Computer Simulation of Tunneling Characteristics of Superconducting Nanostructures

Bogoliubov Laboratory of Theoretical Physics (BLTP)

Asmaa Mahmoud Abdelazim
Ain Shams University
Mohamed Gamal Ahmed Elsheikh
Port Said University
Mohamed Mahmoud Ali Ahmed
Assiut University
Heba Reda Abdalaal Mansour
Assiut University

Supervised by
Prof. Dr. Yu. M. Shukrinov
Assistant supervisor: Dr. M. Nashaat

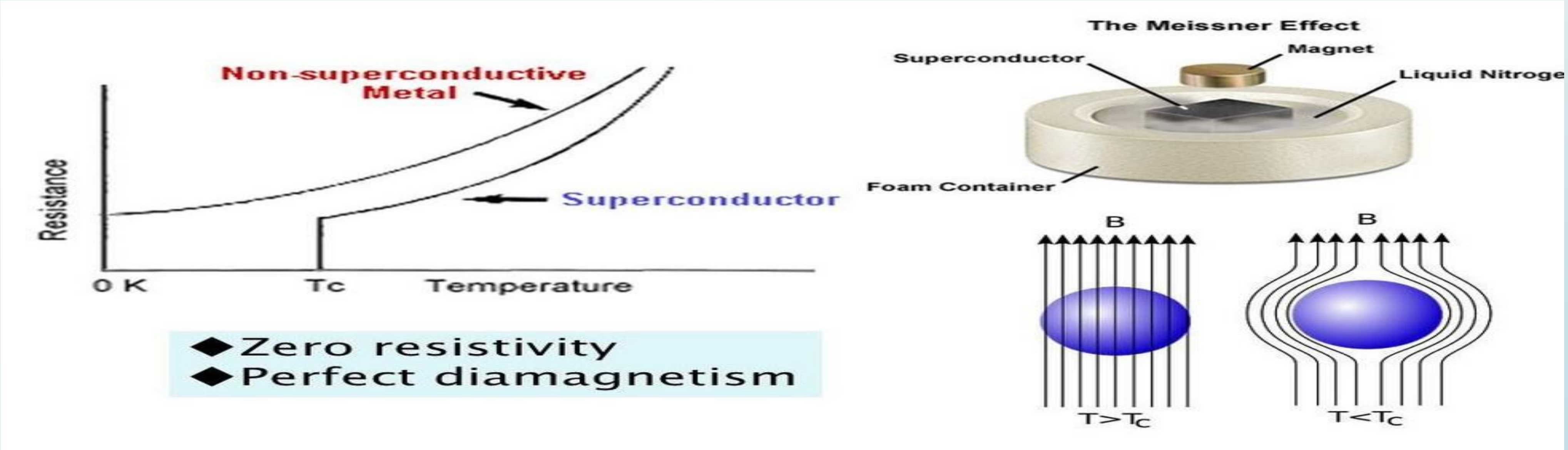
Outline

- Superconductivity
- Josephson Junction
- Application of Josephson Junction
- Modeling of Shunted Josephson Junction
- Results
- Conclusion

Superconductivity

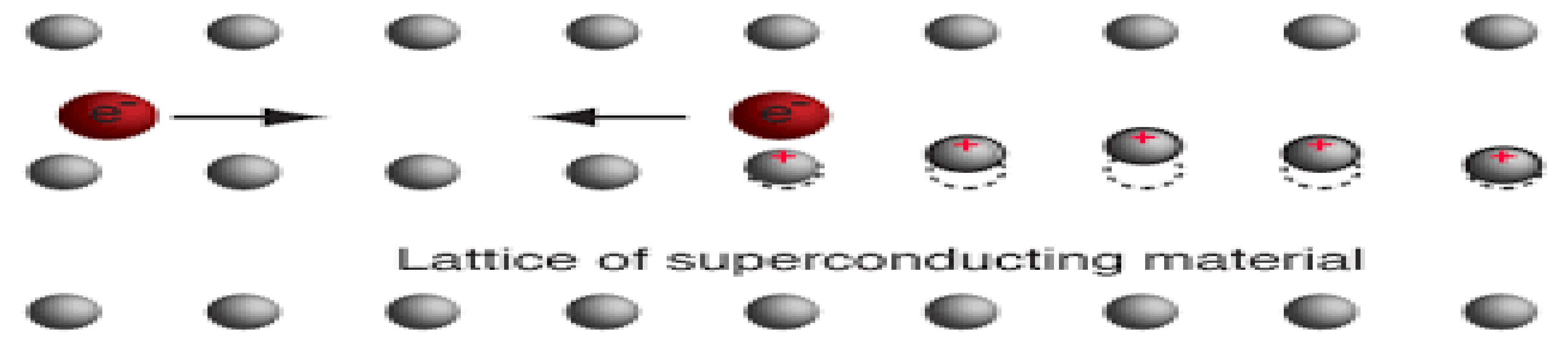
- Superconductivity is the property of certain materials to conduct direct current (DC) electricity without energy loss when they are cooled below a critical temperature (referred to as Tc).

- These materials also expel magnetic fields as they transition to the superconducting state.



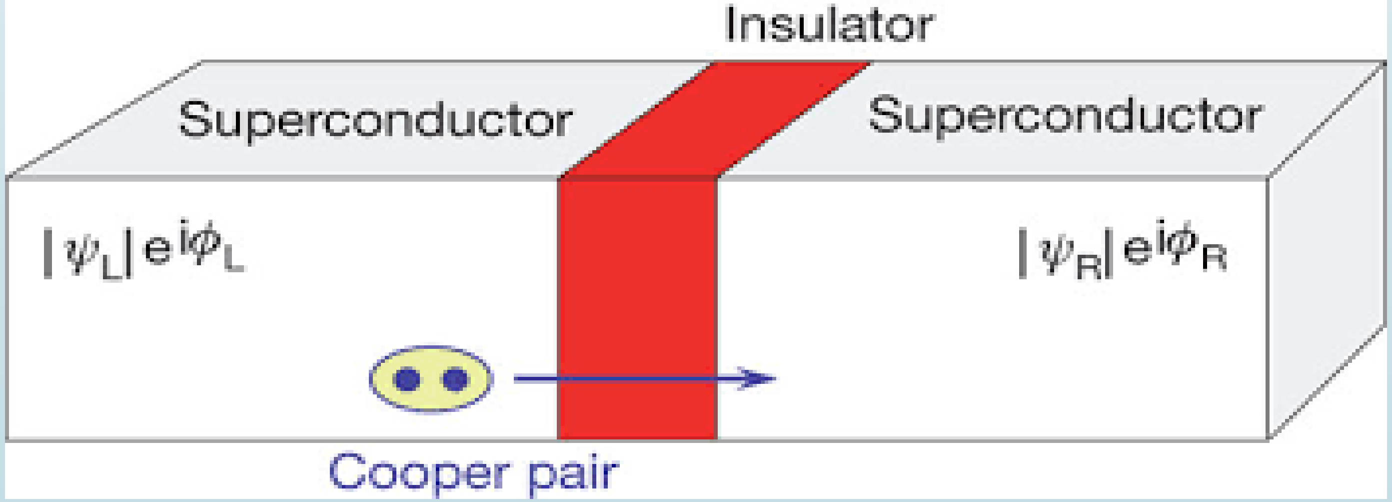
Superconductivity

- No classical interpretation.
- Phonon, electron interaction.
- Cooper pairs (bound state).
- Cooper pairs are bosons with zero spin.
- At low temperature, cooper pairs at their lowest energy form Bose-Einstein condensate state.
- They could be described by single wave function.



