Efficient numerical time-domain simulation of rail vehicles with coupled simulator systems

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KNORR-BREMSE RAIL VEHICLE SYSTEMS BUDAPEST

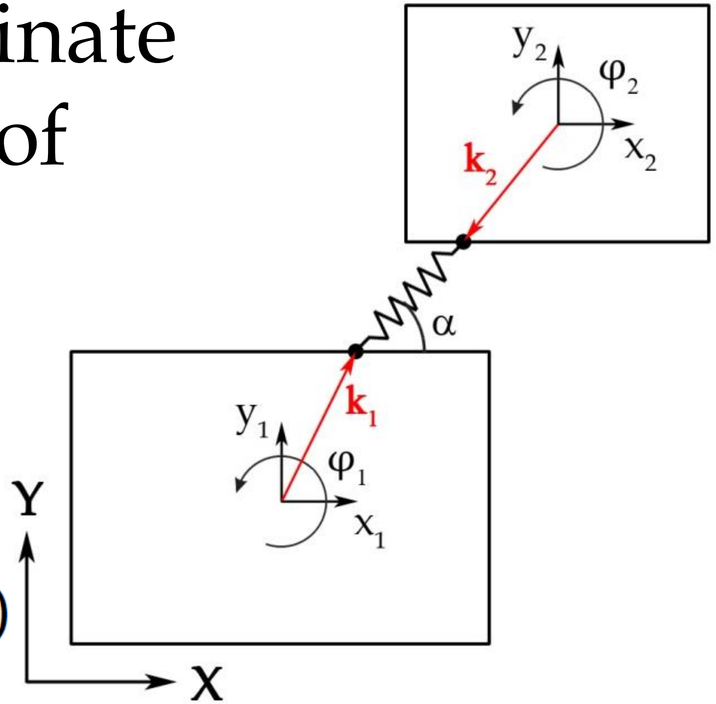
Introduction

- HiL simulation of rail vehicles
  - Horizontal and vertical oscillations
  - Dynamics of wheels
- Configurable partitioned simulator system
  - Linear model: in-plane model of vehicle bodies and springs / dampers
  - Nonlinear model: wheel dynamics with contact

Linear in-plane vehicle model

- In-plane model containing rigid bodies, springs, nodes, external force connections.
- Automatic general coordinate selection and generation of mass-, damping and stiffness matrices.
- Equation of motion

$$\mathbf{M}\,\ddot{\mathbf{q}}(t) + \mathbf{K}\,\dot{\mathbf{q}}(t) + \mathbf{S}\,\mathbf{q}(t) = \mathbf{Q}(t)$$



Fundamental matrix solution

- Cauchy transcription

$$\dot{\mathbf{y}} = \mathbf{A}\,\mathbf{y} + \mathbf{b}$$

- Diagonalization*
  - Using eigensystem or Jordan-normal form

$$\mathbf{y}(t) = \mathbf{\Phi}(t)\,\mathbf{y}_0 + \int_{t_0}^{t} \mathbf{\Psi}(t)\,\mathbf{\Psi}^{-1}(\tau)\,\mathbf{b}(\tau)\,\mathrm{d}\tau$$

