Muzzle Voltage Characteristics of Railguns

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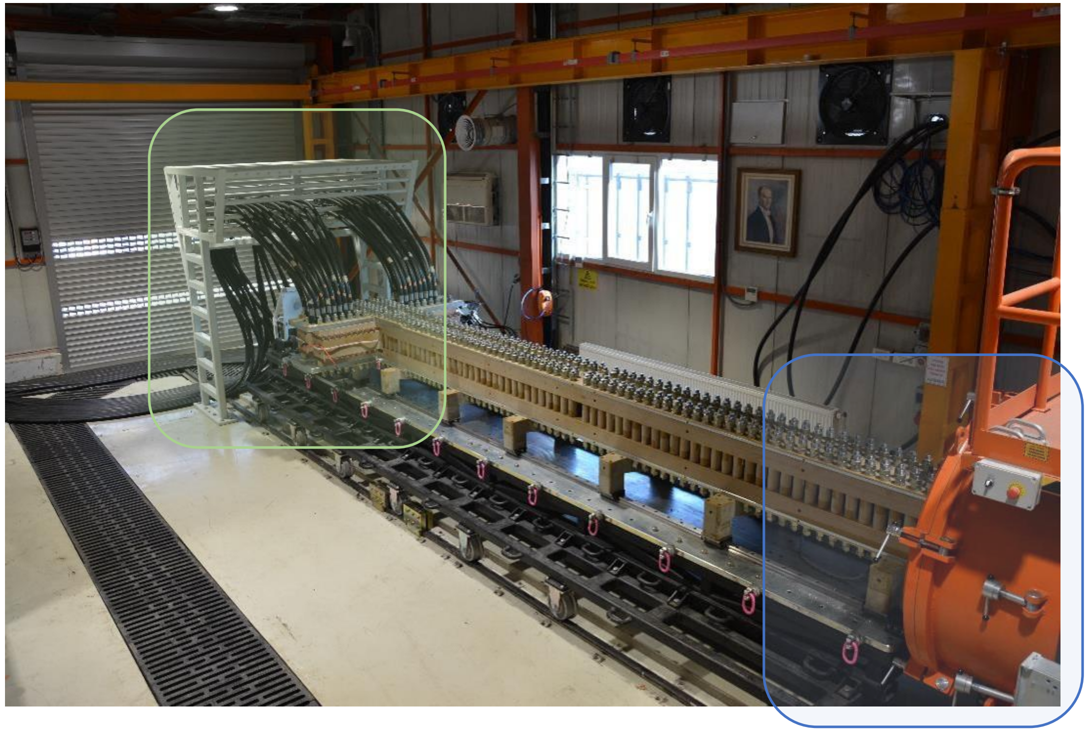
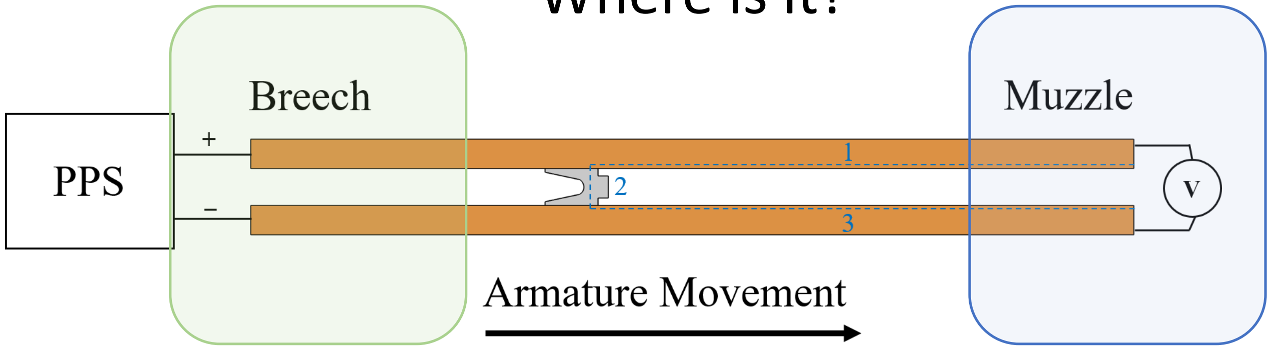
Muzzle Voltage

- ASELSAN Inc. has been working on Electromagnetic launch technologies since 2014.
- EMFY-3 has a 50 × 75 mm rectangular bore and 6-m-length.
- 2.91 MJ muzzle energy is obtained up to now with an 8 MJ PPS (@ $\boldsymbol{\eta}$=**36.37**%).



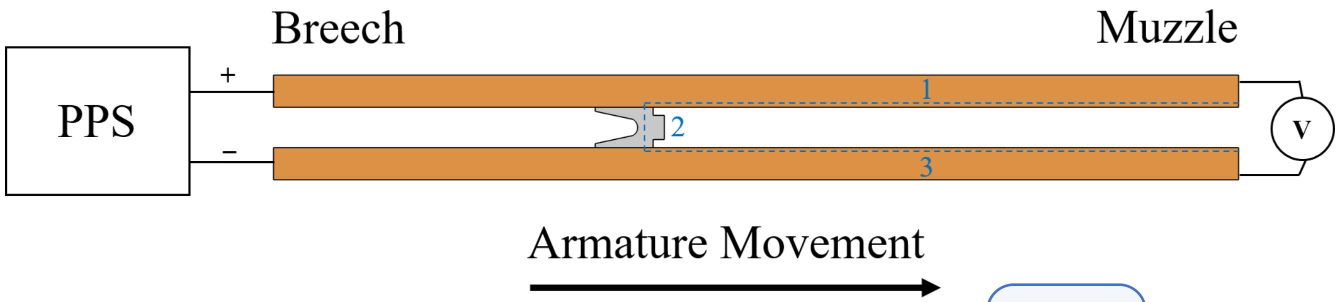
Where is it?



Why is it important?

It is a great diagnostic tools to investigate contact state.
However, it should be decomposed to deliver meaningful data.

Muzzle Voltage Decomposition

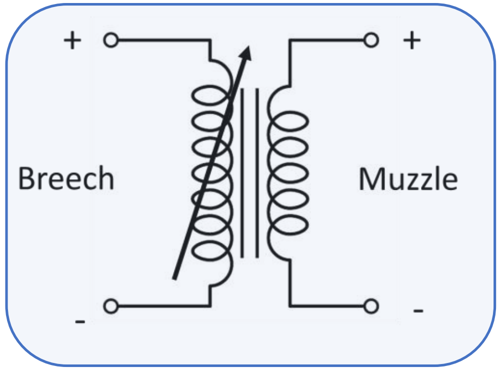


$$U_m = \oint_{C_1} \vec{E}_1 d\vec{l}_1 + \oint_{C_2} \vec{E}_2 d\vec{l}_2 + \oint_{C_3} \vec{E}_3 d\vec{l}_3 + \boxed{\frac{d\Phi}{dt}}$$

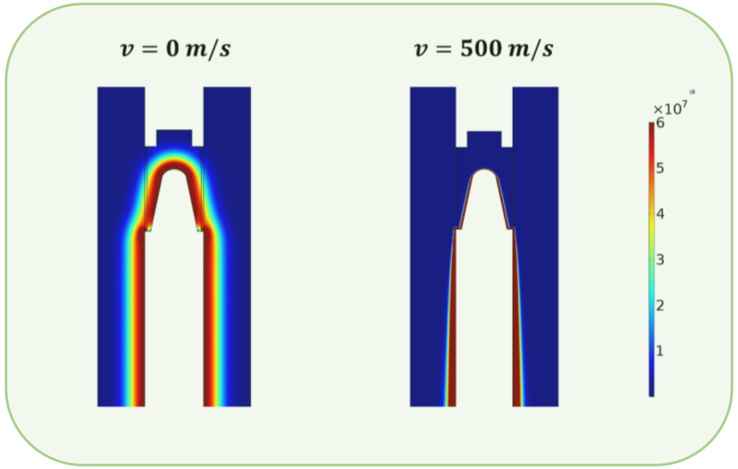
$$U_m = I_r R_a + \boxed{\mathrm{L_m} \frac{dI_r}{dt}} + (\dots) \leftarrow$$ Mutual inductance term [1]

$$U_m = I_r R_a + \mathrm{L_m} \frac{dI_r}{dt} + \boxed{k I_r \sqrt{\frac{\mu_0 \rho_r v}{s}}} \leftarrow$$ VSE term [2]

$$U_m = I_r R_a + \mathrm{L_m} \frac{dI_r}{dt} + k I_r \sqrt{\frac{\mu_0 \rho_r v}{s}} + \boxed{\frac{1}{2} L' I_r v} \leftarrow$$ Back-EMF [3]

