Analysis of preload effect in the axisymmetric damped steel wire using ultrasonic guided wave monitoring

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Introduction:

- ✓ Guided ultrasonic wave propagation characteristics in the axisymmetric prestressed viscoelastic waveguide for acoustic emission (AE) monitoring - semi-analytical finite element (SAFE) method is studied broadly.

- ✓ In this research, the development and results of a method to calculate the characteristics of guided waves in a wire, with the motivation of applications to AE monitoring is presented.

- ✓ The axisymmetric SAFE method is used to study wave properties of a cylindrical waveguide, especially, a high strength steel wire.

- ✓ This study considers the impact of two common factors, structural damping, and initial tensile stress, on the propagation characteristics.

- ✓ A mode suitable for cable AE monitoring is carefully chosen - longitudinal wave modes in the high-frequency region show their potential

A SAFE method for undamped waveguide

The mathematical framework for an infinitely long, axisymmetric waveguide immersed in a vacuum is represented using the semi-analytical method

$$\boldsymbol{u} = \begin{bmatrix} u_r & u_\theta & u_z \end{bmatrix}^T$$

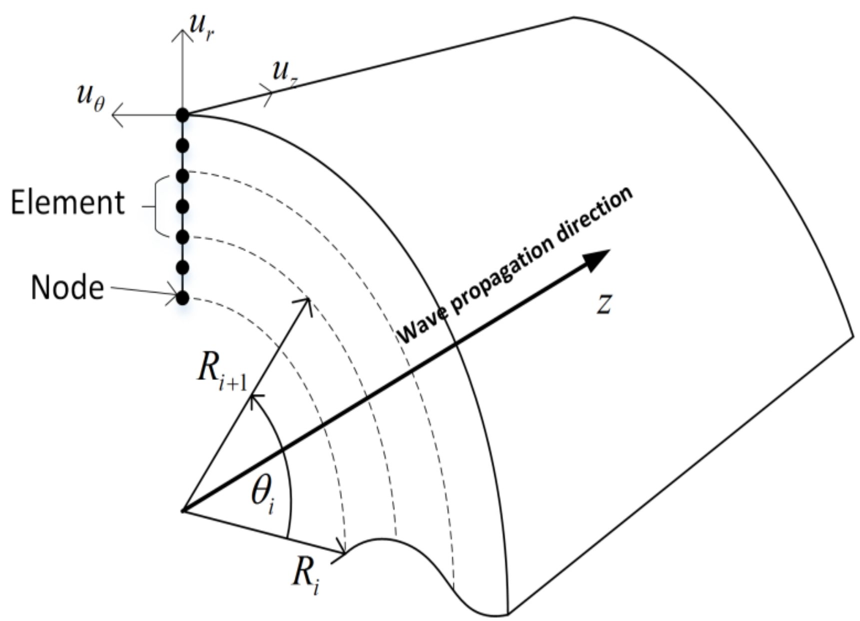
$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_r & \varepsilon_\theta & \varepsilon_z & \gamma_{r\theta} & \gamma_{\theta z} & \gamma_{zr} \end{bmatrix}^T$$

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_r & \sigma_\theta & \sigma_z & \tau_{r\theta} & \tau_{\theta z} & \tau_{zr} \end{bmatrix}^T$$

$$\boldsymbol{u}^j = \begin{bmatrix} \boldsymbol{N}_1(r,\theta) & \boldsymbol{N}_2(r,\theta) & \boldsymbol{N}_3(r,\theta) \end{bmatrix} \begin{bmatrix} \bar{\boldsymbol{U}}_1{}^j \\ \bar{\boldsymbol{U}}_2{}^j \\ \bar{\boldsymbol{U}}_3{}^j \end{bmatrix} \exp(ikz - i\omega t)$$

$$\boldsymbol{N}_m(r,\theta) = \begin{bmatrix} N_m(r)\cos(n\theta) & & \\ & N_m(r)\sin(n\theta) & \\ & & iN_m(r)\cos(n\theta) \end{bmatrix}$$

