Application of Harmony Search to Multi-Objective Optimization for Satellite Heat Pipe Design

Zong Woo Geem and Han Hwangbo

Abstract—**A satellite design requires an optimization of multiple objectives such as performance, reliability, and weight. To consider these objectives simultaneously, multi-objective optimization can be considered. In this study, a new multi-objective method considering both thermal conductance and heat pipe mass is introduced. This method has two steps: At first, each single objective function is optimized; then multi-objective function, which is the sum of individual error between current function value and optimal value in terms of single objective, is minimized. Here, the multi-objective function, representing thermal conductance and heat pipe mass, has five design parameters such as length of conduction fin, cutting length of adhesive attached area, thickness of fin, adhesive thickness, and operation temperature of the heat pipe. Study results showed that the approach using recently-developed meta-heuristic algorithm, harmony search, found better solution than traditional calculus-based algorithm, BFGS.**

Index Terms—**Harmony Search, Optimization, Satellite Heat Pipe Design**

I. META-HEURISTIC ALGORITHM: HARMONY SEARCH

HARMONY SEARCH (HS) is a recently-developed meta-heuristic optimization algorithm mimicking music improvisation [1], where each musician corresponds to each decision variable in optimization; pitch range of each music instrument corresponds to value range of each variable; and each harmony improvised corresponds to each solution vector. Just as musicians polish better harmonies practice after practice, the HS algorithm polishes better vectors iteration after iteration.

The HS algorithm has been applied to various real world optimization problems.

A. Water Network Design

Geem et al. [2] and Geem [3] applied harmony search to optimal design of water distribution networks. The HS model found less or equal design solutions when compared to other meta-heuristic algorithms such as genetic algorithm (GA), simulated annealing (SA), and tabu search (TS).

For the optimal expansion design of water distribution network in New York City, while mathematical method (LP and DP) found a solution of \$78.09 million and GA found a solution of \$37.13 million (after 1,000,000 function evaluations), HS found a solution of \$36.66 million (6,000 evaluations).

B. Pump Switching Operation

Geem [4] applied HS to optimal pump switching for the serial pumping system.

While GA found a solution of 11263.19 (HP, horse power), HS found a solution of 11169.43 HP, which is also better than popular mathematical technique (B&B). The HS (19 seconds) computed much faster than B&B (28 minutes).

C. Structural Design

Lee and Geem [5] and Lee et al. [6] applied HS to the structural designs such as electricity transmission truss as shown in Figure 1.

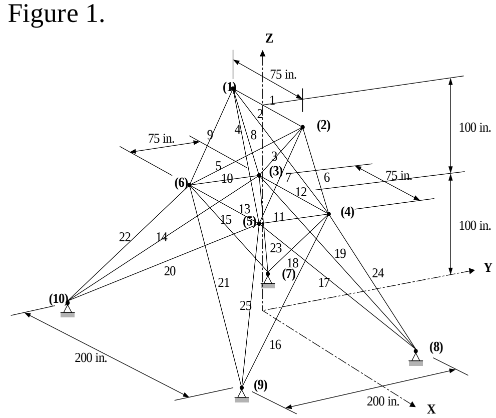

Fig. 1. Transmission Tower Truss

While GA found a solution of 485.05 pounds, HS found a solution of 484.85 lb.

D. Pressure Vessel Design

Lee and Geem [7] applied HS to the pressure vessel design as shown in Figure 2.

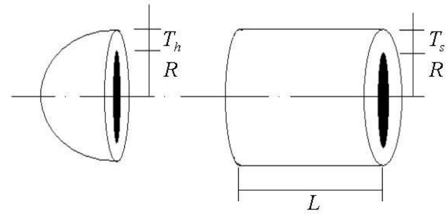

Fig. 2. Schematic of Pressure Vessel

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While B&B found a solution of $7,980.9 and GA found a solution of $7,207.5, HS found a solution of $7,198.4.

E. Environmental Parameter Calibration

Kim et al. [8] applied HS to the parameter calibration for flood routing model (Muskingum model).

While least square method found a solution with SSQ = 143.60 and GA found a solution with SSQ = 38.23, HS found a solution with SSQ = 36.78.

F. Vehicle Routing

Geem et al. [9] applied HS to the school bus routing problem as shown in Figure 3.

While GA found an average operating cost of $409,597, HS found an average cost of $399,870.