Josephson Junction

- A Josephson junction is made by sandwiching a thin layer of a non-superconducting material between two layers of superconducting material.
- The devices are named after Brian Josephson, who predicted in 1962 that pairs of superconducting electrons could "tunnel" right through the non-superconducting barrier from one superconductor to another.
- The overlapping between the wave functions leads to AC and DC currents.



Josephson Junction

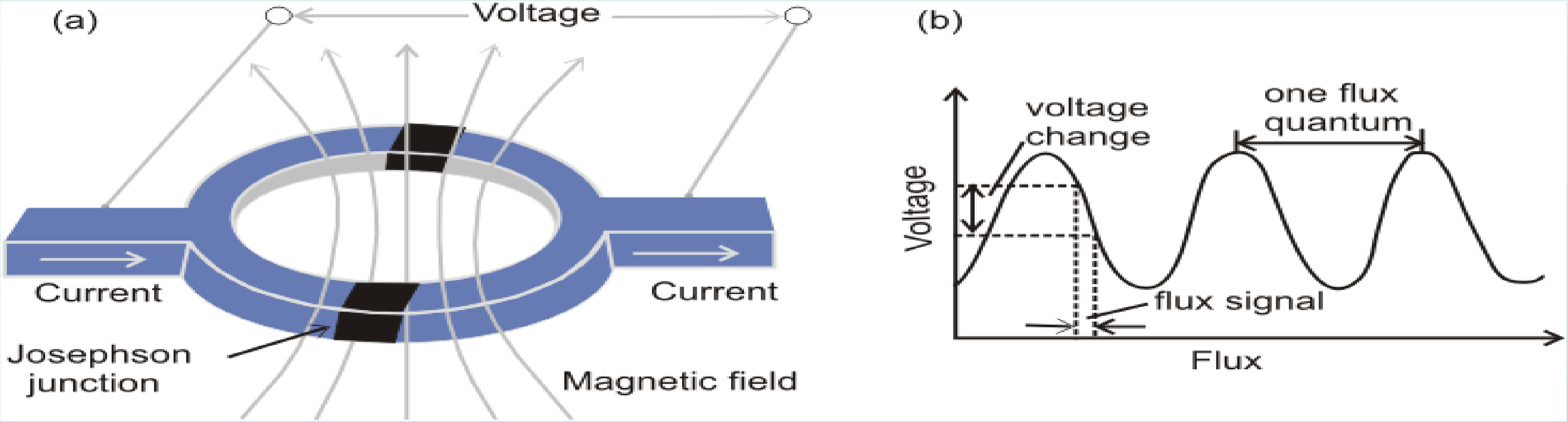
- The DC Josephson current is proportional to the phase difference between the two superconductors wave functions.

$$I_s = I_c \sin(\varphi)$$

- If the phase difference between the two superconductors wave functions varies with time due to applying a voltage on JJ, then an AC superconducting current appears.
- The frequency *f* of the AC Josephson current is proportional to the voltage *V* applied across the junction.

Application of Josephson Junction: SQUID

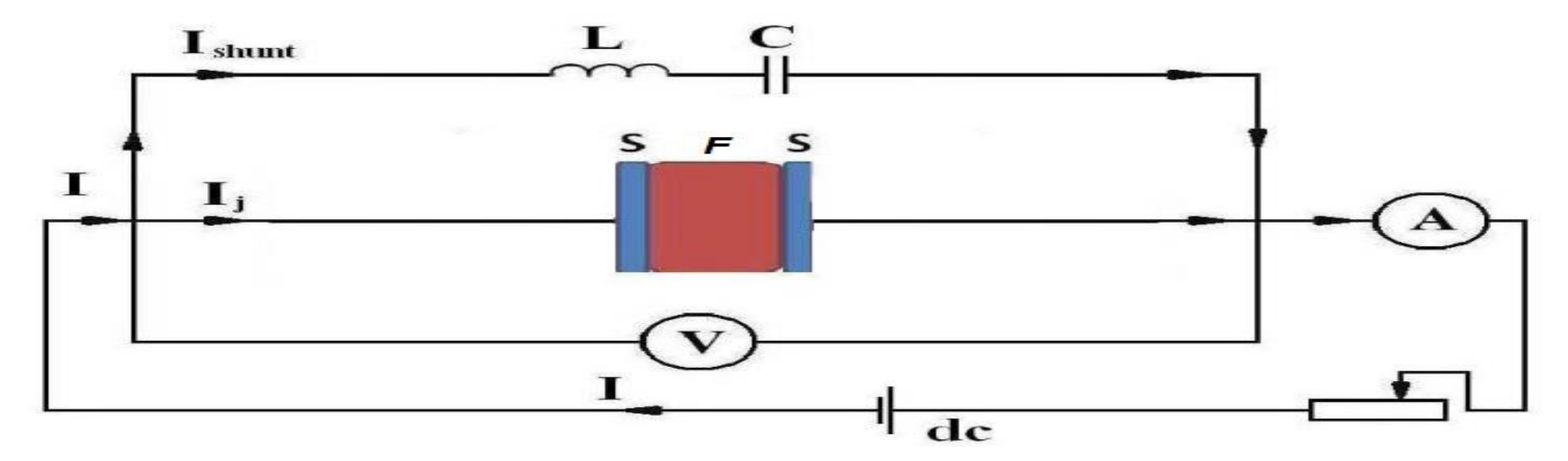
- Determining the subtle magnetic (5×10^{-14} Tesla) flux using a Superconducting quantum interface device (SQUID).
- SQUID is forming by passing a current to two connected JJ's in parallel, the Voltage across the enclosed circuit is very sensitive to the magnetic flux passing normally to it.



Application of Josephson Junction: Qubit

- Qubit: Two-state quantum mechanics system.
- One type of qubit is called charge qubit, where either we have cooper pairs (first state) or the cooper pairs are destroyed (second state).
- It is effective that the change between the two states happens with high frequency.

Modeling of Shunted Josephson Junction



Superconductors Current I_s ⟶ $I_s = I_c \sin(\varphi - r m_y)$

Displacement Current I_{disp} ⟶ $I_{disp} = C\frac{dV}{dt}$

Quasiparticle Current I_{qp} ⟶ $I_{qp} = \frac{V}{R} + r\frac{dm_y}{dt}$

- We study the effect of a parallel LC circuit on the JJ, $\omega_{rc} = \sqrt{\frac{1+C}{LC}}$.

