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Dimensional Synthesis Based Elastodynamic Performance Optimization and Dynamic Simulation of the Parallel DELTA Mechanism

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Abstract

Parallel manipulators have been adopted to develop machine tools with high dynamic performance. However, high acceleration and structural flexibility lead to unwanted structural vibration. In this paper, we focus on the dimensional-synthesis-based elastodynamic performances optimization of 3-DoF translational parallel mechanism. The elastodynamic model is formulated using finite element method [1]. The main consideration for the optimization criteria is to find the maximum regular workspace where the structure must possess high stiffness, high dexterity and high dynamic performance. In the proposed formulation of the design problem, design criteria are considered together for the simultaneous optimization. Hence, a multi-objective optimization problem has been formulated. The proposed design procedure is developed through the implementation of the translational parallel mechanism and, numerical results show the effectiveness of the proposed design method to enhancing rigidity and accuracy of the studied manipulator.

(a) (b) (c)

Figure 1: (a) translational DELTA mechanism, (b) Model verification under ANSYS and (c) Impact test.

1 Elastodynamic Modeling and Experimental Results

The DELTA mechanism with linear actuators is shown in Figure 1-(a). The moving platform is connected to the base by three identical spatial parallelograms using spherical joints. Each parallelogram is connected to the base by a actuated translation joint, the moving platform three translational DoFs with respect to the fixed reference frame. For the calculation of global stiffness matrix K_G and global mass matrix M_G, we implement the analytical approach proposed in [1]. This method is based on matrix structural analysis and the main advantage of this technique is its reduced computational runtime, which is convenient to the design optimization process. Kinematic constraints of spherical joints are introduced in the elastodynamic model by linear equations that constraint nodes displacements. The natural frequencies of free oscillations can be calculated by solving the characteristic equation:

$$| K_G - \omega^2 M_G | = 0 \tag{1}$$

The exactitude of the analytical developed model is verified using ANSYS software. Figure 1-(c) shows the experimental setup used to obtain the Frequency Response Function (FRF) of the mechanism structure. Table 1 shows the comparison of lower frequencies between theoretical values, analysis values computed by ANSYS and experimental values. The element BEAM188 and iterative solver are used for the model under ANSYS, and the finite element model is shown in Figure 1-(b). Through this comparison, it is obvious that the results are very consistent and the effectiveness of the elastodynamic analytical model is approved.

Table 1: Lower frequency values comparison for different configuration of the mechanism.

Configurations (q_1, q_2, q_3)	mm	$(240, 520, 180)$	$(400, 350, 500)$	$(200, 200, 200)$
Theoretical values	Hz	92.1	92.6	89.4
Analysis values (ANSYS)	Hz	88.1	92.8	91,2
Experimental value	Hz	89.8	93.3	91.4

2 Design Optimization

The design optimization problem can be stated as follows: let α_d denote the vector of parameters that describe the geometric and structural dimensions of the parallel manipulator and, try to find the optimal solution α_d^*. This solution corresponds to the optimal mechanical structure according to given performance criteria while all constraints are respected. These constraints concern boundary conditions and the specified performance. Since kinematic, elastostatic and elastodynamic performance are considered simultaneously, the design problem is formulated as a multi-objective optimization problem. The basic concept of multi-objective optimization is the concept of domination. The Pareto-optimal set yields an infinite set of solutions on the boundary of the feasible region, from which the desired solution can be chosen. Therefore, we formulate a design problem as follows:

$$\min\left\{F_{obj1}, F_{obj2}\right\} \text{ subject to } \left| \begin{array}{l} \alpha_d^{\min} \leqslant \alpha_d \leqslant \alpha_d^{\max} \\ \kappa^{\min} \geqslant 0.4 \\ T^{\max} \leqslant 10^{-6} \\ f^{\min} \geqslant 150\text{Hz} \end{array} \right. \quad \text{where } F_{obj1} = M_{mb} \text{ and } F_{obj2} = -r_c \tag{2}$$