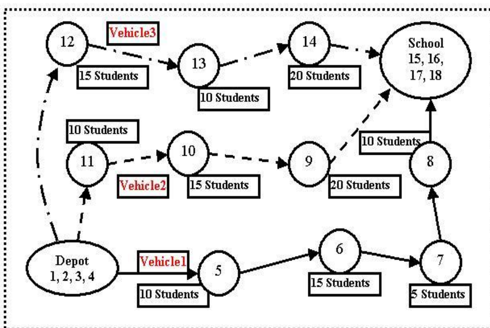

Fig. 3. School Bus Routing

II. Satellite Heat Pipe Design

For the satellite cooling system, heat pipes are generally used, and many researchers have applied optimization techniques to the heat pipe design [10-12].

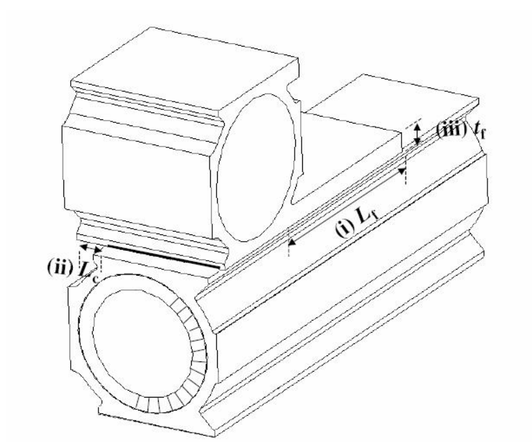

Fig. 4. Schematic of Satellite Heat Pipe

The heat pipe model tackled in this study is illustrated in Figure 4 [12], which has two objectives (thermal conductance and total mass) and five design parameters: (1) length of flange fin (L_f), (2) cutting length of adhesive attached area (L_c), (3) thickness of fin (t_f), (4) Adhesive thickness (t_b), and (5) operation temperature (T_{op}). The parameter ranges are tabulated in Table 1.

TABLE I
Design Parameter Ranges

Parameter	Lower Bound	Upper Bound
L_f	10.0mm	25.4mm
L_c	1.5mm	2.5mm
t_f	1.0mm	1.7mm
t_b	0.12mm	0.22mm
T_{op}	-20.0°C	60.0°C

The objective function of the thermal conductance across the thermal joint of the heat pipe, which is to be maximized, is as follows:

$$
\begin{aligned}
G = f(L_f, L_c, t_f, t_b, T_{op}) &= 0.3745378 - 0.9352909\,\mathrm{tb} \\
&+ 1.01612\,\mathrm{tb}^2 + 0.02324128\,\mathrm{L_c} - 0.007209993\,\mathrm{L_c^2} \\
&+ 0.001838379\,\mathrm{L_f} - 0.00005379707\,\mathrm{L_f^2} + 0.02447391\,\mathrm{t_f} \\
&+ 0.002304583\,\mathrm{t_f^2} - 0.0006483411\,\mathrm{T_{op}} - 0.0000009232971\,\mathrm{T_{op}^2} \\
&- 0.02259702\,\mathrm{t_b}\,\mathrm{L_c} - 0.004735652\,\mathrm{t_b}\,\mathrm{L_c^2} + 0.1102442\,\mathrm{t_b^2}\,\mathrm{L_c} \\
&- 0.009702533\,\mathrm{t_b^2 L_c^2} + 0.005382211\,\mathrm{t_b L_f} - 0.00009540484\,\mathrm{t_b L_f^2} \\
&+ 0.00515048\,\mathrm{t_b^2}\,\mathrm{L_f} - 0.0001232524\,\mathrm{t_b^2}\,\mathrm{L_f^2} + 0.2972589\,\mathrm{t_b}\,\mathrm{t_f} \\
&- 0.1052935\,\mathrm{t_b}\,\mathrm{t_f^2} - 0.5422262\,\mathrm{t_b^2}\,\mathrm{t_f} - 0.1829687\,\mathrm{t_b^2}\,\mathrm{t_f^2}
\end{aligned}
$$

The objective function of the total mass, which is to be minimized, is as follows:

$$
\begin{aligned}
M = f(L_f, L_c, t_f, t_b) = (&1313.877 - 75.5\,\mathrm{L_c} + 11.0\,\mathrm{L_c^2} \\
&+ 1.402597\,\mathrm{L_f} - 1.278314\mathrm{E}{-15}\,\mathrm{L_f^2} + 62.38776\,\mathrm{t_f} \\
&- 6.122449\,\mathrm{t_f^2} - 380.8\,\mathrm{t_b} + 1120\,\mathrm{t_b^2}) \times 21
\end{aligned}
$$

The multi-objective function considering both thermal conductance and total mass, which is to be minimized, can be as follows:

$$
Z = f(L_f, L_c, t_f, t_b, T_{op}) = \left|\frac{G - G^*}{G^*}\right| + \left|\frac{M - M^*}{M^*}\right|
$$

As seen in the above equation, the multi-objective function is expressed as the sum of the absolute values of relative errors between optimal value and current function value, where the optimal value for each objective function can be beforehand calculated using single objective functions for thermal conductance and total mass, respectively.