Modeling of Shunted Josephson Junction

Landau-Lifshitz-Gilbert Equations

$$\frac{dm_x}{dt} = -\frac{\omega_F}{1+\alpha^2 m^2}\{(m_y h_z - m_z h_y) - \alpha[m_x(m_x h_x + m_y h_y + m_z h_z) - h_x m^2]\}$$

$$\frac{dm_y}{dt} = -\frac{\omega_F}{1+\alpha^2 m^2}\{(m_z h_x - m_x h_z) - \alpha[m_y(m_x h_x + m_y h_y + m_z h_z) - h_y m^2]\}$$

$$\frac{dm_z}{dt} = -\frac{\omega_F}{1+\alpha^2 m^2}\{(m_x h_y - m_y h_x) - \alpha[m_z(m_x h_x + m_y h_y + m_z h_z) - h_z m^2]\}$$

where, $h_x = 0,\ h_y = r\,G\,sin(\varphi - r\,m_y), h_z = m_z$

r *is* spin orbit coupling between Josephson current and magnetization.

G is the ratio between the Josephson junction energy and the magnetic energy of the ferromagnetic material.

Modeling of Shunted Josephson Junction

Evolution the Voltage Across JJ

$$\frac{dV}{dt} = I - \beta\left\{\left(\frac{d\varphi}{dt} - r\frac{dm_y}{dt}\right) - sin(\varphi - rm_y) - C\frac{du_c}{dt}\right\}$$

Dissipation factor

Phase difference between superconductors

Equations of the Shunting Circuit

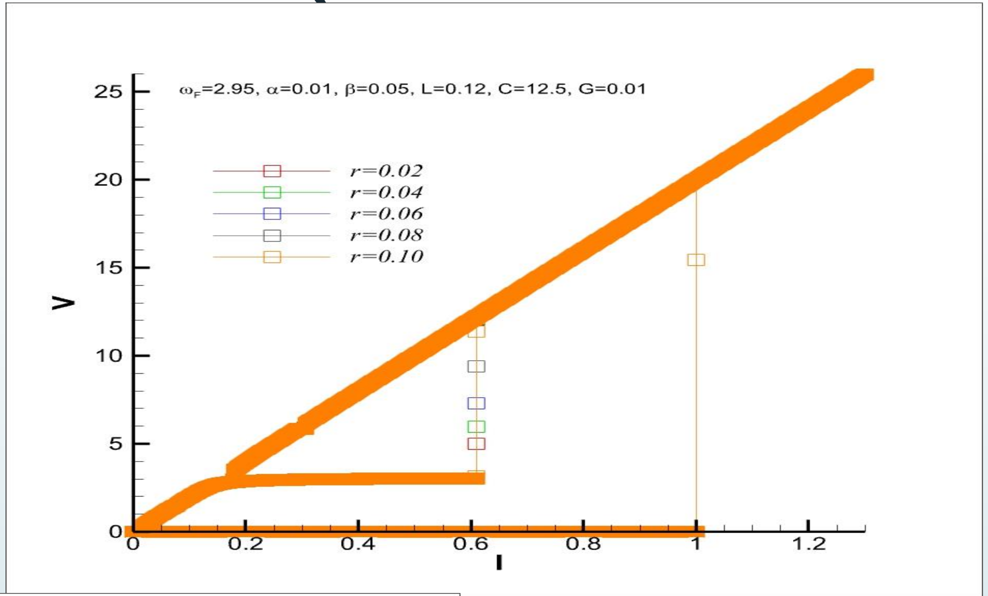
$$\frac{du_c}{dt} = U$$

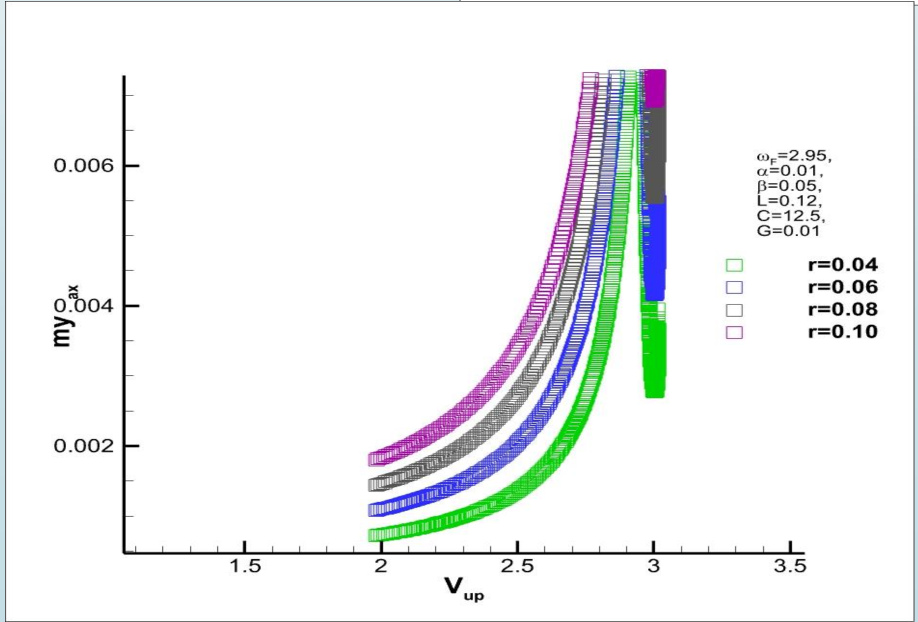
$$\frac{dU}{dt} = \frac{1}{LC}(V - u_c)$$

