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# Real-time insight into adhesion of Hertzian indenter unloaded from a broadband viscoelastic substrate through a physic-augmented machine learning model

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## Abstract

Real-time insights into the adhesive properties of viscoelastic materials, such as polymers and elastomers, greatly benefit engineering applications in gripping technologies, switchable adhesion, friction, biomechanics, soft robotics, and climbing robotics technology. Predicting the adhesive properties in real time supports secure handling, adaptability to diverse surfaces, and fine control. Heinrich Hertz (1) laid the groundwork for contact mechanics in 1882 with his solution for elastic bodies with curved surfaces, but addressing adhesive forces, such as van der Waals interactions, introduced a nonlinear boundary-value problem solvable only through iterative numerical methods. The foundational Johnson-Kendall-Roberts (JKR) theory (2) and later models, such as Derjaguin-Muller-Toporov (DMT) theory (3), have driven significant advances but exhibit limitations in their generalizability, especially when extending to rate-dependent viscoelastic materials (4). We should consider that the adhesion in viscoelastic solids introduces rate-dependent responses and is irreversible. It is generally a "difficult problem in contact mechanics" as noted by Johnson (4). Energy-based theories, such as the Persson-Brener (PB) theory (5), address adhesive crack propagation under steady-state conditions but require fitting parameters and often fall short when considering broad-band viscoelasticity. To overcome these limitations, recent developments, including the extended PB model (XPB) (6), offer improved analytical descriptions for Hertzian contact but remain constrained to specific regimes, such as high Tabor parameters and saturated indentation conditions. We address the adhesive interaction between a rigid sphere and a broad-band viscoelastic half-space using a combination of numerical simulations, analytical modeling, and machine learning (ML). Numerical simulations, based on the Lennard-Jones separation law within a boundary element method framework coupled with time-marching algorithms, are employed to generate a comprehensive dataset that captures viscoelastic effects under diverse conditions. We develop and evaluate multiple ML models to replicate the adhesive behavior, comparing their predictions with analytical solutions from our extended PB model (XPB). While the XPB model accommodates broad-spectrum viscoelasticity, it remains limited to saturated indentation regimes and higher Tabor parameters. Meanwhile, ML models struggle to deliver accurate predictions in scenarios with insufficient data due to high production costs. To overcome these shortcomings, our physics-augmented ML framework integrates XPB knowledge with data-driven insights. It offers improved predictive accuracy across varying indentation depths and loading rates. Our results demonstrate that

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ML models achieve computational efficiency suitable for real-time applications. Furthermore, the physics-augmented models extend the applicability of analytical solutions, bridging gaps in accuracy for scenarios where traditional methods fall short.

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