For the single objective optimization, HS found the maximal thermal conductance of 0.3945 (W/K) or total mass of 25.763 (kg) while BFGS, one of best mathematical techniques, found 0.3808 (W/K) or 25.868 (kg).

For the multiple objective optimization, HS found the maximal thermal conductance of 0.3810 (W/K) and total mass of 26.704 (kg) while BFGS found 0.3750 (W/K) and 26.854 (kg). The multi-objective solution of HS is Pareto optimal one because the conductance (0.3810) of HS is higher than that (0.3750) of BFGS and the mass (26.704) of HS is lower than that (26.854) of BFGS, that is, HS solution is better than BFGS one without disadvantaging at least one objective.

III. Conclusion

This paper introduced various applications of recently developed meta-heuristic algorithm, harmony search. Then, the HS algorithm was applied to the satellite heat pipe design which has two objectives of maximal thermal conductance and minimal total mass. The HS found better results than one of powerful mathematical optimization technique, BFGS.

The authors hope to see various HS applications in aerospace engineering field.

References

[1] Z. W. Geem, J. H. Kim, and G. V. Loganathan, “A New Heuristic Optimization Algorithm: Harmony Search,” *Simulation*, vol. 76, no. 2, pp. 60–68, 2001.

[2] Z. W. Geem, J. H. Kim, and G. V. Loganathan, “Harmony Search Optimization: Application to Pipe Network Design,” *International Journal of Modelling and Simulation*, vol. 22, no. 2, pp. 125-133, 2002.

[3] Z. W. Geem, “Optimal Cost Design of Water Distribution Networks using Harmony Search,” *Engineering Optimization*, vol. 38, no. 3, pp. 259-280, 2006.

[4] Z. W. Geem, “Harmony Search in Water Pump Switching Problem,” *Lecture Notes in Computer Science*, vol. 3612, pp. 751-760, 2005.

[5] K. S. Lee and Z. W. Geem, “A New Structural Optimization Method Based on the Harmony Search Algorithm,” *Computers and Structures*, vol. 82, no. 9-10, pp. 781-798, 2004.

[6] K. S. Lee and Z. W. Geem, S. –H. Lee, and K. –W. Bae, “The Harmony Search Heuristic Algorithm for Discrete Structural Optimization,” *Engineering Optimization*, vol. 37, no. 7, pp. 663-684, 2005.

[7] K. S. Lee and Z. W. Geem, “A New Meta-Heuristic Algorithm for Continuous Engineering Optimization: Harmony Search Theory and Practice,” *Computer Methods in Applied Mechanics and Engineering*, vol. 194, pp. 3902-3933, 2005.

[8] J. H. Kim, Z. W. Geem, and E. S. Kim, “Parameter Estimation of the Nonlinear Muskingum Model Using Harmony Search,” *Journal of the American Water Resources Association*, vol. 37, no. 5, pp. 1131-1138, 2001.

[9] Z. W. Geem, K. S. Lee, and Y. Park, “Application of Harmony Search to Vehicle Routing,” *American Journal of Applied Sciences*, vol. 2, no. 12, pp. 1552-1557, 2005.

[10] V. G. Rajesh and K. P. Ravindran, “Optimum Heat Pipe Design: A Nonlinear Programming Approach,” *International Communications in Heat and Mass Transfer*, vol. 24, no. 3, pp. 371-380, 1997.

[11] F. L. de Sousa, V. Vlassov, and F. M. Ramos, “Generalized Extremal Optimization: An Application in Heat Pipe Design,” *Applied Mathematical Modelling*, vol. 28, pp. 911-931, 2004.

[12] M. J. Jeong, T. Kobayashi, and S. Yoshimura, “Extraction of Design Characteristics of Multiobjective Optimization – Its Application to Design of Artificial Satellite Heat Pipe,” *Lecture Notes in Computer Science*, vol. 3410, pp. 561-575, 2005.

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