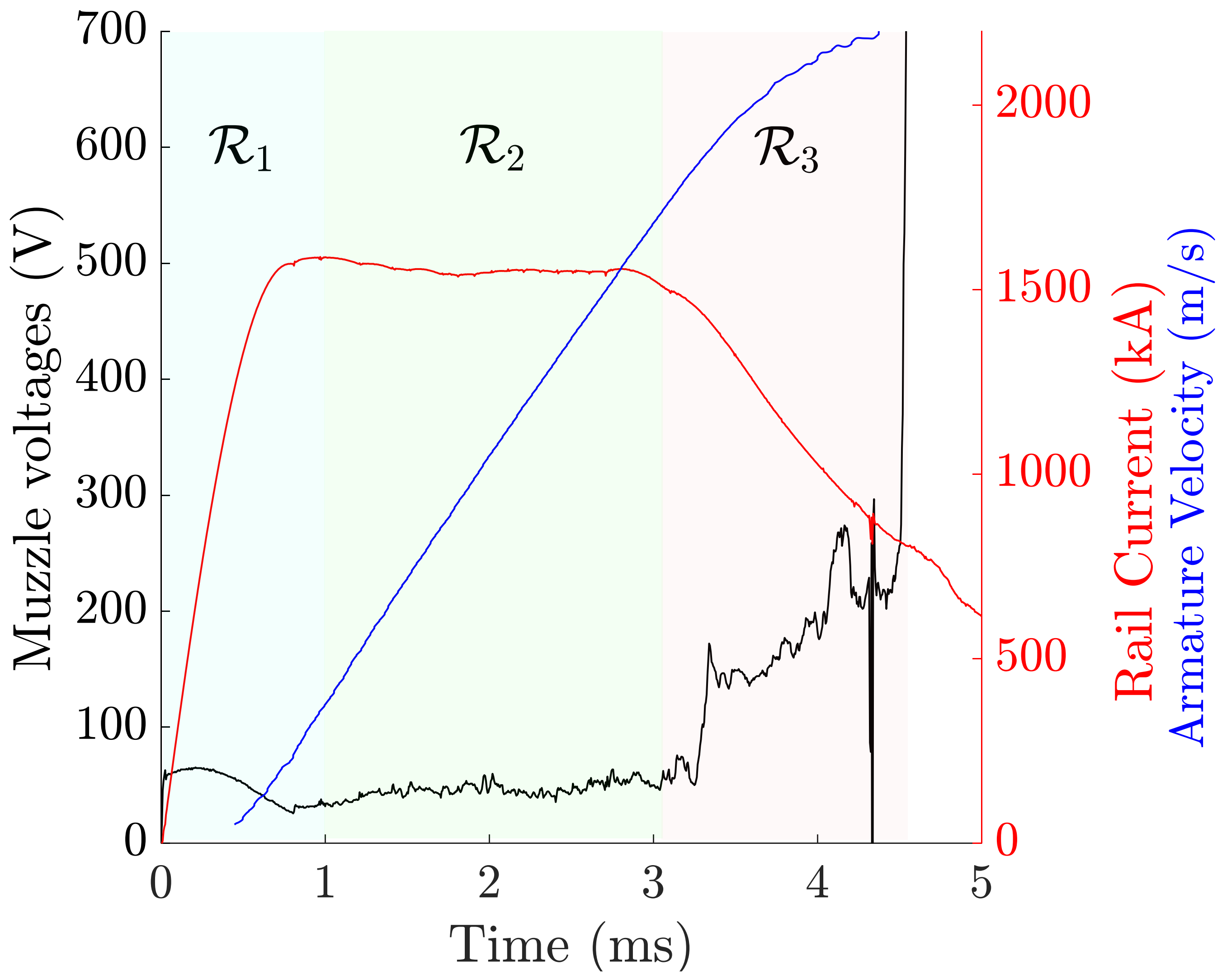


Transformer analogy



VSE

Regions



Region 1

Armature velocity is little;

velocity term is not expected

Region 2

$\frac{dI_{rail}}{dt}$ is little;

inductive term is not expected*

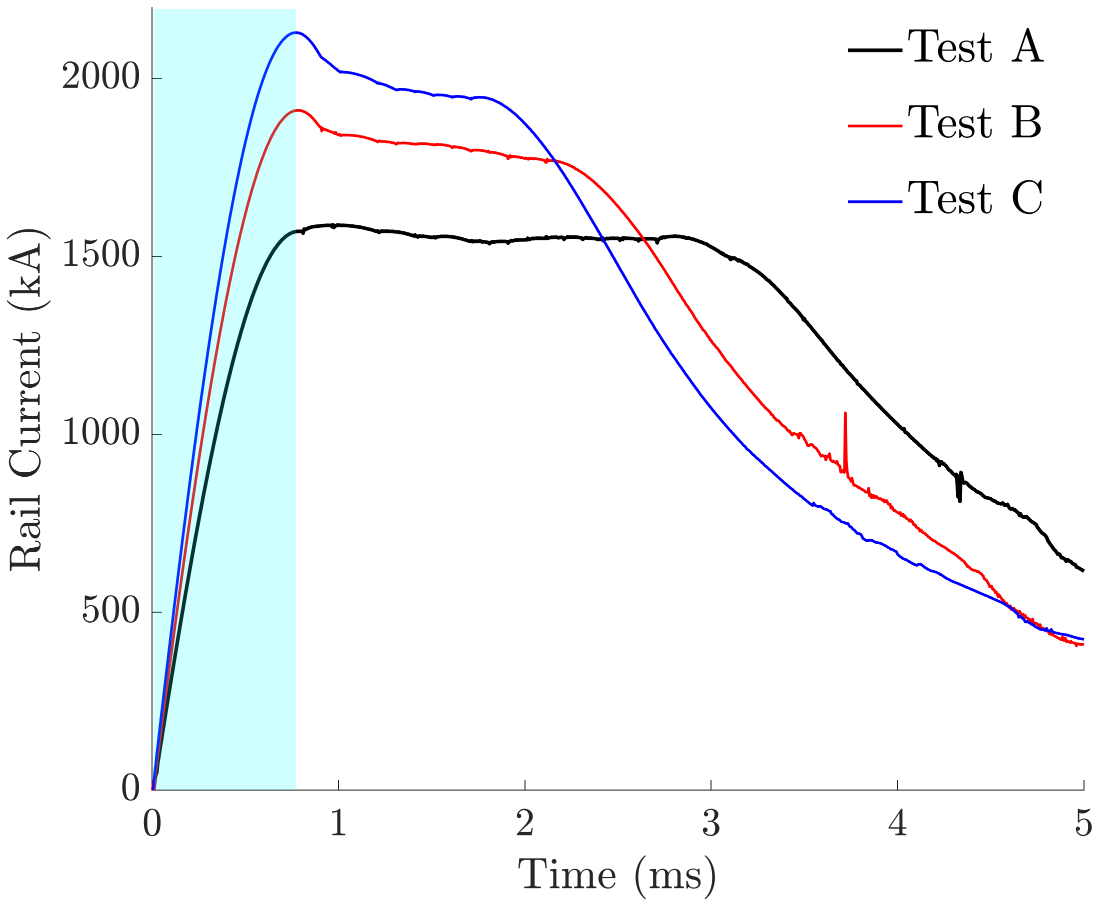
Region 3

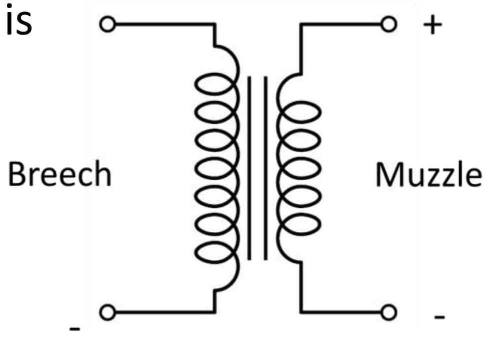
$\frac{dI_{rail}}{dt} < 0$, armature velocity is large