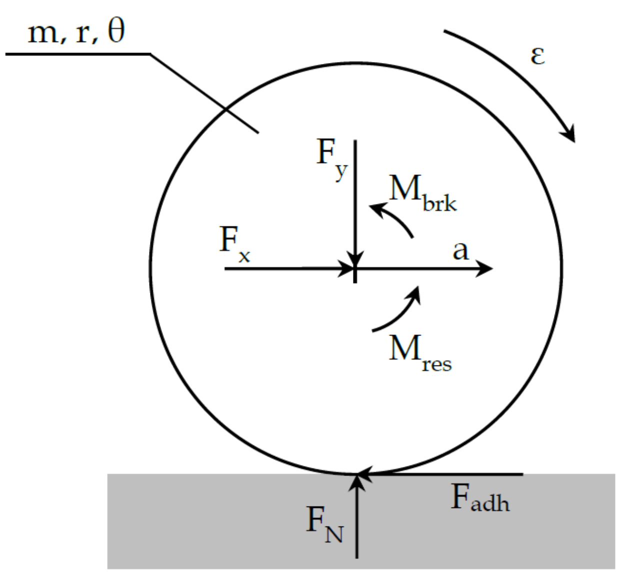
- Formulating a numerical method

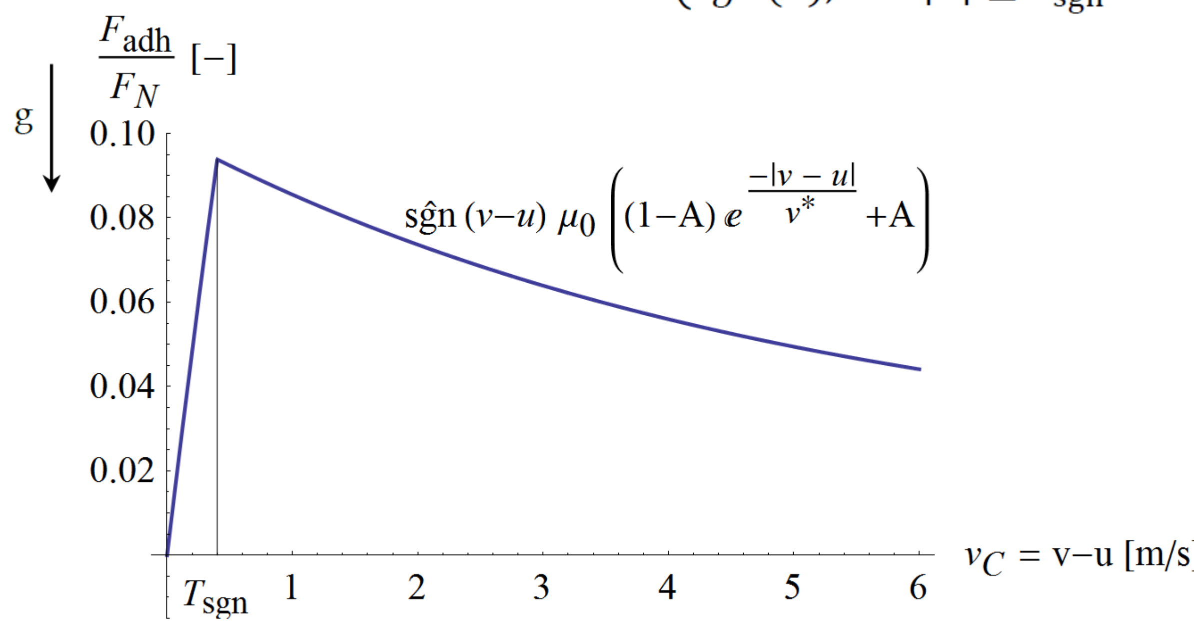
$$\mathbf{y}_{n+1} = \mathbf{\Phi}(\Delta\mathrm{t})\,\mathbf{y}_n + \mathbf{\Omega}_0(\Delta\mathrm{t})\,\mathbf{b}_{0,n} + \mathbf{\Omega}_1(\Delta\mathrm{t})\,\mathbf{b}_{1,n}$$

Nonlinear part

- Dynamics of wheel rotation with rail-wheel adhesion
  - Continuous sgn function

$$\widehat{sgn}(x) = \begin{cases} x \dfrac{1}{T_{sgn}}, & |x| < T_{sgn} \\ sgn(x), & |x| \geq T_{sgn} \end{cases}$$