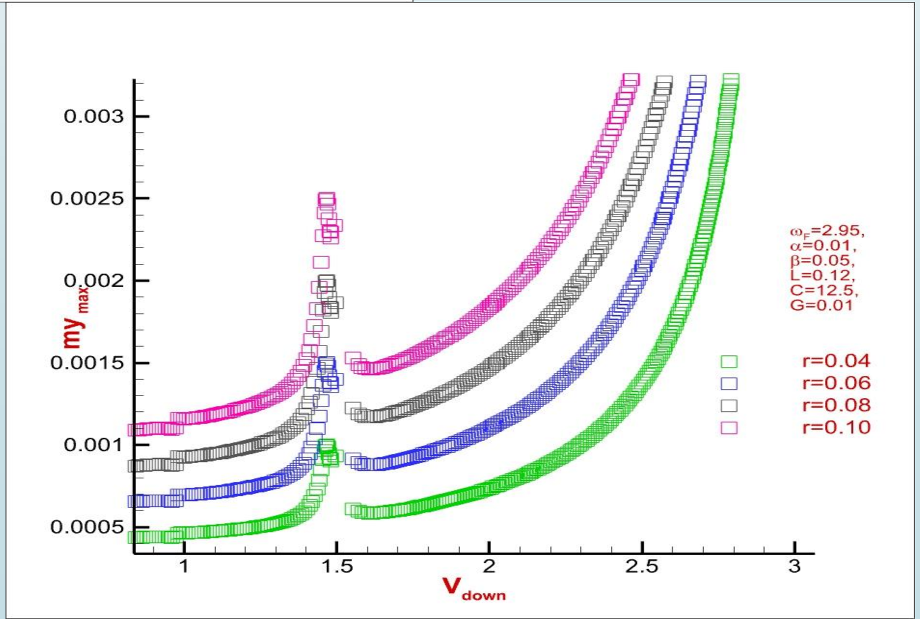
Time Dependence of Phase Shift

$$\frac{d\varphi}{dt} = V$$

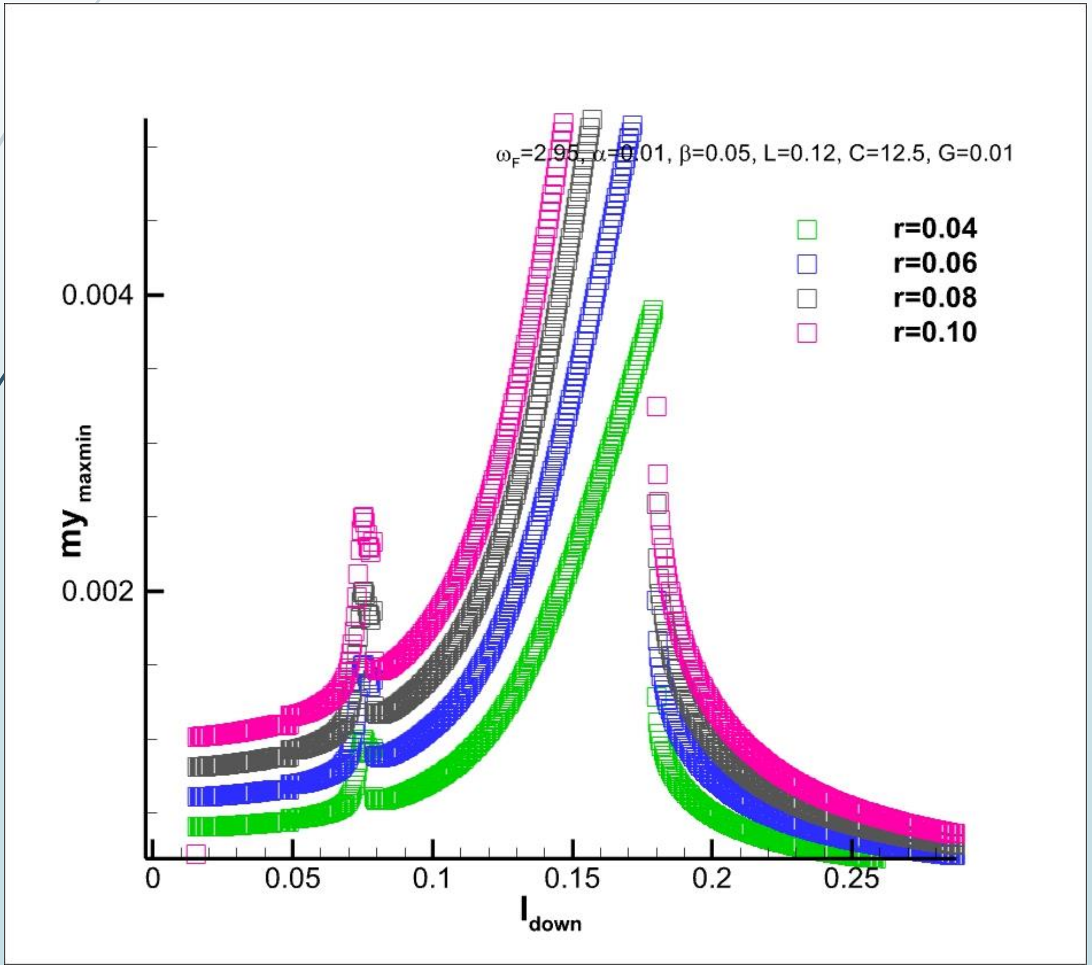
Numerical Results (Effective Parameter *r*)