transition

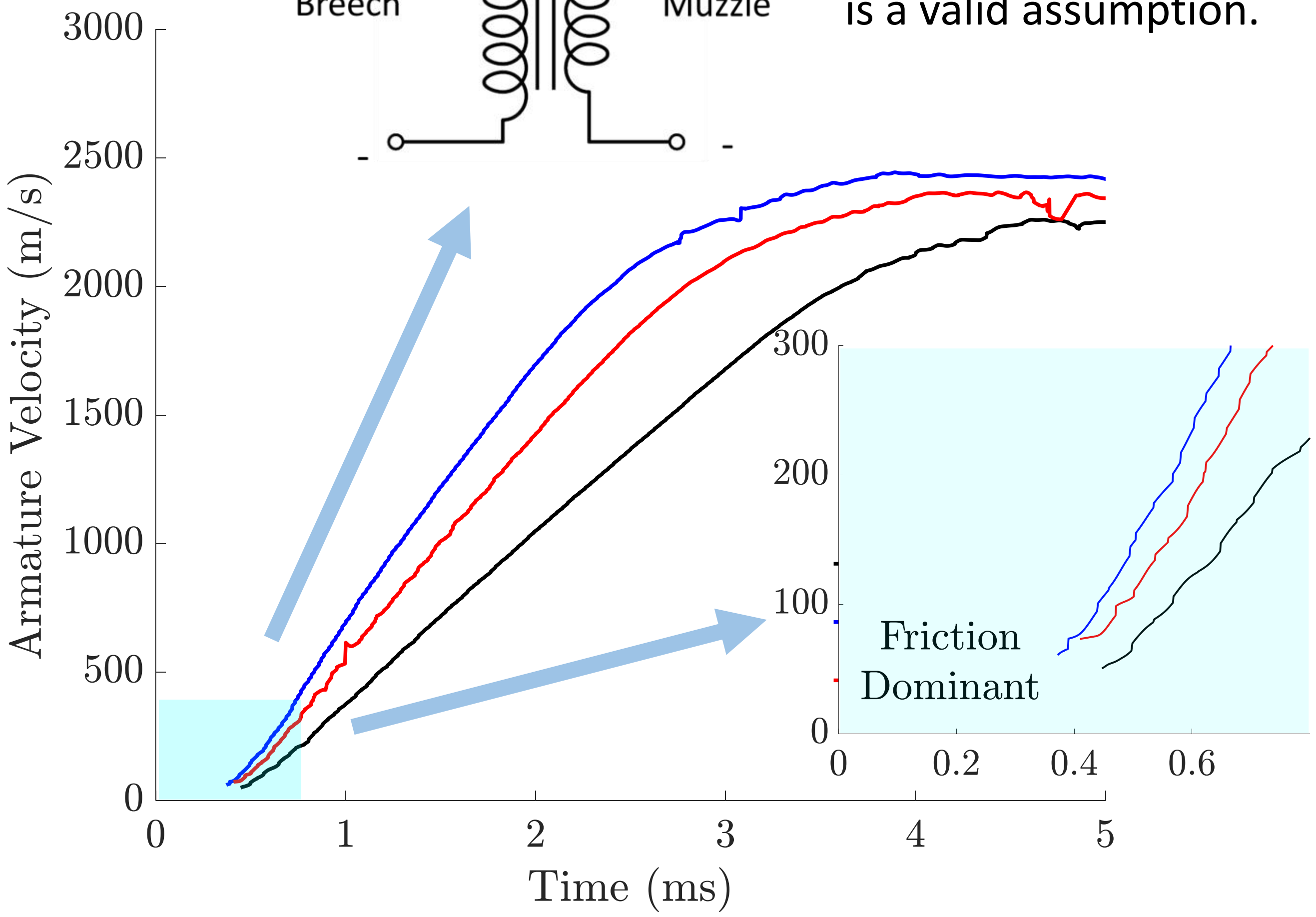
Muzzle Voltage Decomposition

In the first region, capacitive-based module are fired simultanously, the rail current is increased. As the friction kicks in armature movement is little, the linear transformer model is valid.

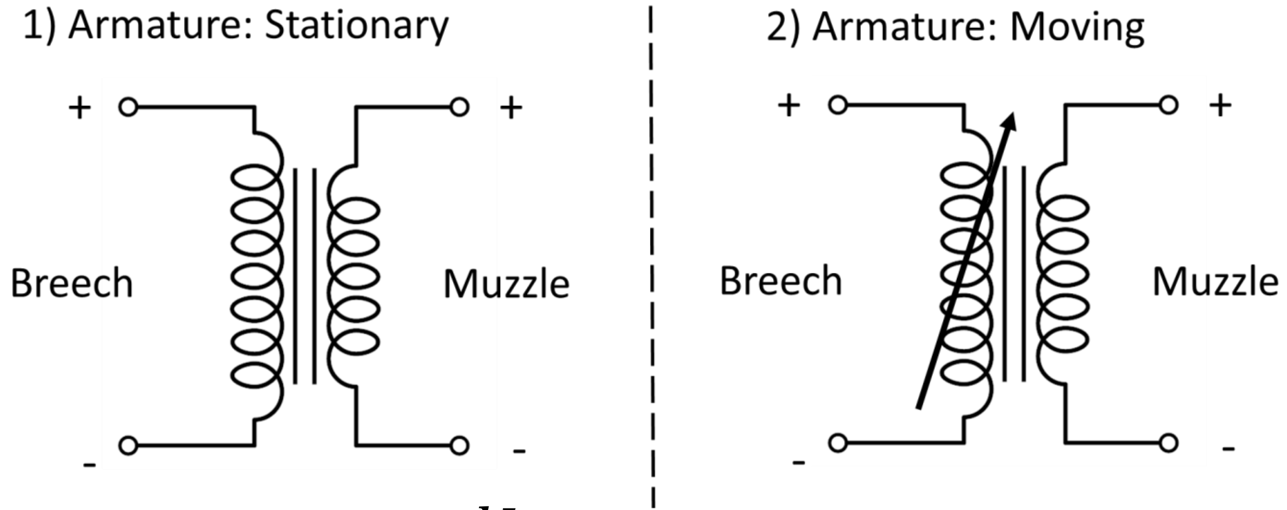




As the armature movement is little, stationary armature is a valid assumption.



Muzzle Voltage Decomposition



$$U_m = I_r \boxed{R_a} + \boxed{\mathrm{L_m}} \frac{dI_r}{dt} + (\ldots)$$

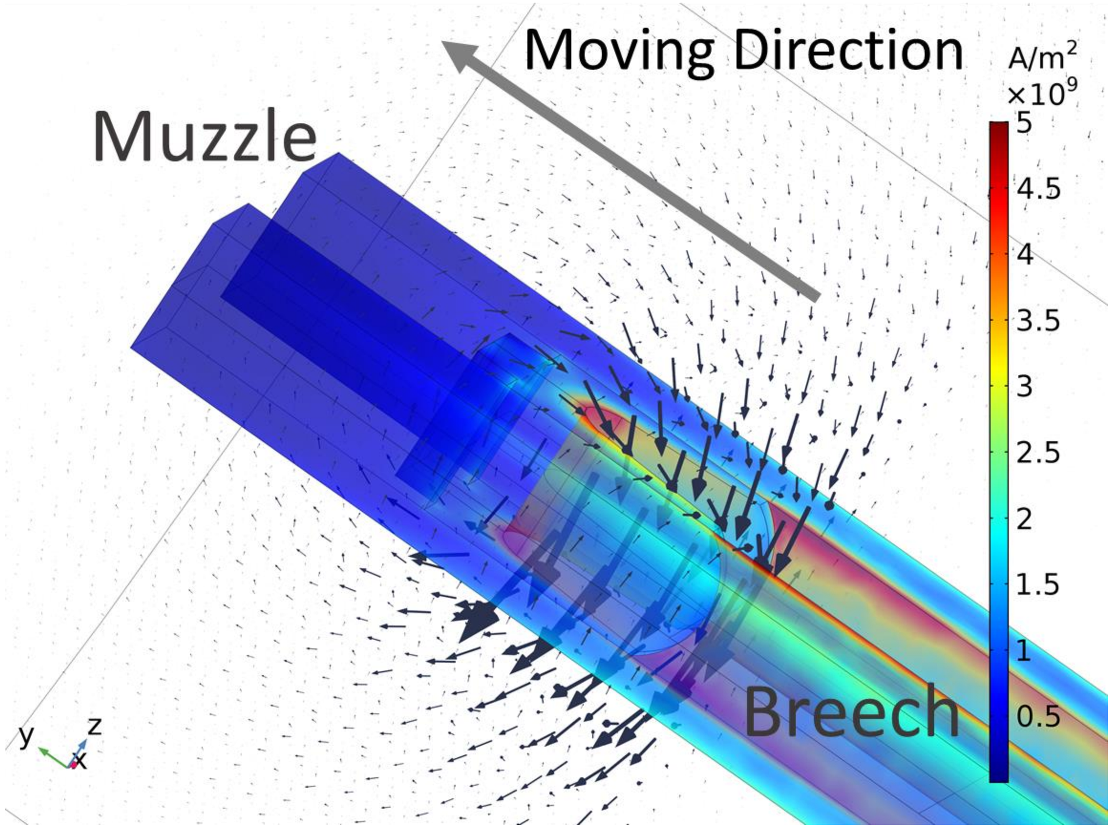
L_m is geometry dependent, can be calculated through 3-D FEM.

R_a is the armature resistance which consists;

1) *the material resistance, (can be calculated with FEM)*
2) *the electrical contact resistance (complex; pressure-phase-temperature dependent).*

I_r *is the rail current (emprical).*

3-D FEM result for L_m calculation



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Decomposition: Region 1

Hypothesis I:

R increased due to thermal loading,
No velocity term,
L_m is constant, in the R_1

$$U_m = I_r R_a + \mathrm{L_m}\frac{dI_r}{dt} + (\ldots)$$

Initial value is determined by $\dot{I}_{rail}$ (*purely inductive*)

1) Muzzle voltage in the first half increased:

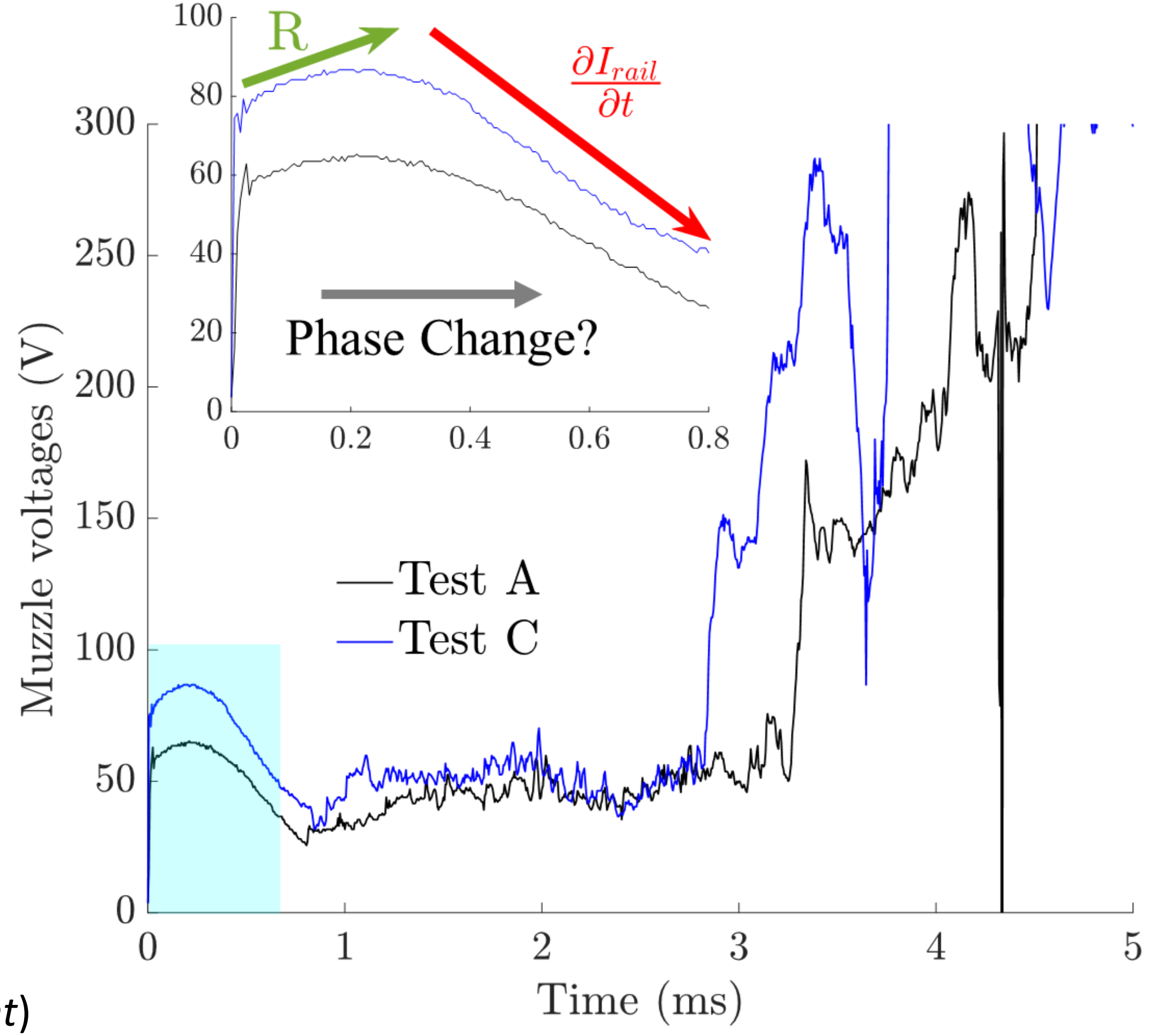
$$I_r \nearrow \quad R_a \nearrow \quad \frac{dI_r}{dt} \searrow \quad \mathrm{L_m} \;—$$

The resistive component is increased (*as the contact temperature increased*)

2) Muzzle voltage in the second half decreased:

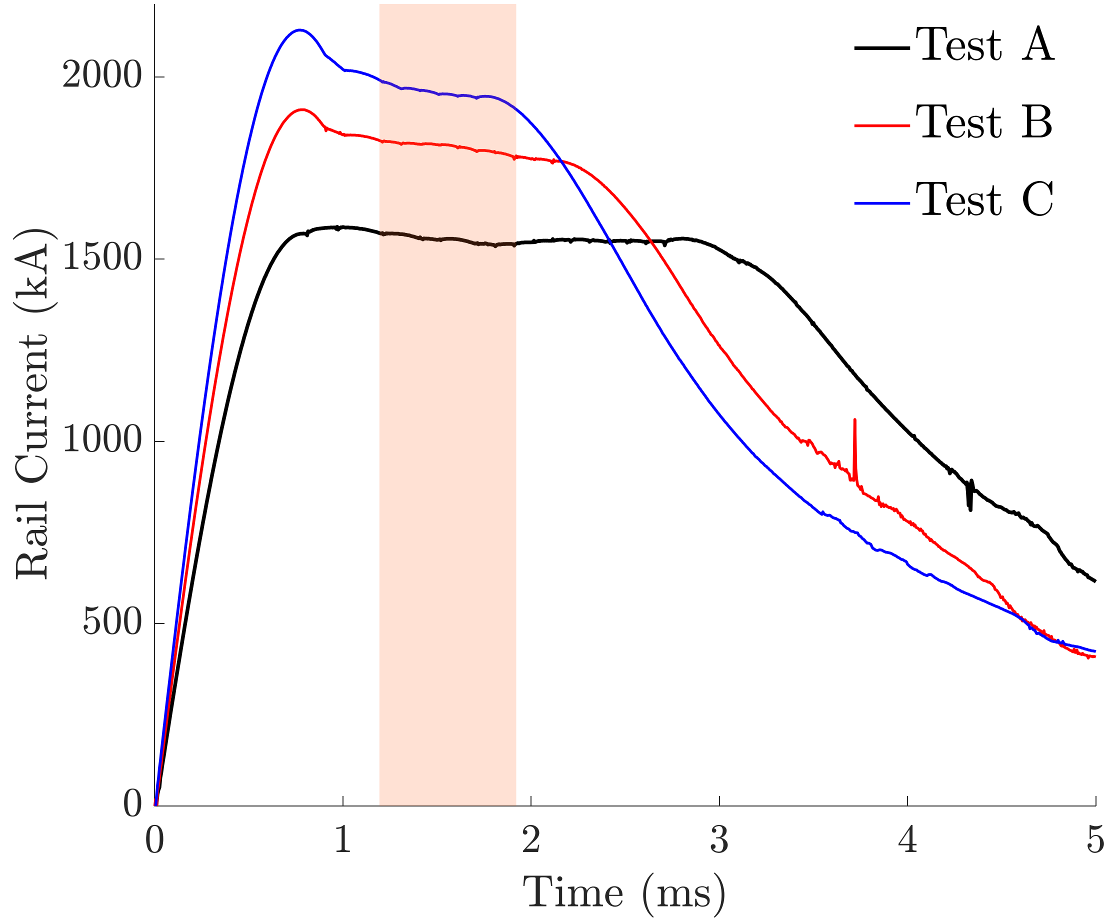
$$I_r \nearrow\nearrow \quad R_a \;\overset{?}{—} \quad \frac{dI_r}{dt} \searrow\searrow \quad \mathrm{L_m} \;—$$

R is constant as the contact forms stable liquid material.
(*inductive voltage is dominant, resistive contribution is constant*)



Decomposition: Region 2

$\frac{dI_{rail}}{dt} \approx 0$ $\dot{v} = C$ $\hat{I}_{rail}$, and $\dot{v}$ are different.

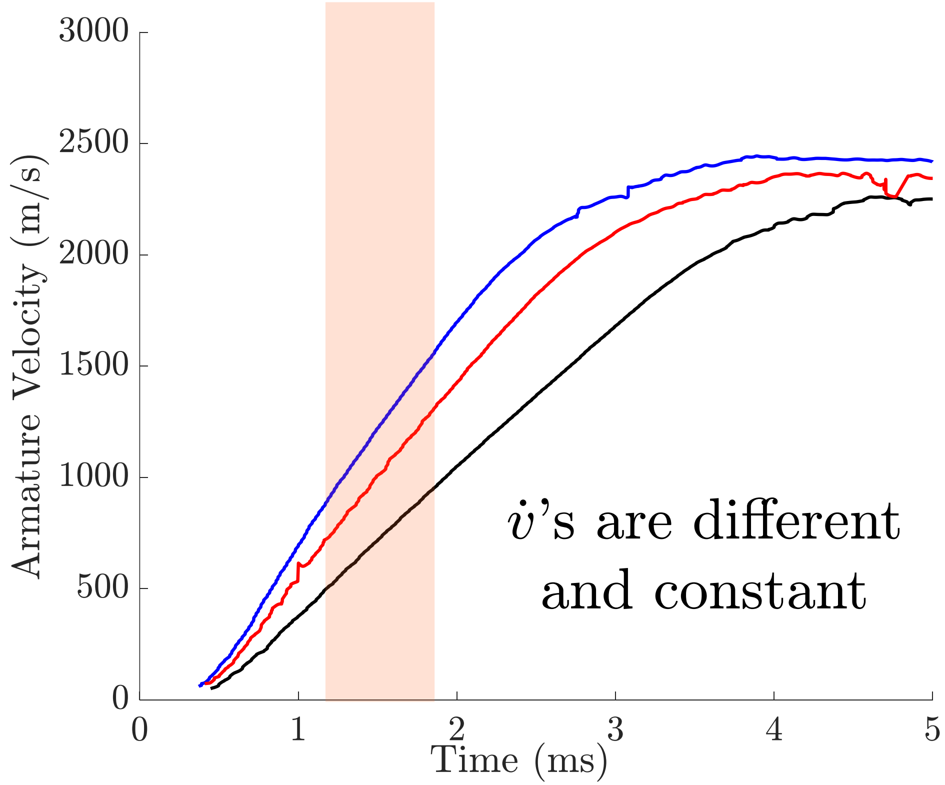


Hypothesis II:

