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TRUSS OPTIMIZATION WITH NATURAL FREQUENCY CONSTRAINTS USING TIKI-TAKA ALGORITHM

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ABSTRACT

In this work, the recently-proposed Tiki-Taka algorithm (TTA) is employed for optimal weight design of truss structures with frequency constraints. This kind of problem are very challenging optimization problems, with large number of locally optimization solutions and non-convexity of search space. To evaluate its performance in this engineering area for the first time in the literature, three benchmark truss optimization problems with frequency constraints are studied. Numerical results indicate that TTA is more efficient, stable, and reliable than other metaheuristics algorithms.

INTRODUCTION

The study of the natural frequencies and mode shapes of structures is a branch of mechanical and civil engineering that has benefited widely from the latest available technologies, especially from advances in computing and from the enormous signal processing power. To avoid the resonance phenomenon and improve the dynamic behavior of a structure these parameters need to be controlled. On the other hand, the construction industry requests design cost-effective (minimal weight) structures that meet the established requirements. However, minimizing the weight of structures can be considered as a difficult problem to solve because the reduction of weight generates conflict with the frequency limits (Millan-Paramo & Filho, 2021). Frequency constraints are highly nonlinear, non-convex, and implicit concerning the design variables (Grandhi, 1993). Hence, proper and powerful optimization methods should be implemented for solving this kind of design problems.

Unlike gradient-based methods, metaheuristic algorithms use mechanisms that allow exploring and exploiting the search space without the need for sensitivity analysis. In recent times, different metaheuristic algorithms have been introduced to solve the problem of optimal design of truss structures with frequency constraints (Cheng & Prayogo, 2017; Gomes, 2011; Ho-Huu, Nguyen-Thoi, Truong-Khac, Le-Anh, & Vo-Duy, 2018; Kaveh & Mahjoubi, 2019; Lieu, Do, & Lee, 2018; Miguel & Fadel Miguel, 2012; Millan-Paramo & Abdalla Filho, 2020; Tejani, Savsani, Patel, & Mirjalili, 2018), however, this area of research has not been fully explored. On the other hand, the No Free Lunch (NFL) theorem (Wolpert & Macready, 1997) indicates that it is not possible to develop a general strategy to solve different types of problems.

The motivation of this study is employed the Tiki-Taka algorithm (TTA) (Ab. Rashid, 2020), for the first time in the literature, for optimal weight design of truss structures with frequency constraints. TTA is inspired by the football playing style introduced by Johan Cruyff and is characterized by short passing, player movement and possession control. The optimal results obtained by TTA are compared with other solutions available in the literature.

This article is organized as follows: In Section 2, the TTA is briefly described. Section 3 presents the general formulation of the size optimization of truss structures with multiple dynamic constraints. Section 4 presents the benchmark truss optimization problems to illustrate the efficiency of the TTA. Finally, in Section 5, our conclusions are presented.

Tiki-Taka Algorithm (Tta)

The TTA is a population-based algorithm inspired by two main characteristics in the tiki-taka tactic, which are short passing and player movement (Ab. Rashid, 2020). The following four steps describe the algorithm in detail:

The algorithm starts with *n* randomly generated solutions in the search space. This matrix is called players (P). Additionally, another matrix that represents ball position, B, is established.

To update ball position, the player will pass the ball to the next nearby player.

To update player position, the player moves and finds a better position in the formation
For more details on the parameters that control this algorithm, please see (Ab. Rashid, 2020).

The flowchart of TTA is illustrated in Fig. 1.

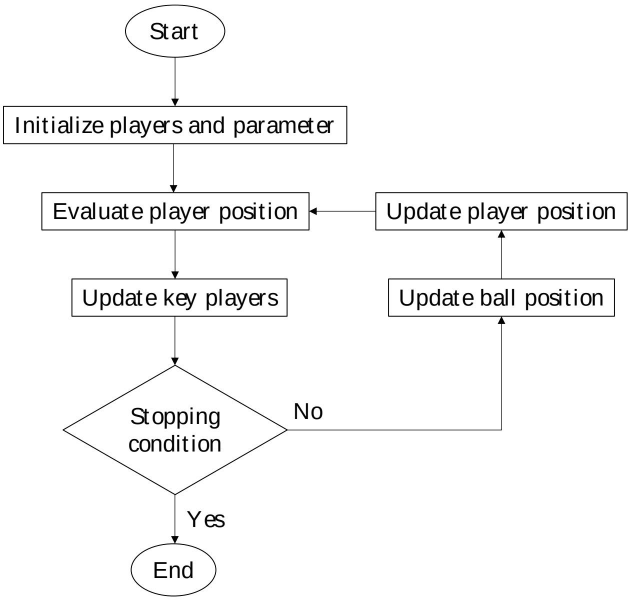

Figure 1. The TTA flowchart (Ab. Rashid, 2020).