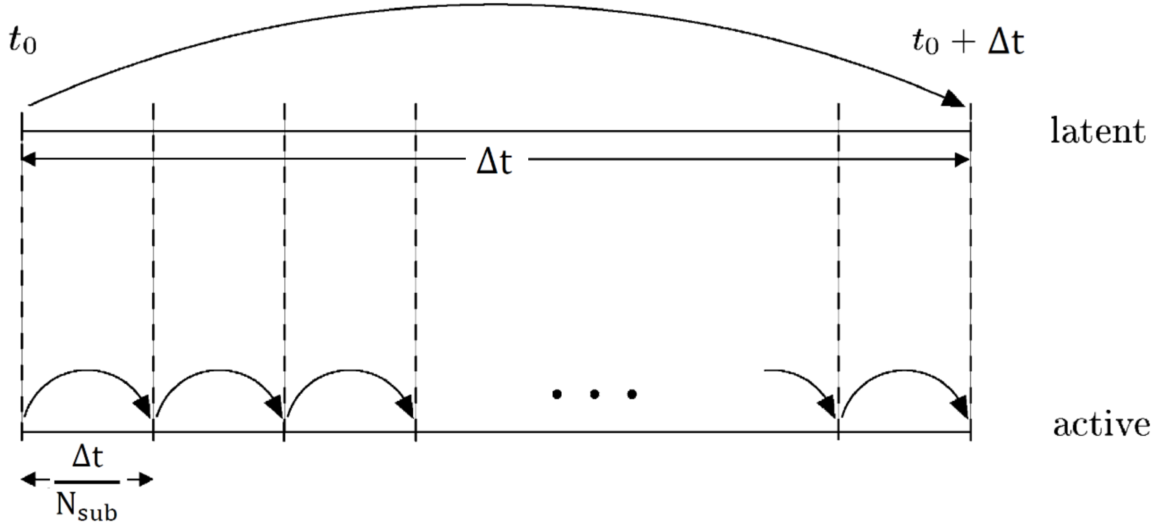




Multi-rate approach

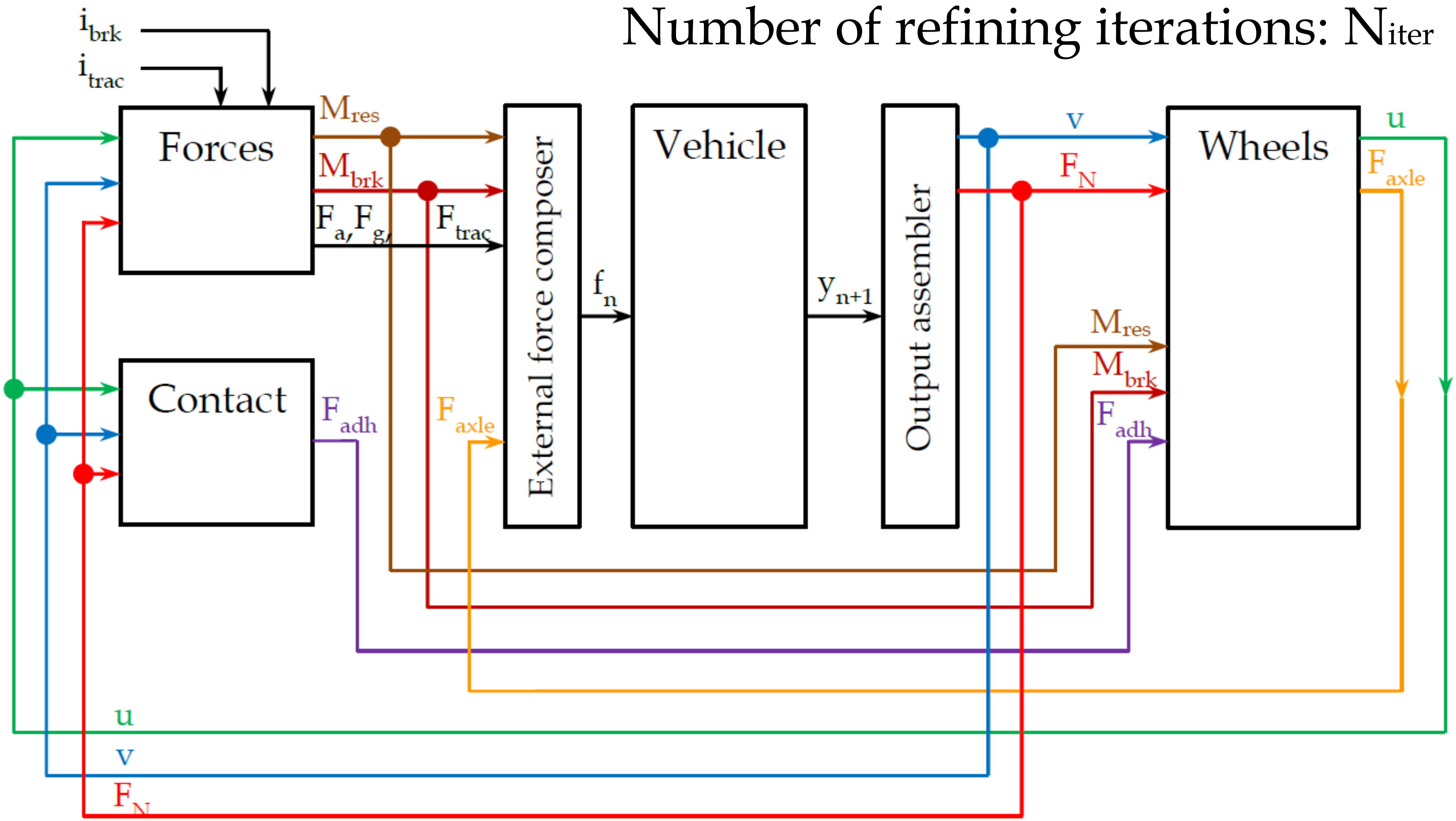
- Subsystems
  - Active part: rotational dynamics of wheels
  - Latent part: oscillations of vehicle bodies (car, bogies, wheels as point masses)
  - Slow first
  - Time steps