Where M_{mb} is the total mass of all moving bodies, r_c is the radius of the maximum inscribed sphere in the workspace, $f^{\min}$ is the global minimum natural frequency, $\kappa^{\min}$ is the global minimum dexterity and $T^{\max}$ is the global maximum trace of the compliance matrix. The quantities $f^{\min}$, $\kappa^{\min}$ and $T^{\max}$ are evaluated all over the workspace before calling the main multi-objective optimization algorithm [2]. Figure 2-(a) shows the Pareto-optimal frontier sets which represent all possible and optimal solutions in decision space. Hence, the designer can intuitively select the final solutions according to its preferences, which reduce the time of design process. We have selected one mechanism from the Pareto-optimal solutions. We use the open code source MBDyn to simulate the response of mechanism which is subjected to a dynamic force $F_{ext} = 100\sin(20\pi)$ N applied to the center of the moving platform during the execution of a rectangular trajectory shown in Figures 2-(b). Figure 2-(c) shows the plot of the position error during task execution. We can easily conclude that the selected mechanism perform the task with a significant accuracy and it can meet dynamic load requirements in spite of its reduced moving mass $M_{mb} = 6.13$ kg.

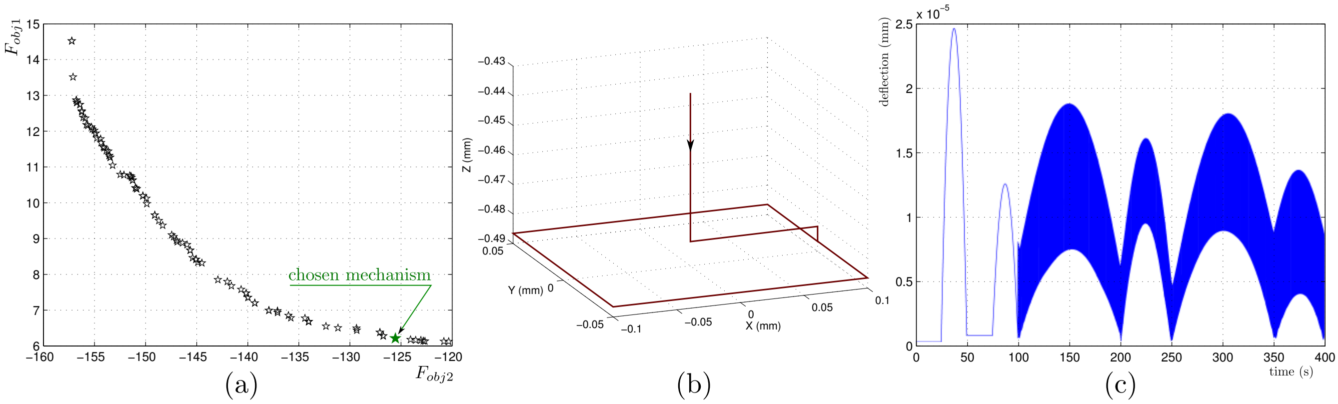

Figure 2: (a) Pareto-optimal frontier sets in criterion space with one selected solution, (b) Trajectory followed by the center of moving platform and (c) Position error plot using the chosen mechanism.

3 Design Optimization

An optimization method for enhancing mechanic performance of the translational parallel manipulator is presented in this work. Based on performed elastodynamic studies, optimal criteria were expressed in order to synthesize a mechanism with improved performance such as uniformity of the dexterity, largest regular workspace, highest global stiffness, and reduced moving mass. The elastodynamic performance are also considered which can avoid a specific spectrum of excitation frequencies under the most likely operation conditions. In our future work, experimantal cuting forces data will be consedered in order to simulate the real dynamic behaviour of mechanism.

References

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[2] B. Bounab. Multi-objective optimal design based kineto-elastostatic performance for the delta parallel mechanism. Robotica, DOI: 10.1017/S0263574714001416, Published online: 04 June 2014.