truss problems statement

The goal of the structural optimization problem is to minimize the weight of the structure while satisfying some constraints on the natural frequencies. The numerical equations for size optimization with a number of constraints on the natural frequencies can be formulated as:

$$\begin{aligned}
&\text{Find,}\quad X = \{A,\},\ \text{where}\quad A = \{A_1, A_2, \ldots, A_n\} \\
&\text{To minimize}\quad W(X) = \sum_{i=1}^{n} \rho_i A_i L_i \\
&\text{Subject to}\quad \begin{cases} f_q - f_q^{min} \geq 0 \\ f_r - f_r^{max} \leq 0 \\ A_i^{min} \leq A_i \leq A_i^{max} \end{cases}
\end{aligned} \tag{1}$$

where W is the weight of the structure; n is the total number of members of the structure; ρ_i, A_i and L_i stand for the material density, the cross-sectional area and the length of the *ith* member, respectively; f_q and f_r are the *qth* and *rth* natural frequencies of the structure, respectively; the superscripts, “max” and “min” denote the maximum and minimum allowable limits respectively.

Numerical Examples And Discussion

In this section, three benchmark problems (Fig. 2) are analyzed to evaluate feasibility and validity of TTA. The design parameters of the problems are given in Table 1. Each problem is solved 30 times independently. The algorithm and the two-node linear bar element for FE analysis are coded in Matlab on a machine with 2.4 GHz and 8 of GB RAM. Three case studies are used, including a 72-bar space truss, a 120 bar dome truss and a 200-bar planer truss. Outcomes of each issue are then compared to those acquired by other methods.

Table 1. Design parameters of benchmark truss design problems

	200-bar planar truss	**72-bar space truss**	**120-bar dome truss**
Young's modulus *E* (GPa)	210	69.8	210
Material density *ρ* (kg/m³)	7860	2770	7971.81
Size variables (cm²)	$0.1 \leq A \leq 30$	$0.645 \leq A \leq 30$	$1 \leq A \leq 129.3$
Frequency constraints (Hz)	$f_1 \geq 5$ $f_2 \geq 10$ $f_3 \geq 15$	$f_1 = 4$ $f_3 \geq 6$	$f_1 \geq 9$ $f_2 \geq 11$

200-bar planar truss structure

Fig 2a shows the first benchmark problem, which is called the planar truss structure of 200 bars. Elements are grouped in 29 groups as depicted in the figure. Hence, this problem includes 29 independent sizing variables. At the top of the structure, a lumped mass of 100 kg is added at nodes 1 to 5.

Table 2 shows that TTA obtained the lightest design (2160.31 kg) with the fewest number of iterations (8000 NI). Moreover, average and standard deviation attained by TTA is more stable than others and its solutions are less spread.

72-bar space truss structure

The second instance is shown in Fig 2b. There are 16 sizing variables and a lumped mass of 2770 kg is attached at all top nodes (nodes 1–4).

Table 3 reveals that the optimal weight achieved by the TTA is 325.97 kg, respectively. Furthermore, the SD obtained by TTA (0.88 kg) is lower than the HSPO, SOS and ISOS. Finally, regarding NI, TTA ranks third among the considered metaheuristics. Natural frequencies optimal obtained by the TTA show that none of the frequency constraints are violated.

120-bar dome truss structure

The 120-bar dome truss, as displayed in Fig. 2c, has a non-structural masses at the free nodes as follow: 3000 kg at node one, 500 kg at the nodes 2 through 13 kg, and 100 kg at the rest of the nodes. The elements are categorized into seven groups using geometrical symmetry,

The results obtained are presented in Table 4. As can be seen, the optimum design achieved by TTA is better than other considered metaheuristics. On the other hand, the proposed algorithm also required less structural analyses to converge to the optimal solution. Regarding NI, TTA ranks second among the considered metaheuristics

