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Comparative Study of Rigid and Flexible Multibody Dynamics in a 3D-Printed Two-Link Robotic Mechanism

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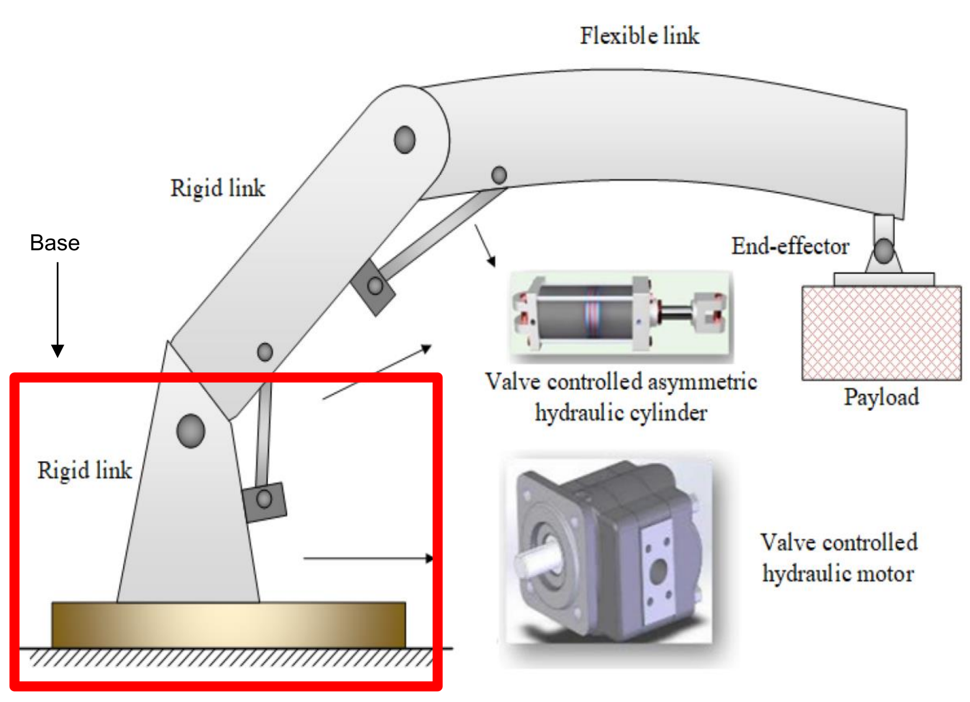
INTRODUCTION & AIM

Additive manufacturing of metals, particularly Laser Powder Bed Fusion (LPBF) using Ti6Al4V, has transformed the way lightweight robotic structures are designed and fabricated. These 3D-printed components often exhibit geometric freedom, reduced mass, and high stiffness-to-weight ratios, which make them ideal candidates for robotic links and compliant mechanisms. However, this flexibility also introduces challenges in accurately predicting dynamic behavior. Traditional rigid-body formulations inherently neglect deformation, structural vibration, and stiffness-dependent dynamic coupling, all of which can significantly influence precision, stability, and control of slender mechanisms. To address this limitation, flexible multibody dynamics models allow the structure to deform while in motion, capturing the combined effects of elasticity, modal interactions, and distributed mass.