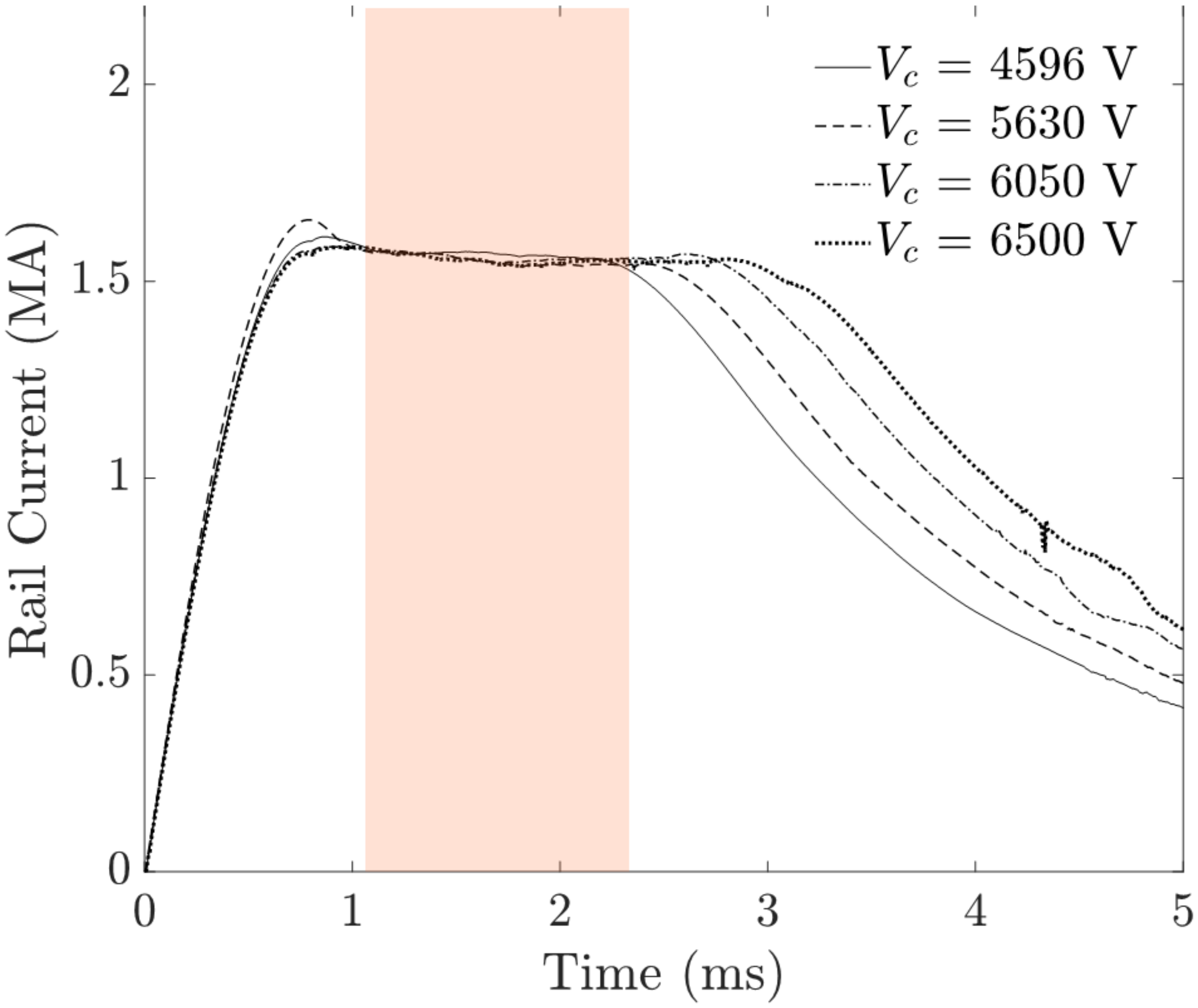
No velocity or $\dot{v}$ term *(falsifiable)*