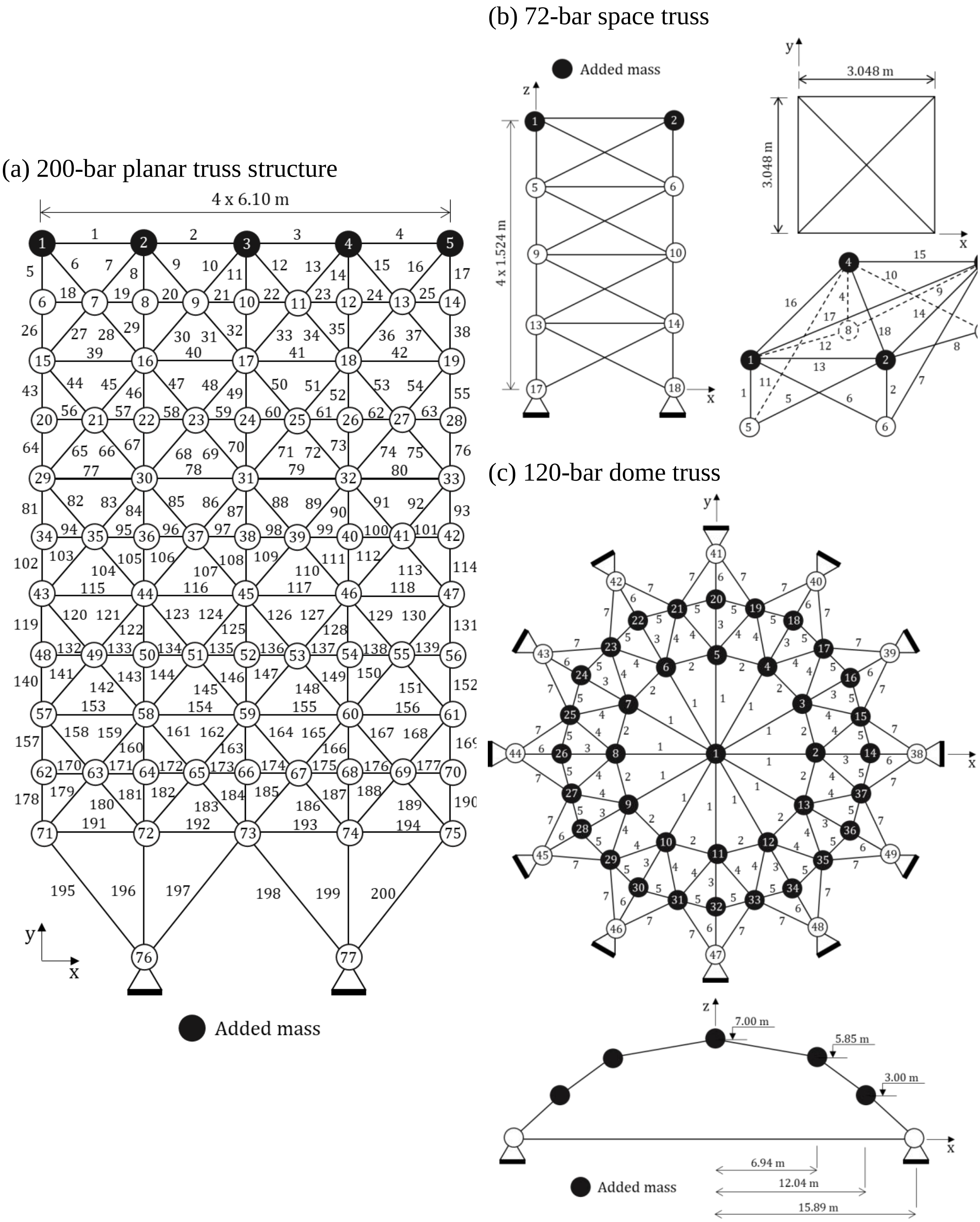

Figure 2. Truss optimization problems

Table 2. Optimal results obtained by TTA and other metaheuristic algorithms for the 200-bar planar truss