SAFE model



$$\bar{\boldsymbol{U}}_m{}^j = \begin{bmatrix} U_{rm} & U_{\theta m} & U_{zm} \end{bmatrix}^T$$

$$\boldsymbol{\varepsilon}^j = \begin{bmatrix} \boldsymbol{B}_1 & \boldsymbol{B}_2 & \boldsymbol{B}_3 \end{bmatrix} \bar{\boldsymbol{U}}^j \exp(ikz - i\omega t)$$

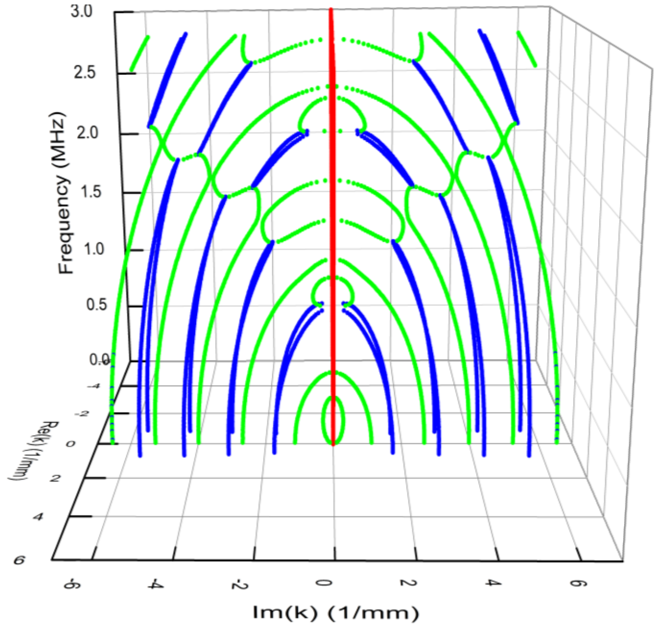
Wavenumber-frequency curve analysis for undamped waveguide

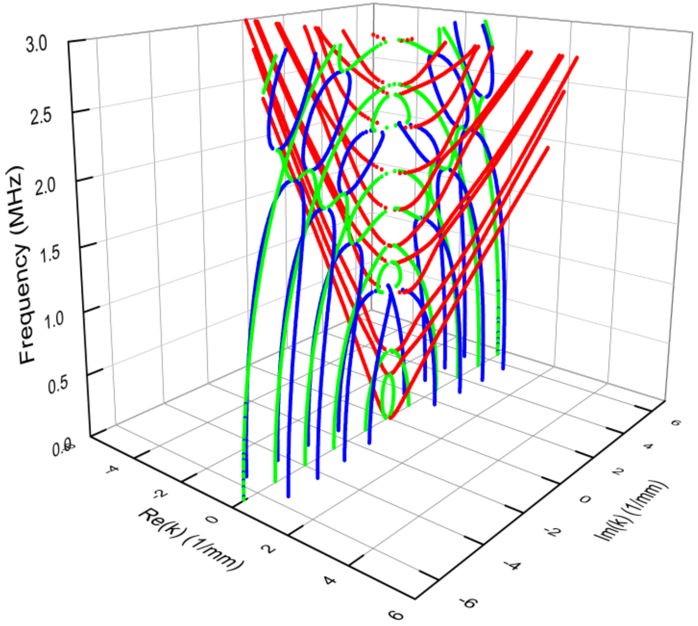
- The solution of transcendental equations and the general semi-analytic method is used to obtain the wavenumber-frequency curve in the positive wavenumber domain.

- In this research, high-strength steel wire with a diameter of 5 mm is considered for numerical investigations.