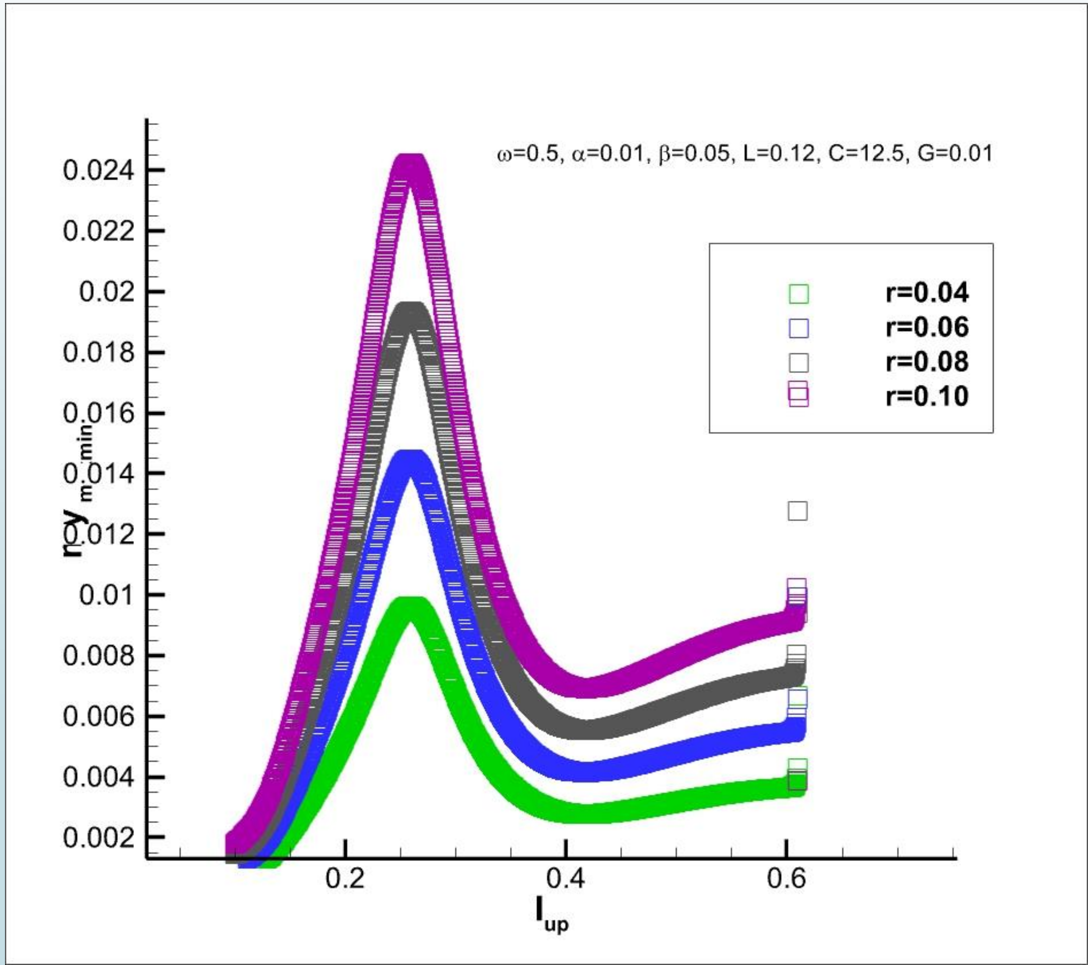




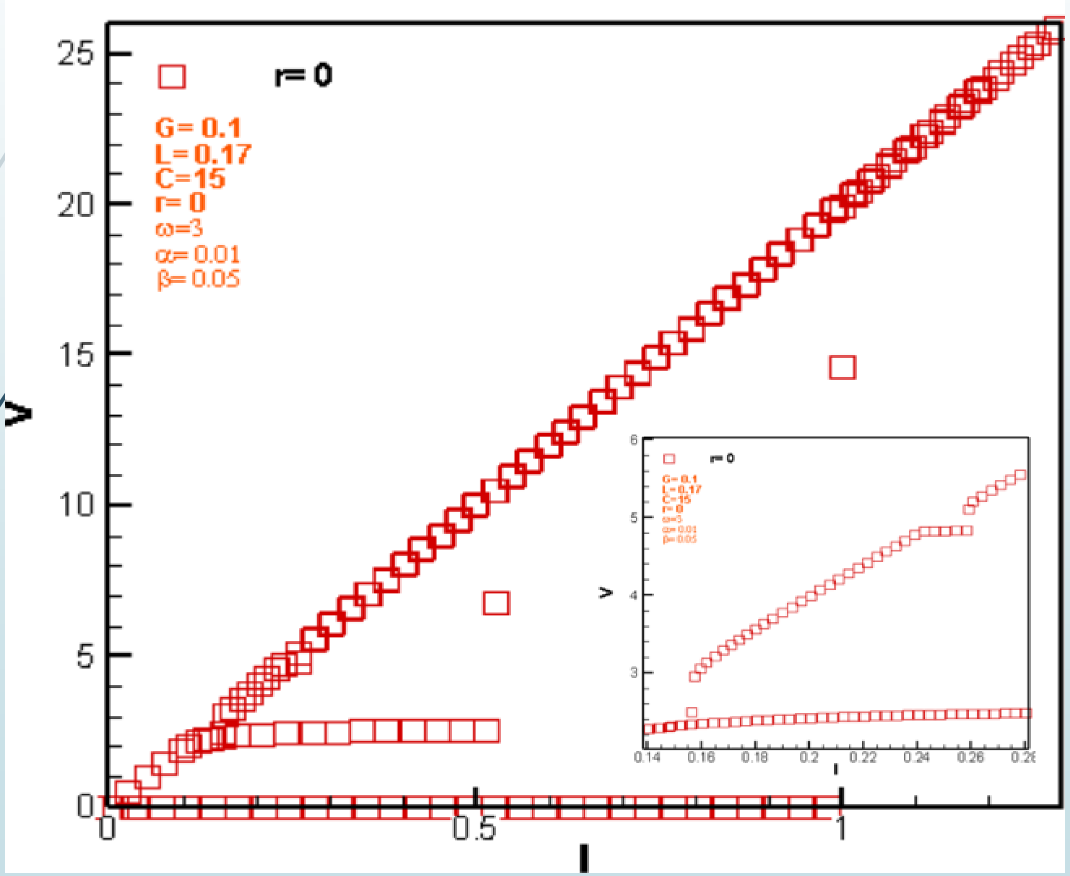


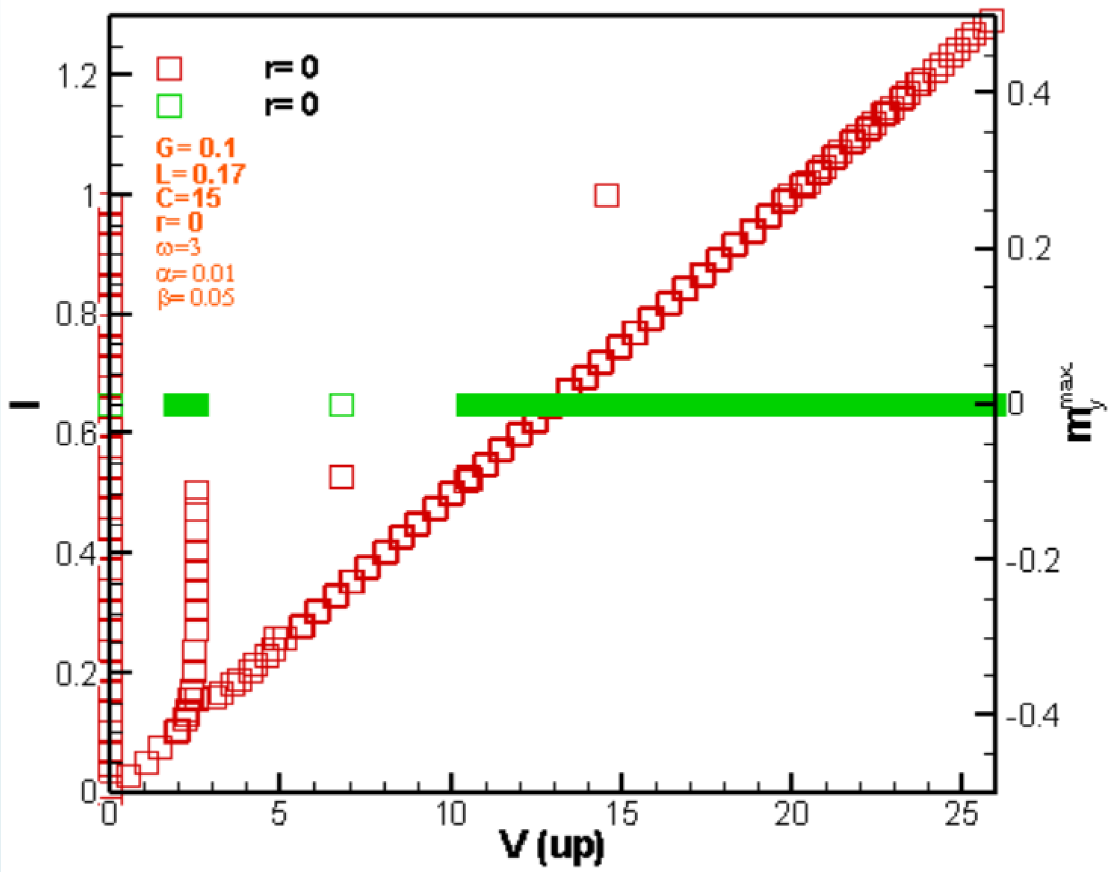
Numerical Results (Effective Parameter *r*)