Variables (cm^2)	**CSS-BBBC**	**HALC-PSO**	**HSPO**	**SOS**	**ISOS**	**AHEFA**	**This study**
	(Kaveh & Zolghadr, 2012)	(Kaveh & Ilchi Ghazaan, 2015)	(Kaveh & Mahjoubi, 2019)	(Tejani, Savsani, & Patel, 2016)	(Tejani et al., 2018)	(Lieu et al., 2018)	**TTA**
A_1	0.2934	0.3072	0.3014	0.4781	0.3072	0.2993	0.3000
A_2	0.5561	0.4545	0.4594	0.4481	0.5075	0.4508	0.4922
A_3	0.2952	0.1000	0.0781	0.1049	0.1001	0.1001	0.1000
A_4	0.1970	0.1000	0.0983	0.1045	0.1000	0.1000	0.1001
A_5	0.8340	0.5080	0.5062	0.4875	0.5893	0.5123	0.5718
A_6	0.6455	0.8276	0.8199	0.9353	0.8328	0.8205	0.8105
A_7	0.1770	0.1023	0.1000	0.1200	0.1431	0.1011	0.1026
A_8	1.4796	1.4357	1.3968	1.3236	1.3600	1.4156	1.5268
A_9	0.4497	0.1007	0.1000	0.1015	0.1039	0.1000	0.1000
A_{10}	1.4556	1.5528	1.5735	1.4827	1.5114	1.5742	1.5148
A_{11}	1.2238	1.1529	1.1490	1.1384	1.3568	1.1597	1.1670
A_{12}	0.2739	0.1522	0.1186	0.1020	0.1024	0.1338	0.1320
A_{13}	1.9174	2.9564	3.10264	2.9943	2.9024	2.9672	2.7903
A_{14}	0.1170	0.1003	0.1000	0.1562	0.1000	0.1000	0.1058
A_{15}	3.5535	3.2242	3.2433	3.4330	3.4120	3.2722	3.2372
A_{16}	1.3360	1.5839	1.5968	1.6816	1.4819	1.5762	1.5789
A_{17}	0.6289	0.2818	0.2422	0.1026	0.2587	0.2562	0.4348
A_{18}	4.8335	5.0696	5.3968	5.0739	4.8291	5.0956	4.9853
A_{19}	0.6062	0.1033	0.1000	0.1068	0.149	0.100	0.3810

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A_{20}	5.4393	5.4657	5.2582	6.0176	5.5090	5.4546	5.0956
A_{21}	1.8435	2.0975	2.1434	2.0340	2.2221	2.0933	2.1949
A_{22}	0.8955	0.6598	0.8293	0.6595	0.6113	0.6737	0.6100
A_{23}	8.1759	7.6585	7.3013	6.9003	7.3398	7.6498	8.7671
A_{24}	0.3209	0.1444	0.1128	0.2020	0.1559	0.1178	0.1645
A_{25}	10.9800	8.0520	7.9108	6.8356	8.6301	8.0682	7.0580
A_{26}	2.9489	2.7889	2.8674	2.6644	2.8245	2.8025	2.7848
A_{27}	10.5243	10.4770	10.8526	12.1430	10.8563	10.5040	10.1177
A_{28}	20.4271	21.3257	20.8993	22.2484	20.9142	21.2935	21.4519
A_{29}	19.0983	10.5111	10.7515	8.9378	10.5305	10.7410	10.4464
Best weight (kg)	2298.61	2156.73	2157.77	2180.32	2169.46	2160.74	2160.31
f_1 (Hz)	5.010	5.000	5.0000	5.0001	5.0000	5.0000	5.0000
f_2 (Hz)	12.911	12.254	12.1499	13.4306	12.4477	12.1821	12.2876
f_3 (Hz)	15.416	15.044	15.0004	15.2645	15.2332	15.0160	15.0058
Average weight (kg)	–	2157.14	2169.05	2303.30	2244.64	2161.04	2163.02
SD (kg)	–	0.24	10.82	83.59	43.48	0.18	3.72
NI	–	13000	11640	10000	10000	11300	8000

Table 3. Optimal results obtained by TTA and other metaheuristic algorithms for the 72-bar space truss

