Abstract

The increasing demand for automation of in vitro diagnostic instruments requires precision and reliability in mechanical subsystems, as well as cost efficiency in the consumable field. This thesis addresses two aspects within this context: (1) the dynamic modeling and experimental validation of the incubator ring, and (2) the design and optimization of a novel foldable reagent kit handle intended to reduce logistical volume in shipping phase.

In Part I, a comprehensive multibody dynamic model was developed to predict motion accuracy of the incubator ring assembly. Measured roundness profiles were reconstructed through Fourier series and integrated into multibody environment using MSC Adams 2022.1. Experimental validation using laser triangulators confirmed the prediction accuracy of the model. Next, a study on influence of errors' order, amplitude, and errors combination was conducted. Vertical stability was studied implementing small concentrated or distributed errors on the surface of the ring. The validation results confirm the predictive capacity of the model, with deviations within 20%. The parametric study produced the insight on which errors and their combination affect most the motion accuracy of the ring during rotation. In the worst-case scenario, the combination of errors produces 0.49 mm error, reaching the operational limits of gripping access. The vertical accuracy study shows that the vertical displacement and motor torque are strictly dependent on the preload of spring-loaded bearings. This modeling workflow provides a transferable framework for predictive tolerance analysis in rotational subsystems with elastic components.

In Part II, the focus shifted towards the design and optimization of a foldable reagent kit handle, aimed at improving shipping costs, maintaining ergonomic stability and instrument compatibility. Concept generations yielded several configurations, all including a living hinge design. Among all, one concept was selected to be developed and optimized, based on operational and user requirements. The design was created in SolidWorks 2022, prototyped with SLA printer Formlabs Form 2, and iteratively refined through experimental and computational testing. Multibody simulations quantified the folding torque and the contact forces between supporting elements. Finite element analysis assesses the stress and strain distribution on the supporting pole of the new handle design. Results show a folding torque of ~ 330 N*mm, lying well within ergonomic comfort limits. Finite element analysis demonstrated that local stress reaches the peak of 47.0 MPa, while local strain reached plastic region with 0.15 mm/mm; however, it was identified as non-critical for the application, consistent with viscoelastic strengthening of polypropylene under rapid actuation. The redesigned two-vial kit achieved a 23% reduction in packaging volume, while a three-vial kit resulted in 7% volume reduction. This corresponds to approximately € 0.35 million annual air-freight savings, without functional compromise.

Together, the two parts demonstrate an integrated model-based design methodology linking computational modeling, additive manufacturing, and experimental validation to address mechanical and cost efficiency challenges in modern IVD world. This workflow contributes not only to specific design improvements, but also a generalizable framework for digitally driven mechanical design in regulated biomedical manufacturing environments.