$$\delta t = \frac{\Delta t}{N_{sub}}$$



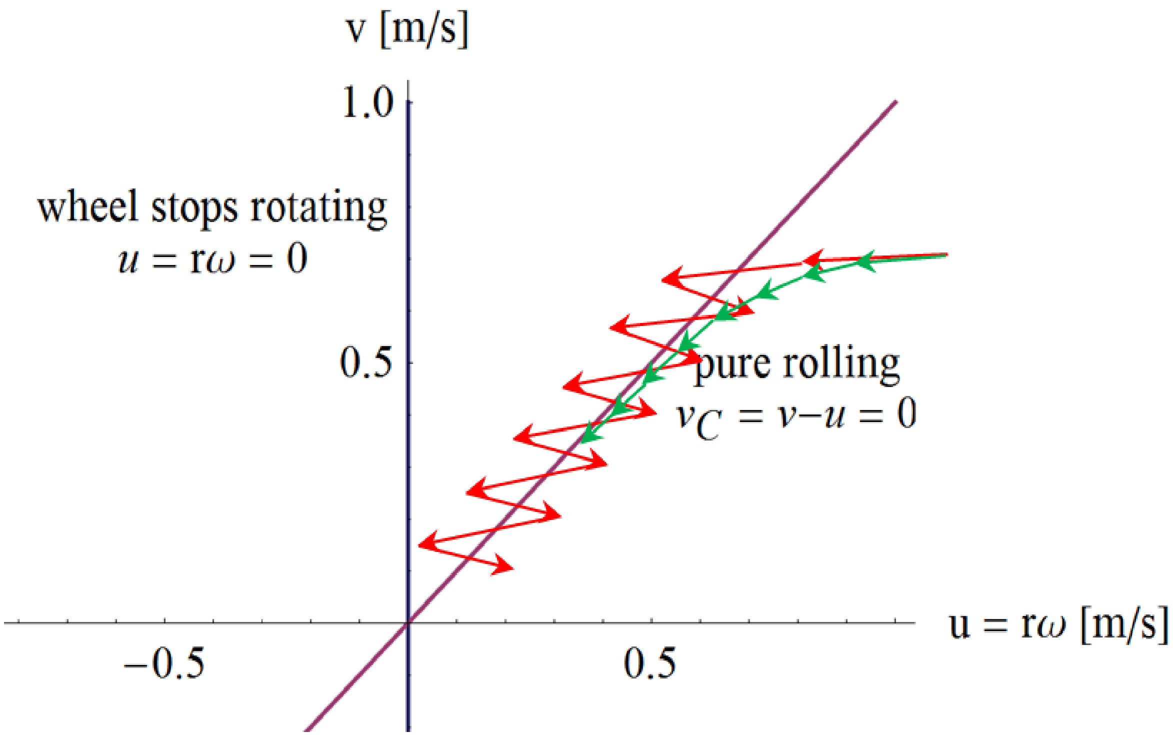
Simulator framework

Number of refining iterations: N_{iter}



Results

- Micro-slip region can be tuned (Tsgn)
  - Instability of wheel dynamics

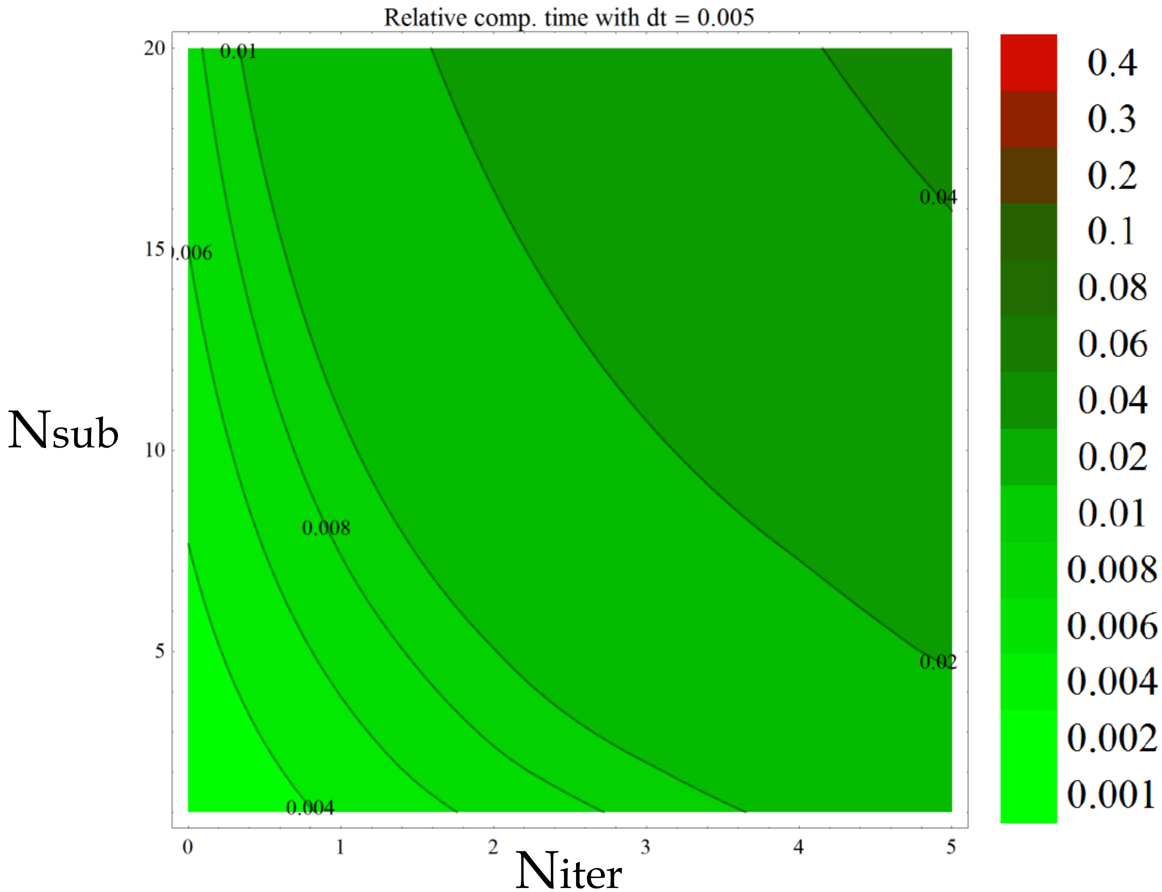


Results

- Error analysis (N_{iter} & N_{sub})
  - At larger macro time steps ($\Delta t = 0.02$ [s]) the error gradually reduces by decreasing the micro time step (by increasing N_{sub}).
  - At smaller macro time steps the error does not depend on N_{sub}, but rather decreases by utilizing additional iterations. (N_{iter})

