Toward Multi-Scale Learning of Adhesive Contact Forces: From Single Asperities to Rough Surfaces

Ali Maghami[1], Merten Stender[2], Michele Ciavarella[1], and Antonio Papangelo[1]

[1] *Department of Mechanics, Mathematics, and Management, Politecnico di Bari, Bari, Italy*
[2] *Chair of Cyber-Physical Systems in Mechanical Engineering, Technische Universität Berlin, Germany*

Prediction of contact forces is essential for robotics, virtual prototyping, and physically based rendering of deformable objects. However, modeling viscoelastic adhesion and rough-surface multi-asperity interactions remains computationally expensive, limiting their use in real-time applications [1]. Based on our previous efforts [2], we present a data-driven framework that learns the full-time evolution of adhesive forces in viscoelastic Hertzian contacts and generalizes these predictions to multi-asperity and rough-surface settings. Our method begins with high-fidelity single-asperity simulations or experiments, from which we construct a coherent global time–displacement representation of viscoelastic indentation. We then train several stateful sequence-to-sequence neural networks (CNN-based and LSTM-based architectures) to predict the corresponding time-resolved adhesive force response. The models successfully learn rate effects, hysteresis, and unloading behavior directly from data, enabling fast and stable inference suitable for interactive applications. Figure 1a illustrates the single-asperity Hertzian model, and Figure 1b shows the learning performance of the four architectures evaluated. Finally, following proven concepts in multi-asperity modeling [3], we embed the learned single-asperity response into a multi-asperity formulation with a global reference surface. This framework lays the groundwork for real-time, physically accurate adhesive contact modeling in computer graphics and animation.

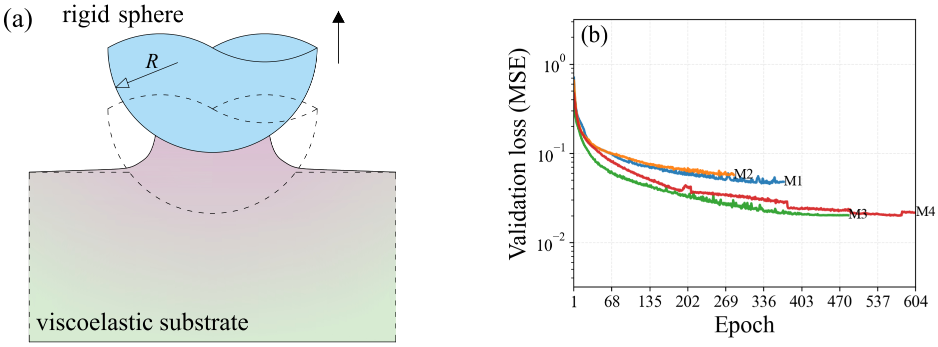

Figure 1: (a) Geometry of the viscoelastic Hertzian single-asperity model. (b) Learning curves for the four architectures evaluated (CNN-based, LSTM-based, and hybrids).

References

[1] A. Maghami, Q. Wang, M. Tricarico, M. Ciavarella, Q. Li, and A. Papangelo, Bulk and fracture process zone contribution to the rate-dependent adhesion amplification in viscoelastic broad-band materials, *J. Mech. Phys. Solids*, 193:105844, 2024.

[2] A. Maghami, M. Stender, and A. Papangelo, Pull-off force prediction in viscoelastic adhesive Hertzian contact by physics augmented machine learning, *Int. J. Solids Struct.*, 322:113584, 2025.

[3] A. Papangelo, N. Hoffmann, and M. Ciavarella, Load-separation curves for the contact of self-affine rough surfaces, *Sci. Rep.*, 7(1):6900, 2017.