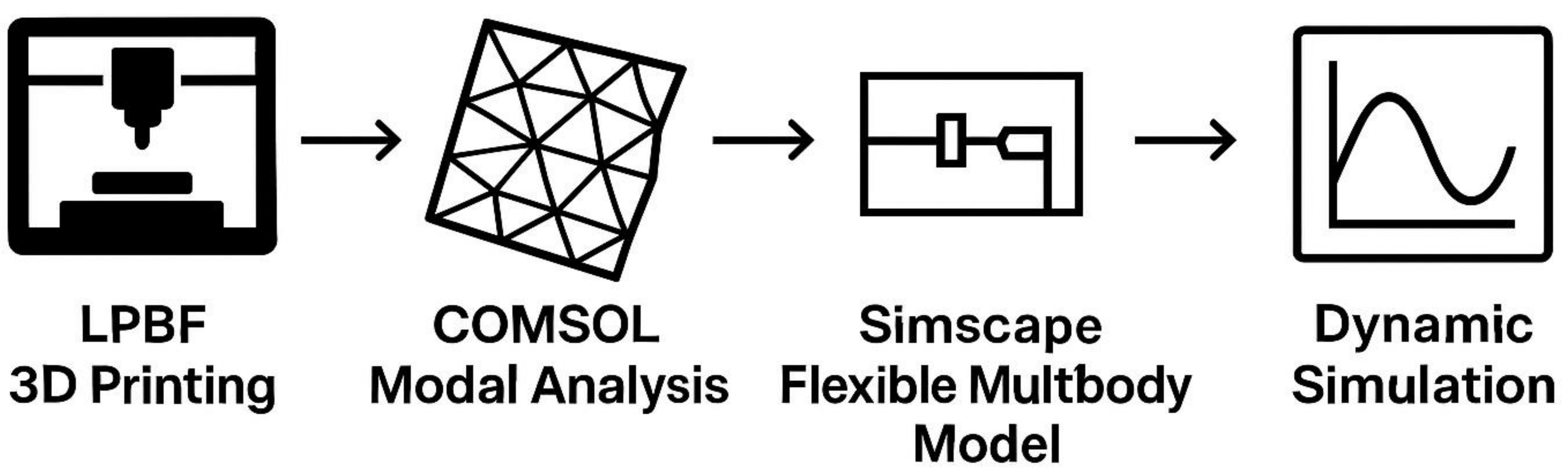
Aim: To compare Rigid MBD vs Flexible MBD for a 3D-printed two-link metal robotic mechanism using Simscape Multibody + FEM modal data.

