by other researchers. The comparison of results shows that ADEA provides better results than the results reported by other researchers. In spring design problem, ADEA gives improvement of 1.67% over PSO, in pressure vessel design problem, ADEA gives improvement of 2.87% over TLBO.

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