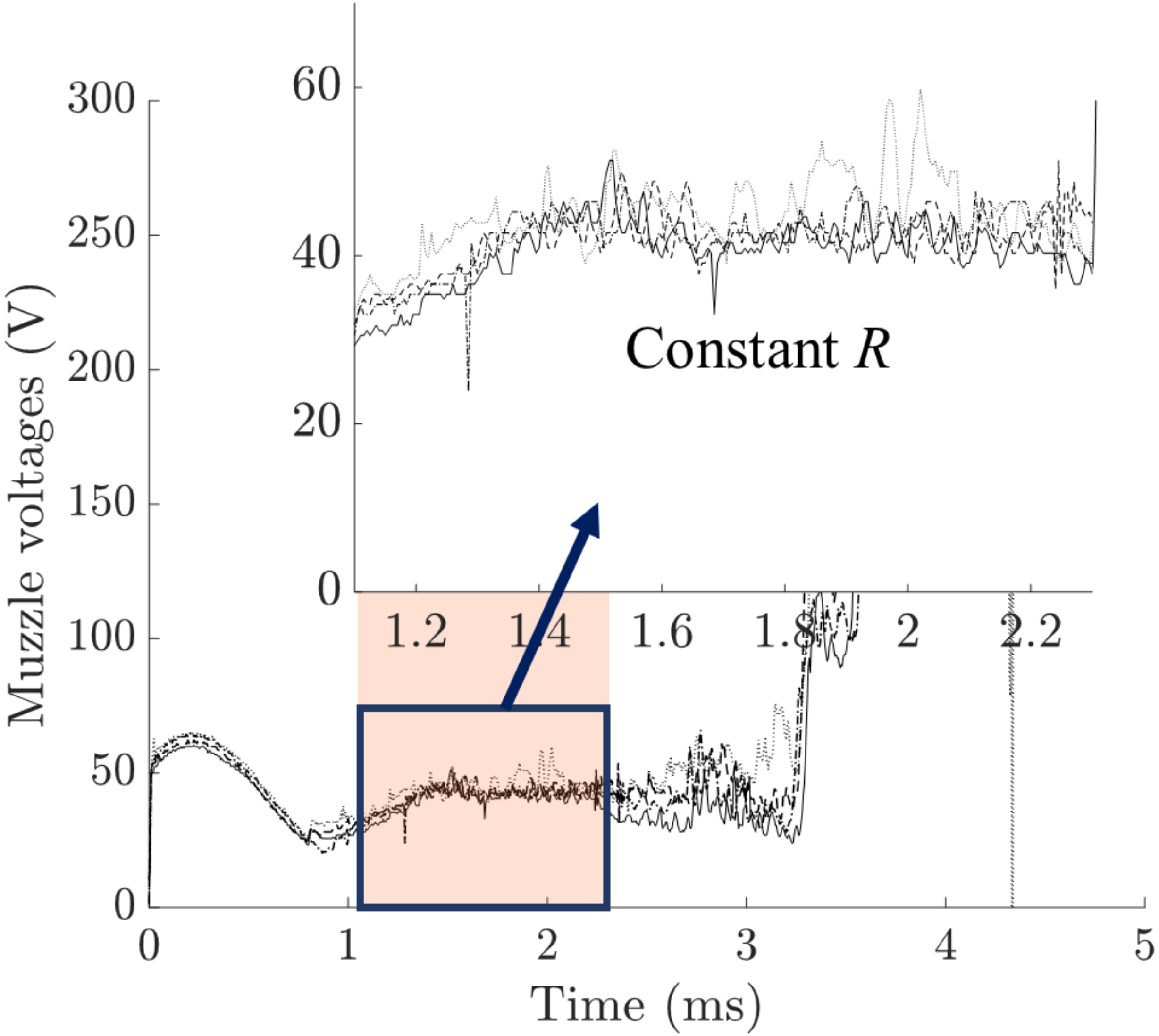
R is constant, if the contact is stable

L_m is constant

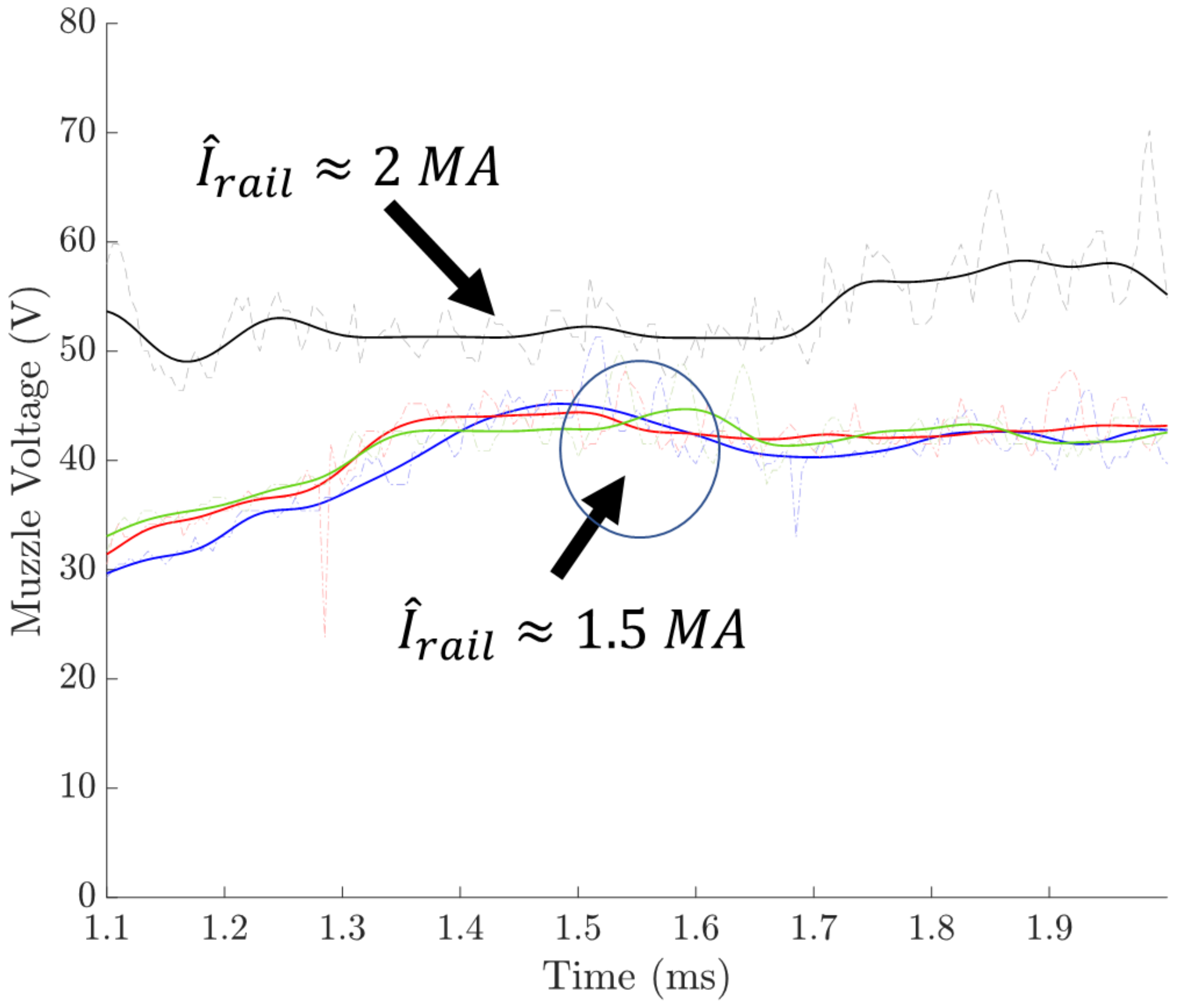


Decomposition: Region 2





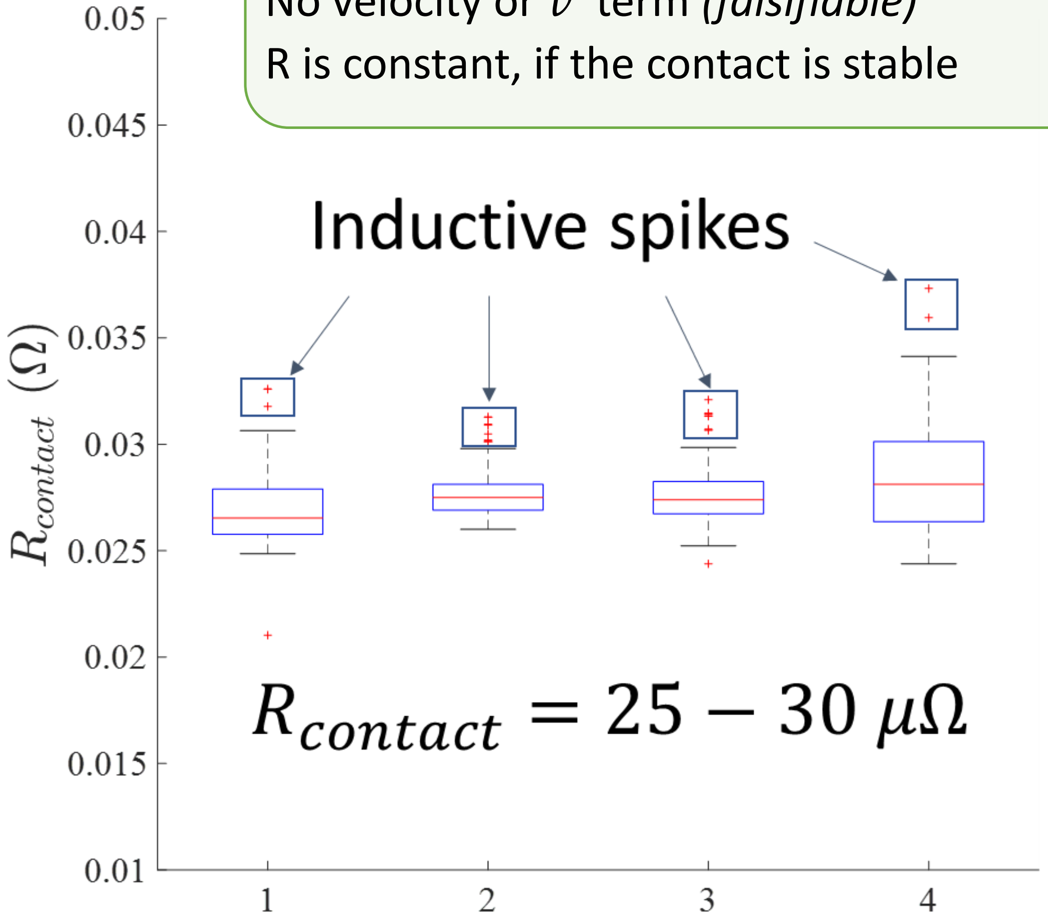
Decomposition: Region 2



Hypothesis II:

No velocity or $\dot{v}$ term *(falsifiable)*

R is constant, if the contact is stable



$$R_{contact} = 25 - 30\ \mu\Omega$$

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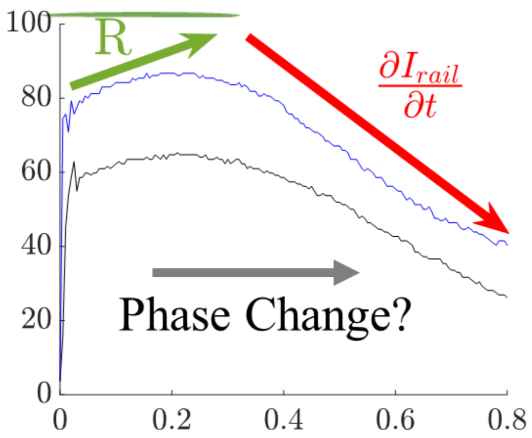
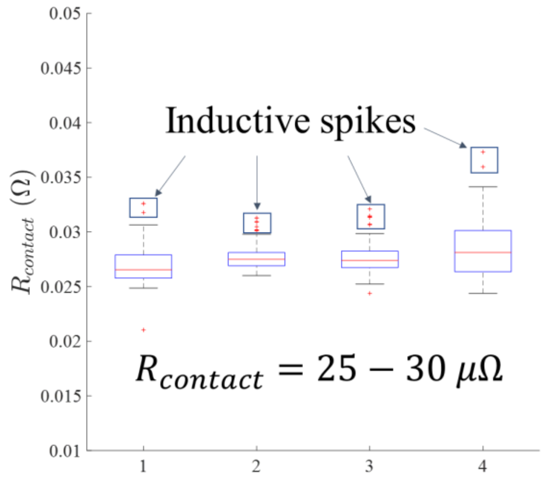


$$\varnothing(x) = \frac{1}{1+e^{-x}}$$

Sigmoid function



R_c extraction

Hypothesis I:

R increased due to thermal loading,

No velocity term

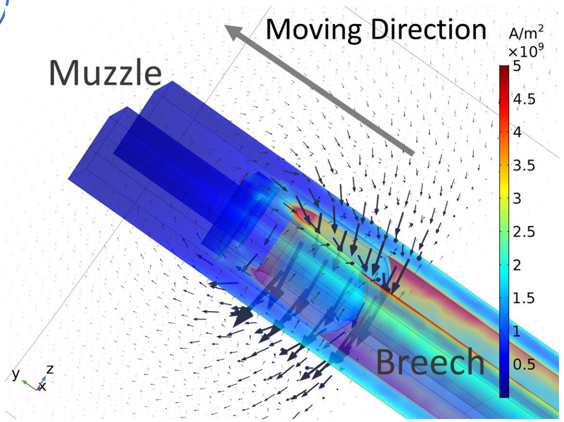
L_m is constant, in the R_1

Hypothesis II:

R is constant, if the contact is stable

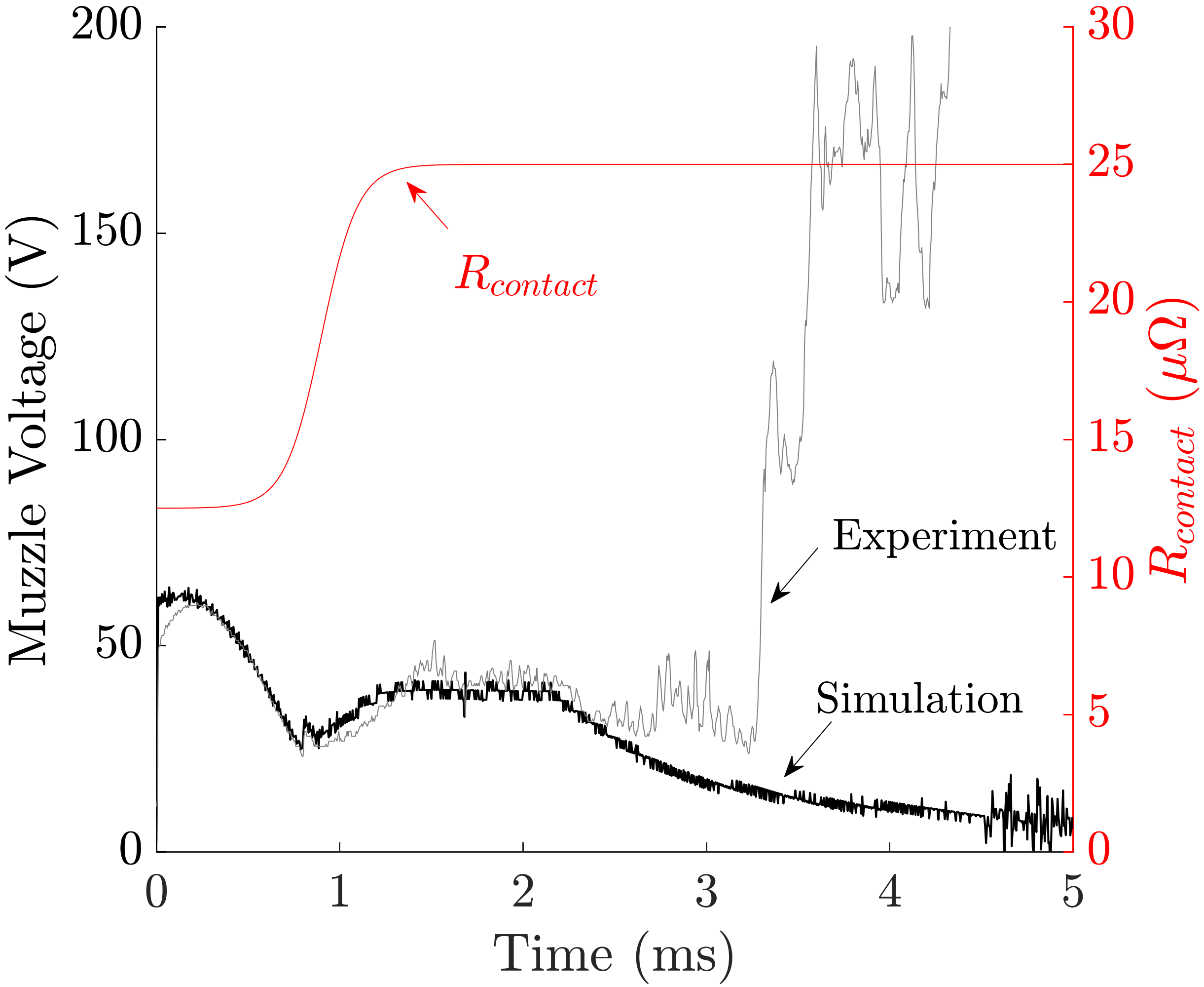
No velocity term

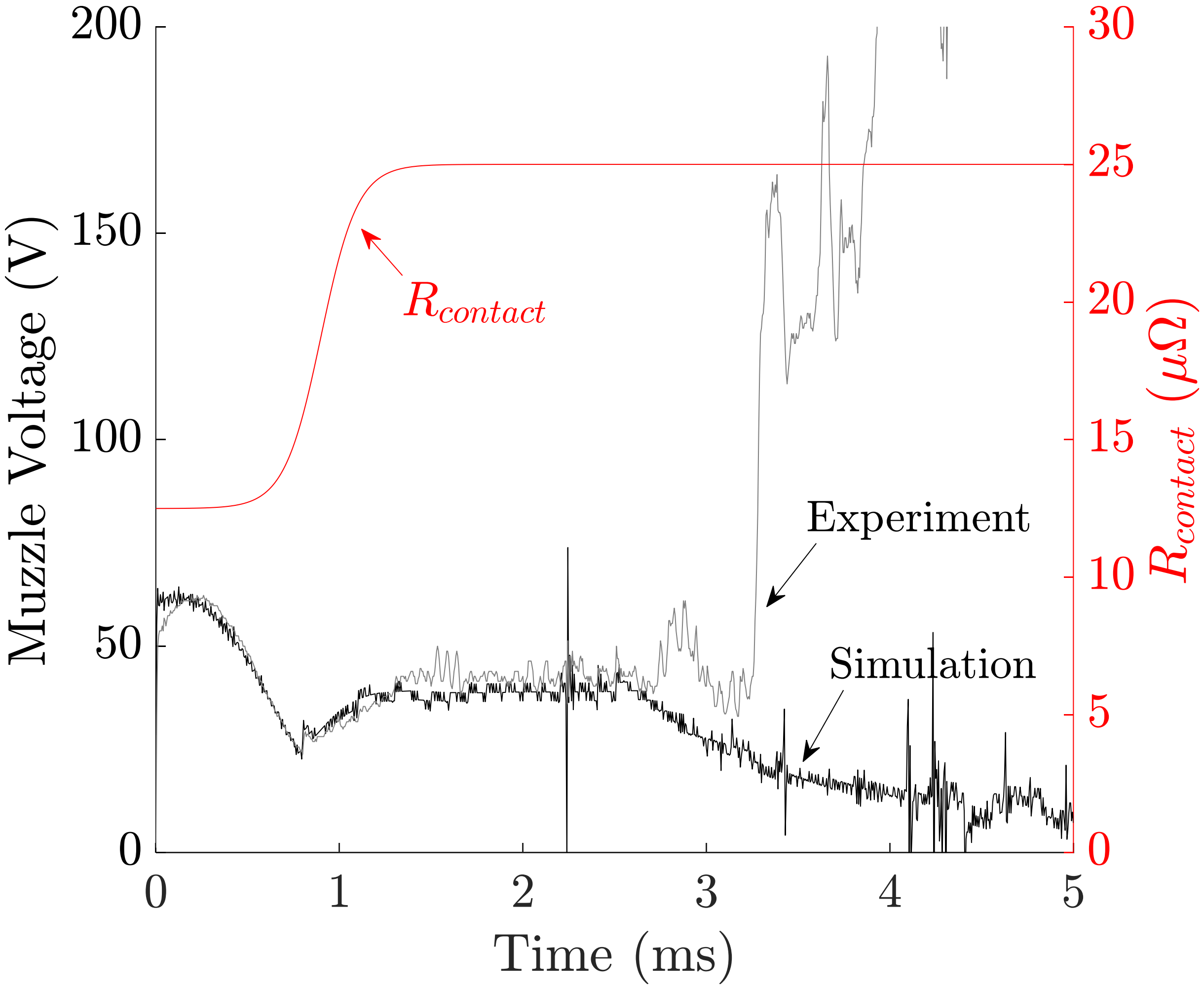
L_m is constant, in the R_2



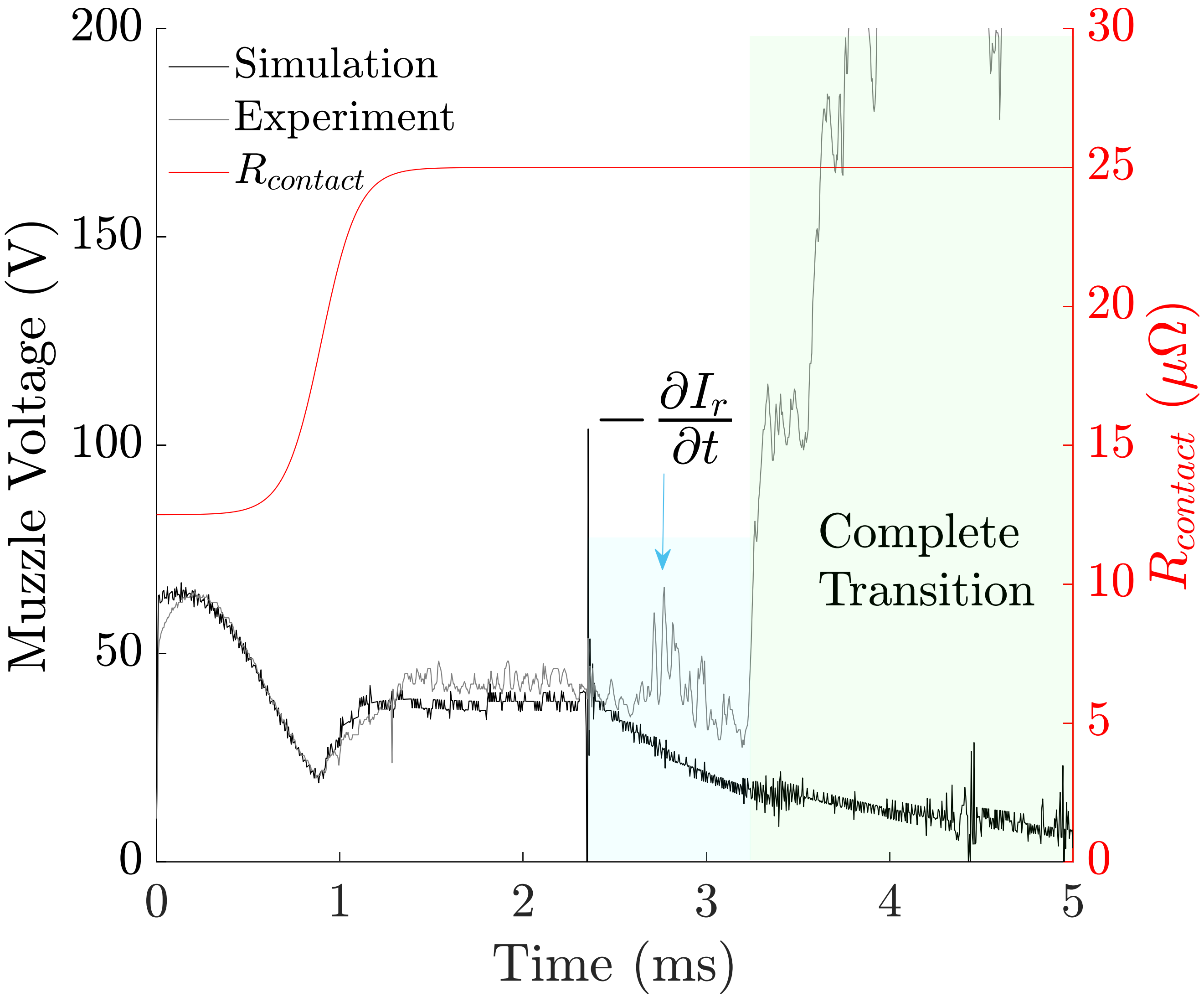
L_m calculation

Results (R_1 & R_2)



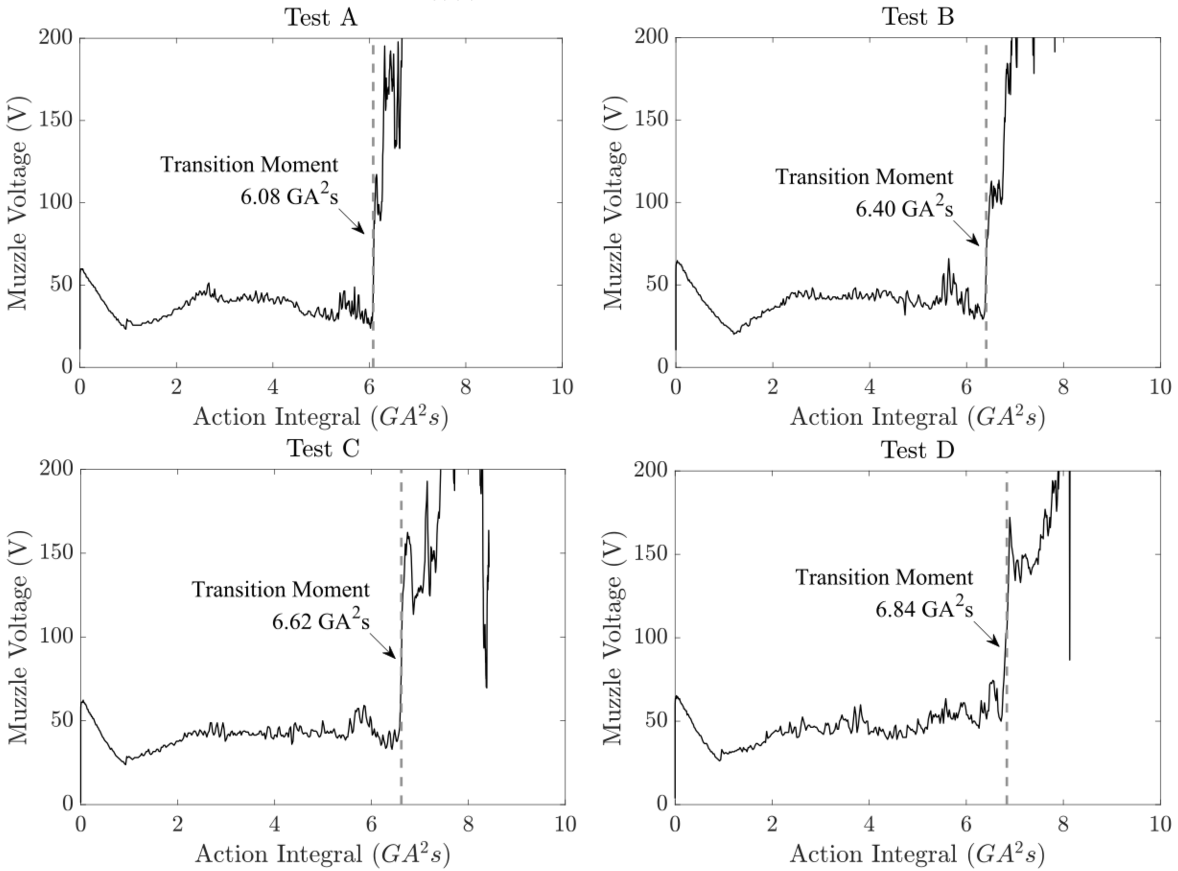


The Transition



$\frac{dI_{rail}}{dt} < 0$ increases R_c, may trigger transition

The complete transition does not depend solely on v, action integral, or I_{rail}.



Conclusion

1. $\mathrm{R_c}$ is dynamic due to phase change in $\mathrm{R_1}$, and it can be modelled with a simple sigmoid function.
2. $\mathrm{L_m}$ is constant in $\mathrm{R_1}$, and $\mathrm{R_2}$, and it can be exploited with 3-D FEA.
3. Muzzle voltage is not depend on the armature velocity at R_1, and R_2.
4. At R_2, R_c is constant as the sliding contact has stable liquid film $(25 - 30\ \mu\Omega)$.
5. -$\frac{dI_{rail}}{dt}$ enforces transition. However, there is no correlation % of I_{rail}.
6. The complete transition starting point does not depend on v, action integral or I_{rail}.

Discussion&Speculations

- Saying there is no velocity term in the muzzle voltage is big; contradicts with previous studied.
  - There can be still a velocity term but it can be negligible.
    - [1] has laminated steel containment, which can be amplified inductive term at VSE velocities.
    - EMFY-3 has non-conductive containment. (*the difference*)
- Saying there is no relation between $\frac{dI_{muzzle}}{dI_{rail}}$ and the transition contradicts with [4];
  - However we saw transition at 93% $\frac{dI_{muzzle}}{dI_{rail}}$.
- We said that there is sole correlation between transition point, and v, action integral, and $\frac{dI_{muzzle}}{dI_{rail}}$ but;
  - We saw a power correlation (Speculation!)

$$C = \Delta t_p \, (\Delta t_d)^{2.5}$$

Thank you for listening!

Any question?

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Thesis Work

N. Tosun *et al.*, "A Hybrid Simulation Model for Electromagnetic Launchers Including the Transient Inductance and Electromotive Force," in ***IEEE Transactions on Plasma Science***, vol. 48, no. 9, pp. 3220-3228, Sept. 2020, doi: 10.1109/TPS.2020.3016930.