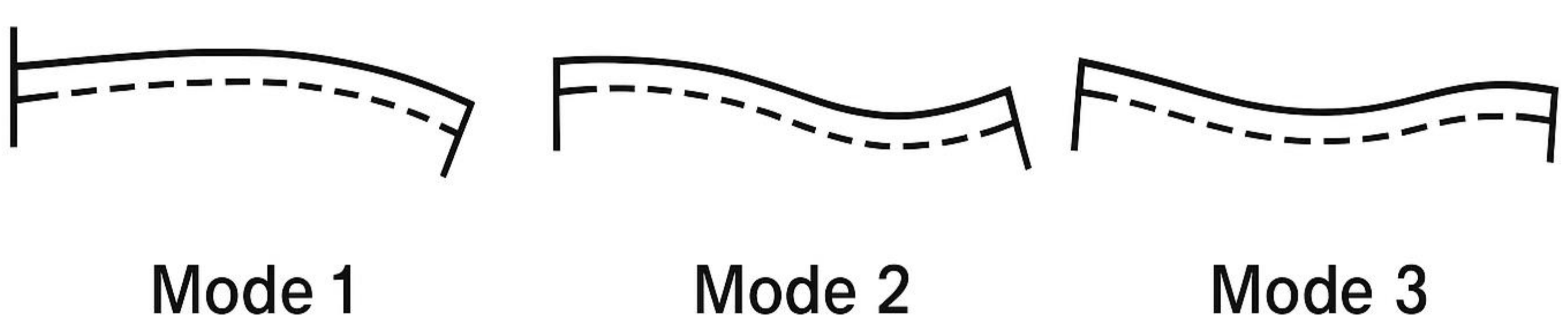


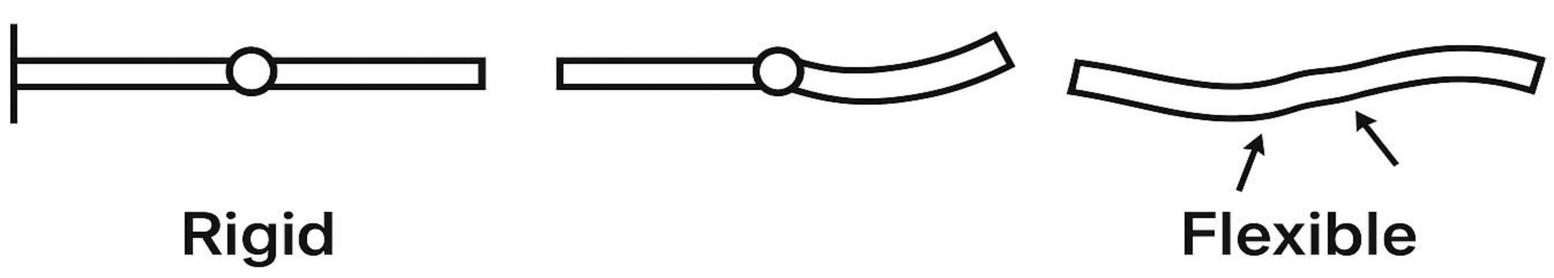
METHOD

The study employs a two-link planar robotic mechanism fabricated through LPBF using Ti6Al4V. Material properties, including a Young's modulus of approximately 110 GPa and a density of 4430 kg/m³, were incorporated into the model to ensure realistic simulation behavior. A rigid multibody model was first constructed in MATLAB Simscape Multibody, representing the links as perfectly rigid components connected through ideal revolute joints.

To account for structural flexibility, a second model was developed where each link was treated as a flexible body represented through modal reduction. The first three bending modes for each link were extracted from COMSOL Multiphysics through eigenfrequency analysis and exported to Simscape. Both models were subjected to identical harmonic torque excitation at the base joint at an input frequency of 12 rad/s. System responses, including angular displacement, vibration amplitudes, natural frequencies, modal energy distributions, and tip deflection, were recorded and analyzed.





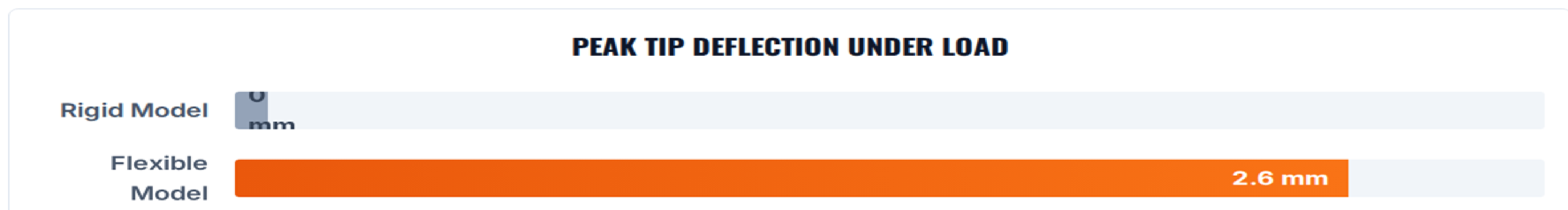


RESULTS & DISCUSSION

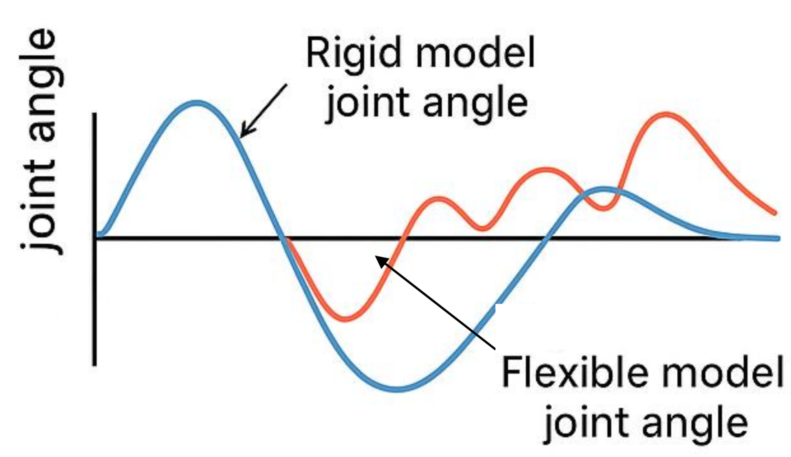
A comparative study of rigid and flexible multibody dynamics in a 3D-printed two-link robotic mechanism reveals that the rigid-body assumption is inadequate for high-precision applications, as it fails to capture critical dynamic phenomena like vibrations and elastic deformations. Flexible body models, while more complex, are necessary for accurate prediction of behavior and effective control.