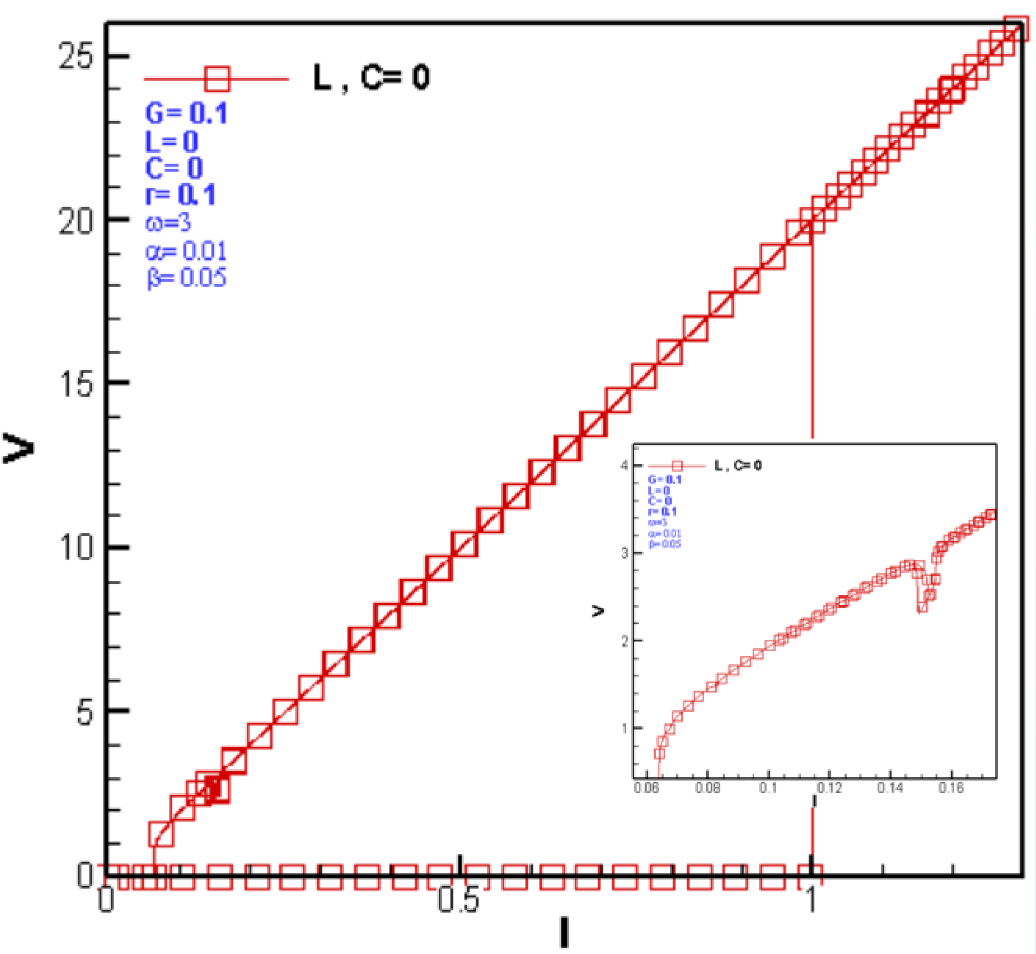


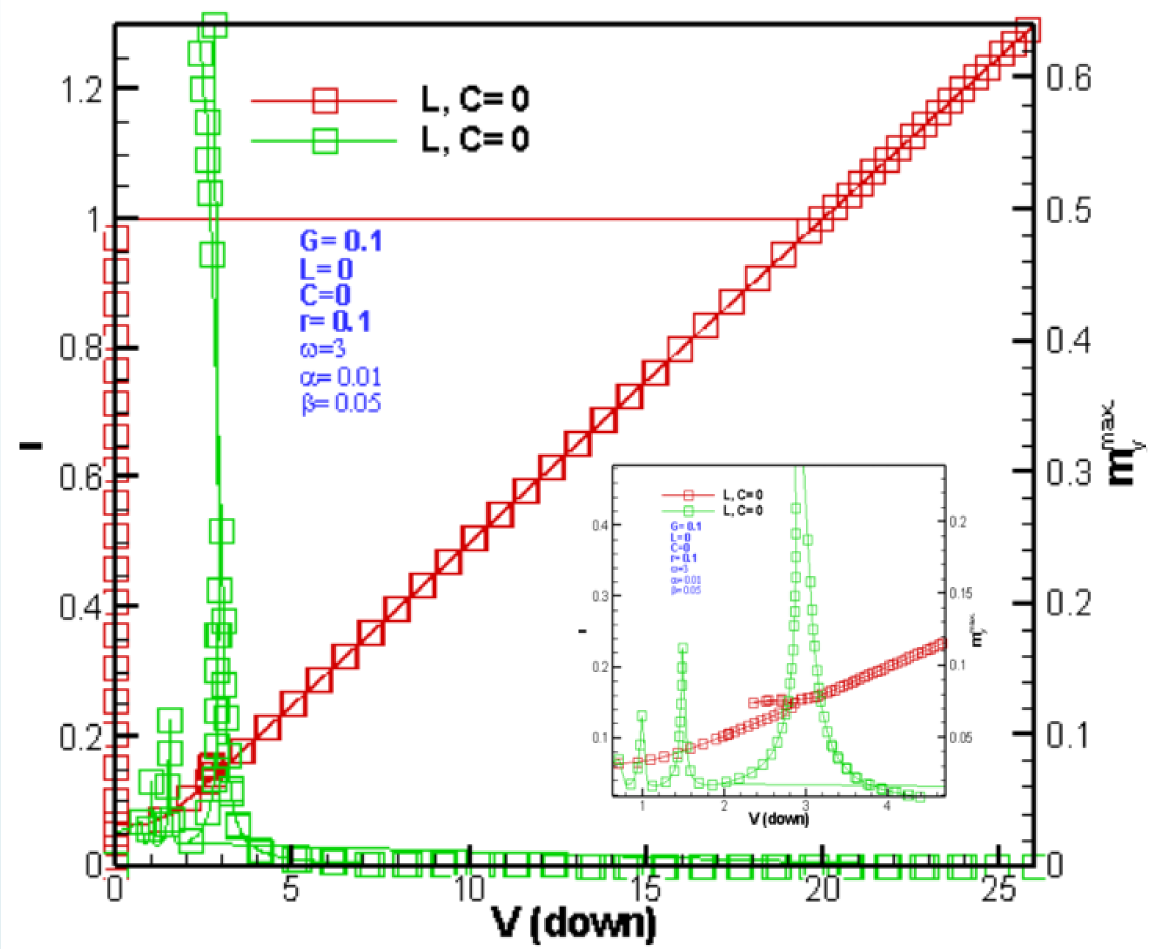
Numerical Results (Effective Parameter $r = 0$)