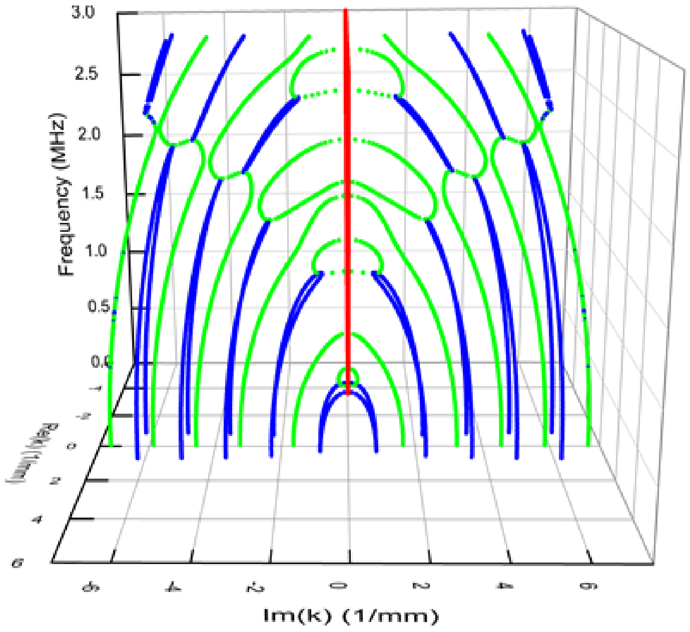
Young's Modulus, E (MPa)	Density, ρ (kg/m^3)	Poisson's ration, ν	Diameter, d (mm)	Longitudinal wave velocity, C_L (m/s)	Shear wave velocity, C_S (m/s)
2×10^5	**7850**	**0.3**	**5**	**5856.4**	**3130.4**

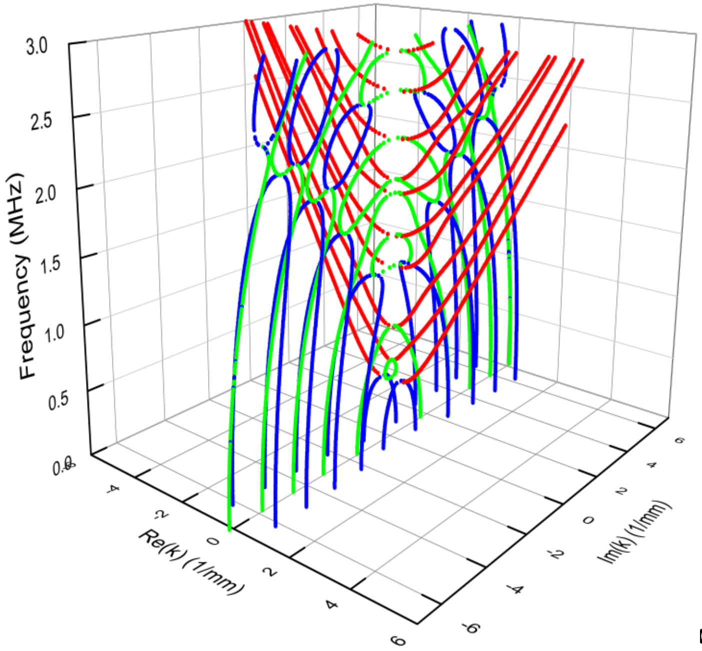
Complex $k-\omega$ curves for undamped waveguide