N. Tosun *et al.*, "A Hybrid Simulation Model for Electromagnetic Launchers Including the Transient Inductance and Electromotive Force," in ***IEEE Transactions on Plasma Science***, vol. 48, no. 9, pp. 3220-3228, Sept. 2020, doi: 10.1109/TPS.2020.3016930.

H. Polat, N. Tosun, D. Ceylan and O. Keysan, "Optimization of a Convex Rail Design for Electromagnetic Launchers," in ***IEEE Transactions on Plasma Science***, vol. 48, no. 6, pp. 2266-2273, June 2020, doi: 10.1109/TPS.2020.2993785.

N. Tosun *et al.*, (2021): Bus Impact on the Inductance Distribution of Electromagnetic Launchers. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.15370881.v1

N. Tosun *et al.*, (2021): Inductance Gradient Calculations of EMFY-3 Electromagnetic Launcher. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.15372999.v1

Submitted to the IEEE Transactions on Plasma Science

N. Tosun *et al*. (2020): Electromagnetic Launcher Speed Control with a Multilevel Fast Triggering Time Algorithm (MFTTA). TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.13011512.v1

You have been invited to the thesis defend.

@ Tue 7 Sept 2021 13:40 - 16:30 (TRT)

Other Work

N. Tosun, E. Sert, E. Ayaz, E. Yılmaz and M. Göl, "Solar Power Generation Analysis and Forecasting Real-World Data Using LSTM and Autoregressive CNN," *2020 International Conference on Smart Energy Systems and Technologies (SEST)*, 2020, pp. 1-6, doi: 10.1109/SEST48500.2020.9203124.

References

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- [2] Y. Dreizin and J. Barber, “On the origins of muzzle voltage,” IEEE Transactions on Magnetics, vol. 31, no. 1, pp. 582–586, 1995.
- [3] L. Chen, J. He, Y. Pan, and Z. Xiao, “Muzzle voltage of railgun in zero velocity and launch experiments,” in 2008 14th Symposium on Electromagnetic Launch Technology, 2008, pp. 1–5.
- [4] S. Satapathy and H. Vanicek, “Down-slope contact transition in railguns,” IEEE Transactions on Magnetics, vol. 43, no. 1, pp. 402–407, 2007.