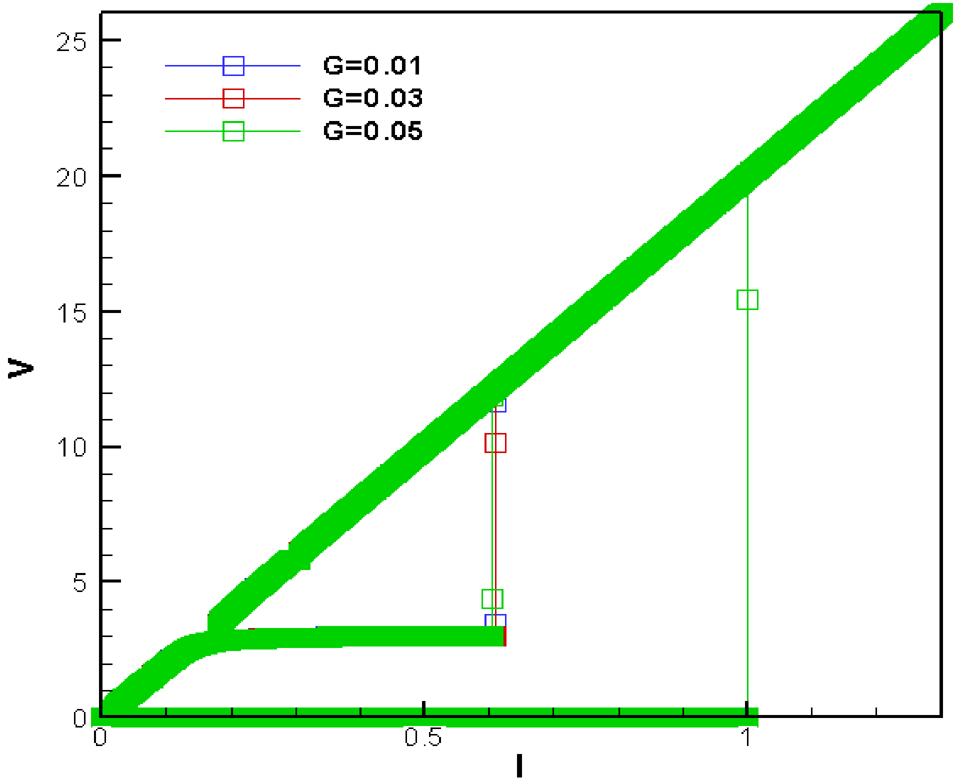
Numerical Results (without shunting $L = C = 0$)

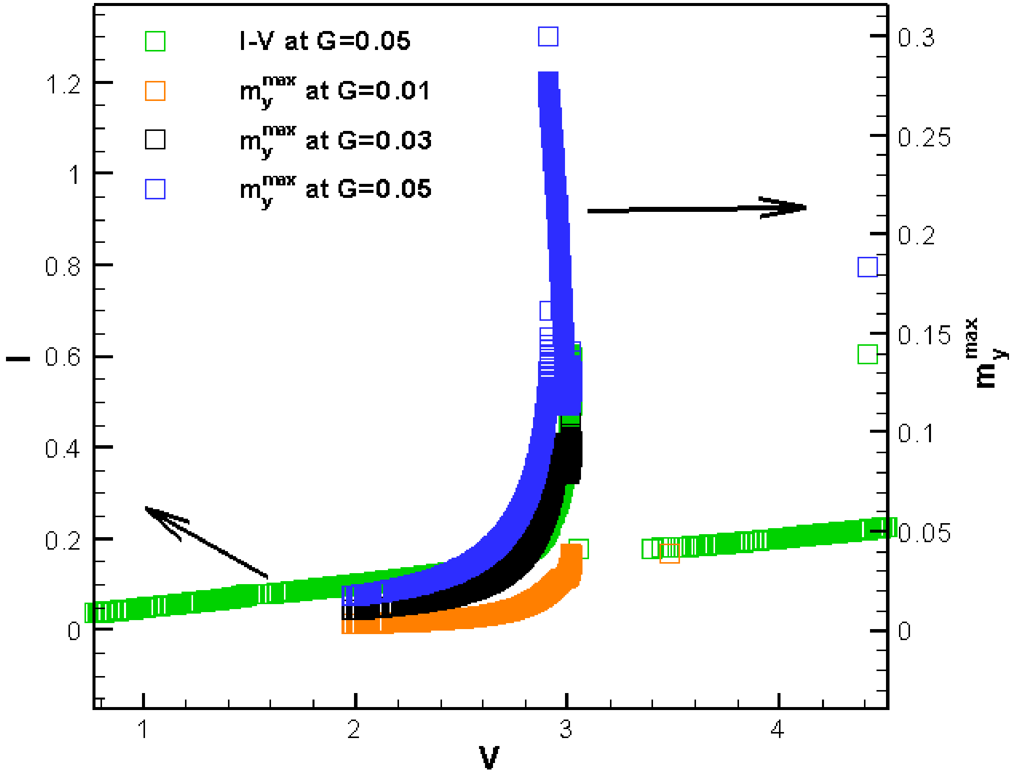




Numerical Results (Effective Parameter G)

$\beta = 0.05,\ L = 0.12,\ C = 12.5,\ r = 0.2,\ \alpha = 0.01,\ \omega_{rc} = \omega_F = 3$