Comparative Analysis:

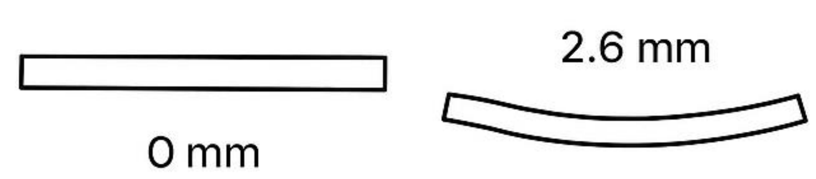
Feature	Rigid Multibody Dynamics Model	Flexible Multibody Dynamics Model
Modeling	Simpler; assumes links/joints are perfectly stiff.	More complex; incorporates elasticity and deformation, often using Finite Element Analysis (FEA) or the Assumed Modes Method (AMM).
Accuracy	Lower for lightweight, high-speed, or 3D-printed robots where links have notable deflection.	Higher accuracy in predicting actual system behavior, particularly tip position and vibration.
Computational Cost	Lower; computationally efficient.	Higher; requires more processing power and time due to the added degrees of freedom and complex calculations for deformation.
Key Phenomena Captured	Primary, large-scale motion; ignores vibrations.	Captures vibrations, elastic deformation, and coupling effects between rigid body motion and structural deflection.
Control System Design	Simpler to design linear controllers (e.g., PID); these often struggle with the real-world system's unmodeled flexibility.	Requires more advanced, potentially non-linear or adaptive control algorithms to manage vibrations and ensure accuracy.



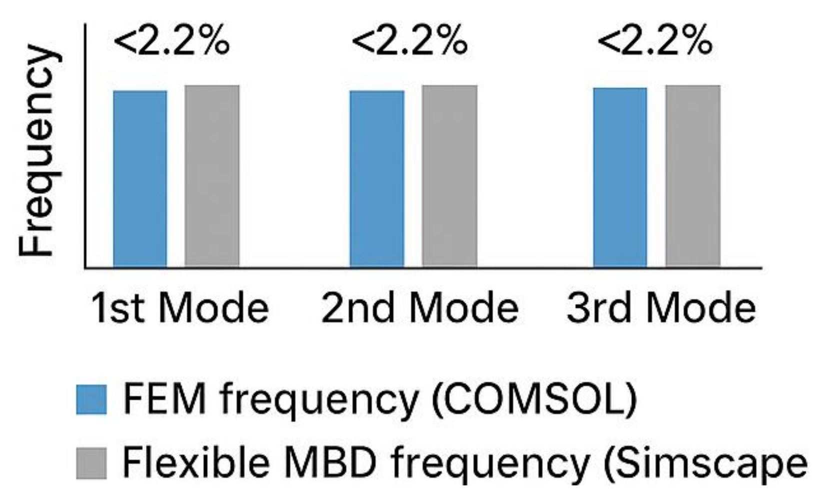
Time-Series Comparison Plot



Tip Deflection Comparison



Modal Frequency Bar Chart



Stiffness Sensitivity Plot

CONCLUSION

This comparative study demonstrates that flexible multibody modeling provides essential insights into the dynamic behavior of lightweight, additively manufactured robotic structures. Rigid-body approximations fail to capture deformation-driven phenomena such as vibration, elastic oscillation, and stiffness-dependent modal coupling. The integration of Simscape Multibody with FEM-derived modal data proved effective in capturing realistic dynamic characteristics, while the results highlight the necessity of flexible modeling for accurate prediction and design optimization.

FUTURE WORK / REFERENCES

The framework presented in this work lays the foundation for future investigations involving structural optimization, control-oriented modeling, and digital-twin development. It also provides a baseline for extending this methodology to mechanisms with more complex geometries, compliant joints, and multi-material structures fabricated through advanced metal additive manufacturing techniques.

References:

1. Shabana, A.A. *Dynamics of Multibody Systems*, 5th ed.; Cambridge University Press: Cambridge, 2020.
2. Batista, M.; et al. Dynamic modeling of flexible-link manipulators: Review and trends. *Mech. Syst. Signal Process.* 2021, *149*, 107188.