Results

- Computation time requirement



Conclusion

- The main requirement is to produce wheel angular velocity output at a rate of 5 [ms]
  - We can allow larger macro time steps with appropriate micro time step. This saves computational time.
  - Utilizing further refining iterations, the error of the calculation can be reduced further.
- Configurable simulator system
  - Accurate linear part

Thank You for your attention!

- Feel free to ask questions
- Demonstration of the simulator

Question

„The author states that all calculations are purely analytical thus numerical errors are not introduced in the calculations. A little bit later it turns out that it is not true, because the fundamental matrices are calculated numerically, and the diagonalization is also done numerically.

How serious are these numerical errors compared to a numerical integrator, like RK4?"

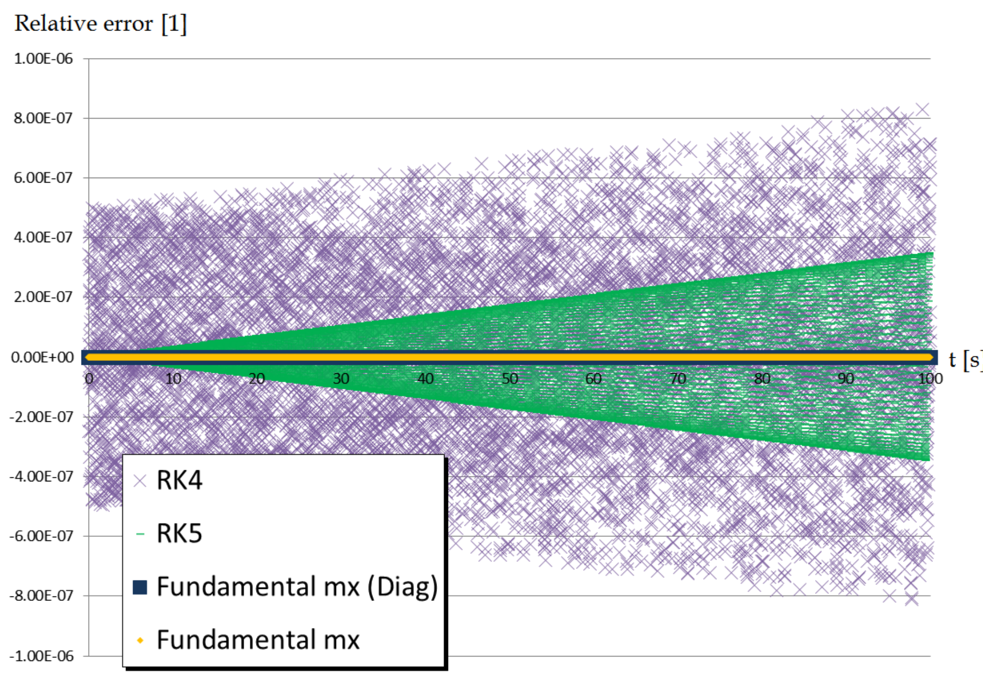
Answer

This question was examined in *„Effiecient real-time simulation of vehicle dynamics systems"* (TDK)

Simple 2 DoF model with known solution, 100 [s]

Error of RK method family accumulates faster, magnitude: 10^{-7}

Error magnitude of Fundamental mx. solution: 10^{-13}



Comment

„An approximation of the sign() function is presented for the handling of adhesion force in section 6.5. One can realize that this function cannot describe the reality, because at zero velocity the adhesion force is also zero"

There is slip in the the adhesion regime!