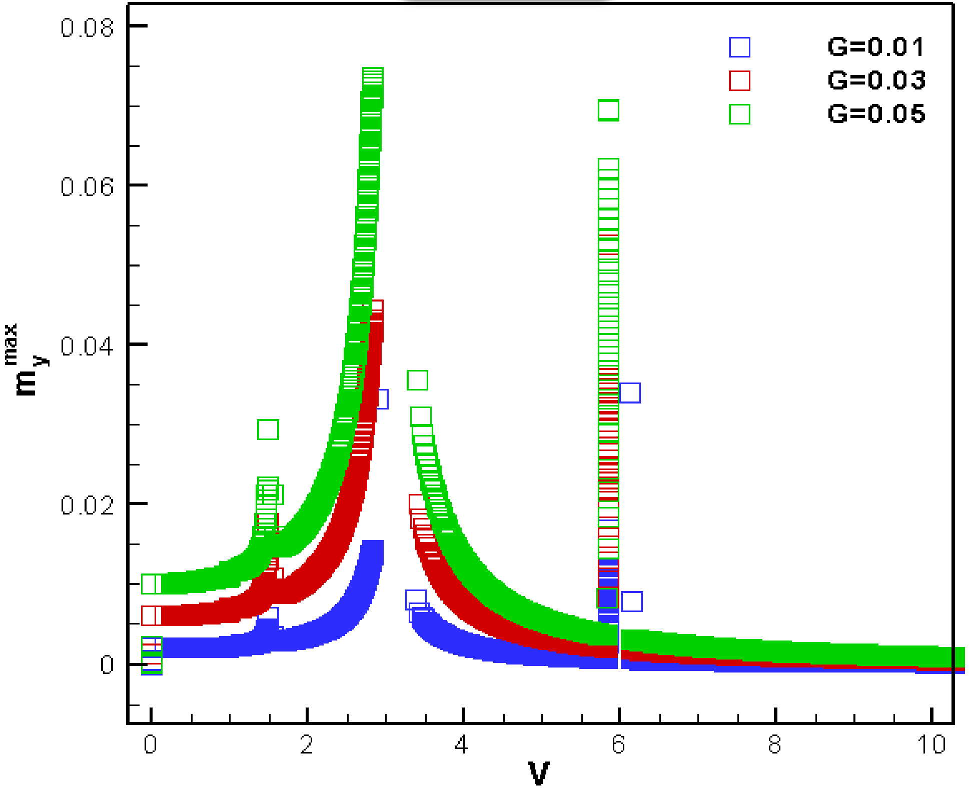




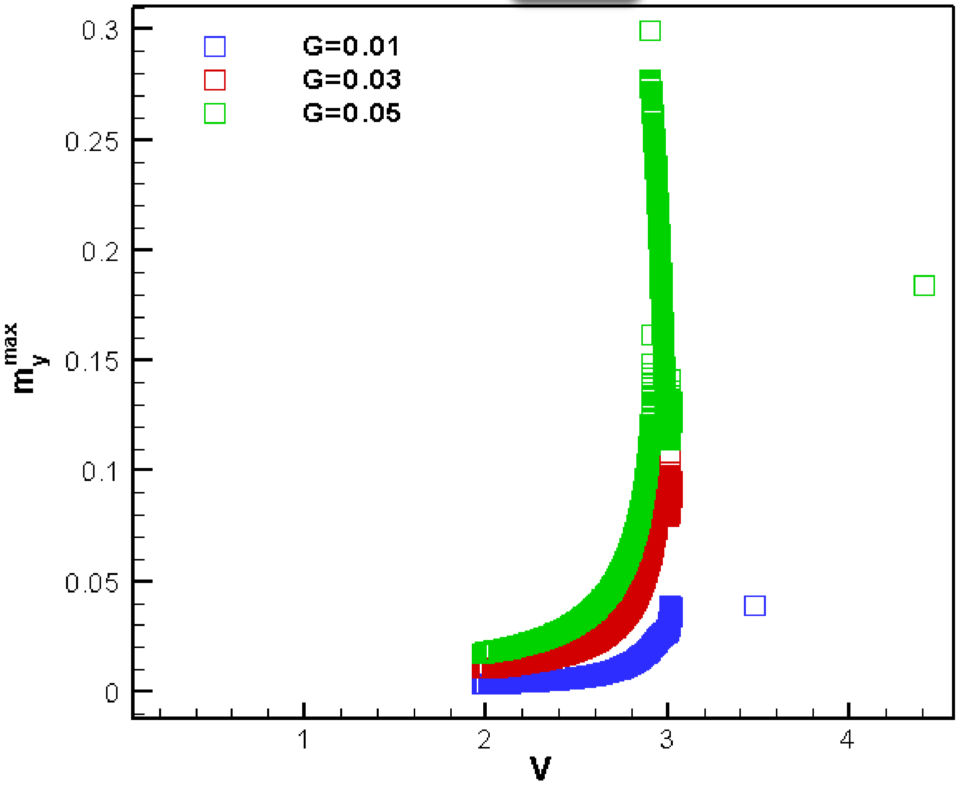
Numerical Results (Effective Parameter G)

$\beta = 0.05,\ L = 0.12,\ C = 12.5,\ r = 0.2,\ \alpha = 0.01,\ \omega_{rc} = \omega_F = 3$

Down

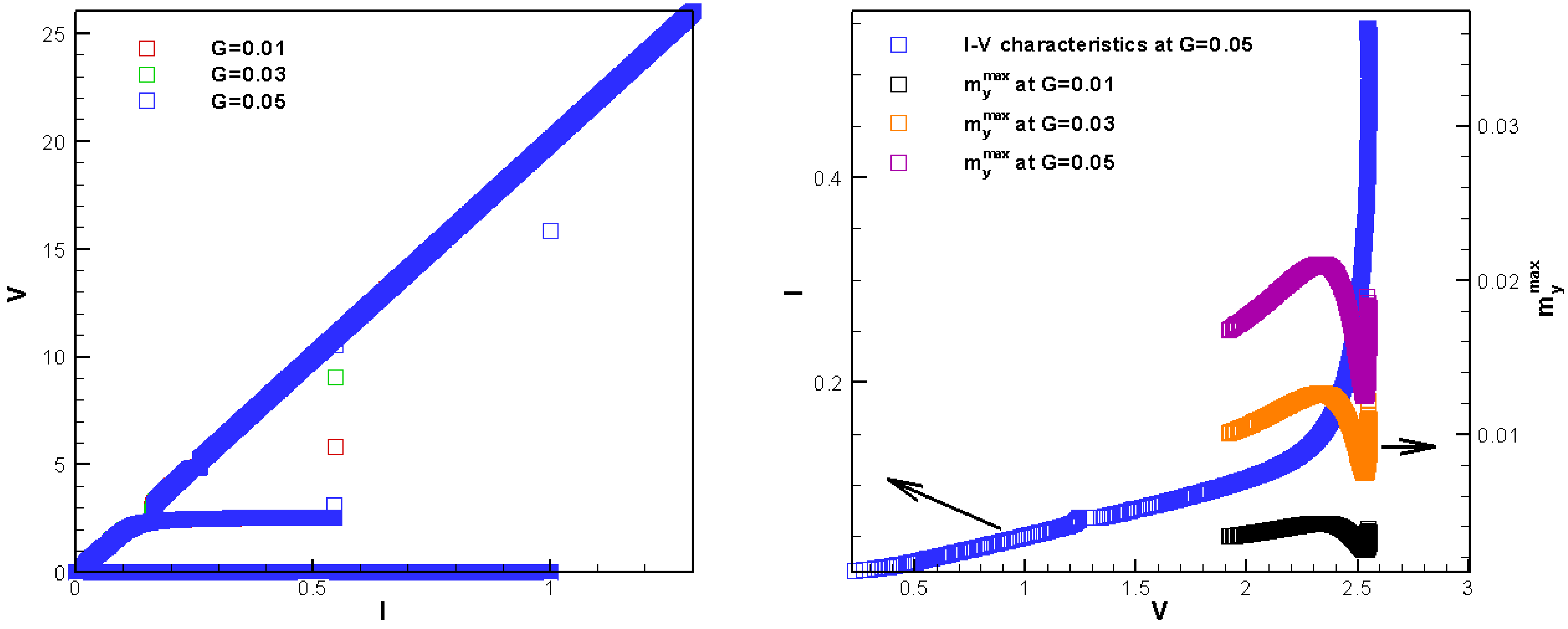


Up



Numerical Results (Effective Parameter G)

$\beta = 0.05,\ L = 0.17,\ C = 11.5,\ r = 0.2,\ \alpha = 0.01,\ \omega_{rc} = 2.5, \omega_F = 3$



Conclusion

- We got a background about Josephson junction and its applications.
- We have learned how to model and simulate a set of nonlinear differential equations.
- We became familiarized with the language of C++.
- Our study describe I-V characteristics curves at different values of r and G,and ω_{rc}.
- There is no variation noted in I-V characteristic curve as a result of variation of the spin-orbital coupling r.

Conclusion

- We noted that the behavior of I-V characteristics curves doesn’t change, but the value of the branch resonance varies with ω_{rc}.
- The resonance frequency of magnetic moment appears at the resonance frequency of LC shunting circuit.
- According to magnetic moment with voltage and with current in both directions up and down, it is noted that the maximum value of magnetic moment increased with increasing r.
- From our study on Josephson junction, we can manipulation of maximum amplitude value of magnetic moment and its direction.


THE COUTURE
TRAVELING TO
SIBERIA

Thanks for Listening