Variables (cm^2)	**CSS-BBBC**	**TLBO**	**HSPO**	**SOS**	**ReDE**	**ISOS**	**AHEFA**	**This study**
	(Kaveh & Zolghadr, 2012)	(Farshchin, Camp, & Maniat, 2016)	(Kaveh & Mahjoubi, 2019)	(Tejani et al., 2016)	(Ho-Huu et al., 2018)	(Tejani et al., 2018)	(Lieu et al., 2018)	**TTA**
A_1-A_4	2.854	3.5491	3.4315	3.6957	3.5327	3.3563	3.5612	3.1016
A_5-A_{12}	8.301	7.9676	7.8436	7.1779	7.8303	7.8726	7.8736	7.8981
A_{13}-A_{16}	0.645	0.6450	0.6450	0.6450	0.6453	0.6450	0.6450	0.6450
A_{17}-A_{18}	0.645	0.6450	0.6450	0.6569	0.6459	0.6450	0.6451	0.6450
A_{19}-A_{22}	8.202	8.1532	8.0390	7.7017	8.0029	8.5798	7.9710	9.9797
A_{23}-A_{30}	7.043	7.9667	7.9306	7.9509	7.9135	7.6566	7.8928	7.8862
A_{31}-A_{34}	0.645	0.6450	0.6450	0.6450	0.6451	0.7417	0.6450	0.6450
A_{35}-A_{36}	0.645	0.6450	0.6450	0.6450	0.6451	0.6450	0.6451	0.6465
A_{37}-A_{40}	16.328	12.9272	12.7040	12.3994	12.7626	13.0864	12.5404	13.0424
A_{41}-A_{48}	8.299	8.1226	7.9684	8.6121	7.9657	8.0764	7.9639	8.0786
A_{49}-A_{52}	0.645	0.6452	0.6451	0.6450	0.6452	0.6450	0.6459	0.6450
A_{53}-A_{54}	0.645	0.6450	0.6450	0.6450	0.6450	0.6937	0.6462	0.6450
A_{55}-A_{58}	15.048	17.0524	17.0169	17.4827	16.9041	16.2517	17.1323	15.6047
A_{59}-A_{66}	8.268	8.0618	8.0127	8.1502	8.0434	8.1703	8.0216	8.0024
A_{67}-A_{70}	0.645	0.6450	0.6450	0.6740	0.6451	0.6450	0.6450	0.6450
A_{71}-A_{72}	0.645	0.6450	0.6450	0.6550	0.6473	0.6450	0.6451	0.6450
Best weight (kg)	327.51	327.57	324.23	325.56	324.25	325.01	324.24	325.97
f_1 (Hz)	4.0000	4.000	4.0000	4.0023	4.0000	4.0000	4.0000	4.0000

f_3 (Hz)	6.0040	6.000	6.0000	6.0020	6.0001	6.0008	6.0000	6.0000
Average weight (kg)	–	328.68	325.42	331.12	324.32	329.47	324.41	326.78
SD (kg)	–	0.73	0.90	4.23	0.05	2.66	0.24	0.88
FEs	–	15000	8820	4000	10840	4000	8860	5500

Table 4. Optimal results obtained by TTA and other metaheuristic algorithms for the 120-bar dome truss

Variables (cm^2)	**CSS-BBBC**	**DPSO**	**CBO**	**HALC-PSO**	**ISOS**	**This study**
	(Kaveh & Zolghadr, 2012)	(Kaveh & Zolghadr, 2014)	(Kaveh & Mahdavi, 2015)	(Kaveh & Ilchi Ghazaan, 2015)	(Tejani et al., 2018)	**TTA**
A_1	17.478	19.607	19.6917	19.8905	19.6662	20.1310
A_2	49.076	41.290	41.1421	40.4045	39.8539	39.4371
A_3	12.365	11.136	11.1550	11.2057	10.6127	14.0635
A_4	21.979	21.025	21.3207	21.3768	21.2901	20.6287
A_5	11.190	10.060	9.8330	9.8669	9.7911	8.8935
A_6	12.590	12.758	12.8520	12.7200	11.7899	14.6434
A_7	13.585	15.414	15.1602	15.2236	14.7437	12.9765
Best weight (kg)	9046.34	8890.48	8889.13	8889.96	8710.06	8712.55
f_1 (Hz)	9.000	9.0001	9.0000	9.0000	9.0001	9.0000
f_2 (Hz)	11.007	11.0007	11.0000	11.0000	10.9998	11.0000
Average weight (kg)	–	8895.99	8891.25	8900.39	8728.56	8717.52
SD (kg)	–	4.26	1.79	6.38	14.23	4.98
FEs	–	6000	6000	17000	4000	5500

CONCLUSIONS

In this paper the TTA is used, for the first time in the literature, in the optimization of truss structure with frequency constraints. Numerical results indicate that the performance of the TTA is comparable to the other state-of-the-art methods in terms of the best weight, average weight, standard deviation (SD) and NI required by the optimization process. Regarding SD, the results show that is more stable than others and its solutions are less spread.

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