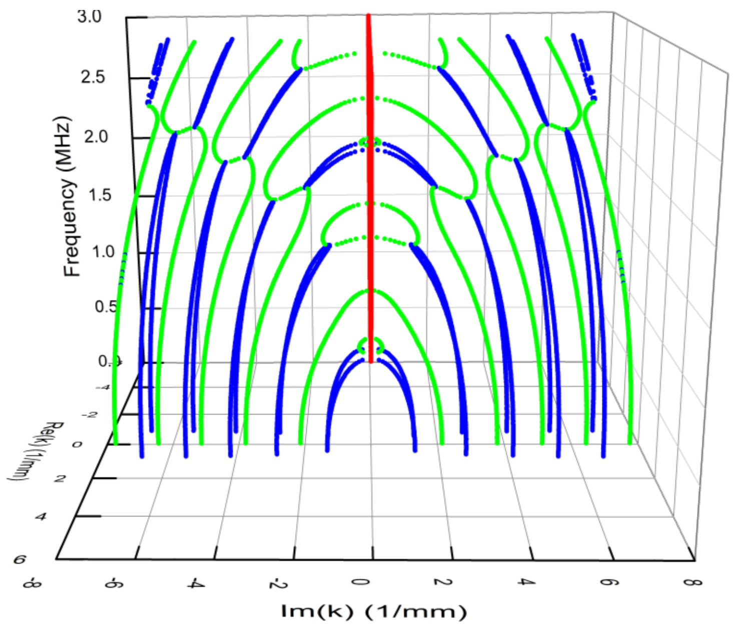
$F(1,m)$ mode complex $k-\omega$ curve

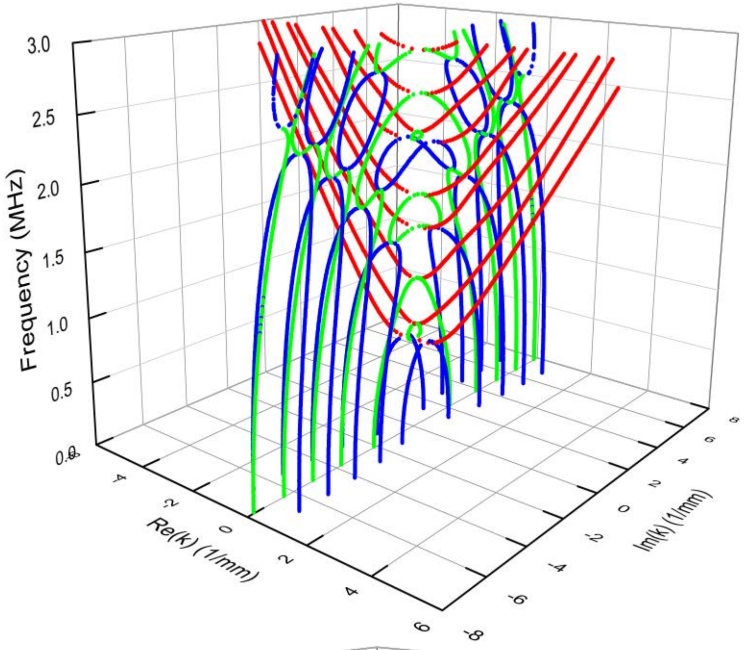




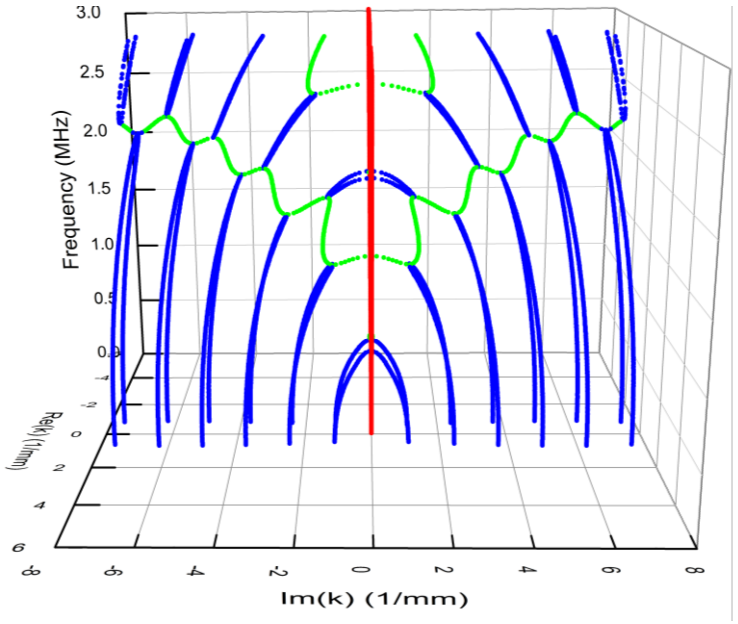
$F(2,m)$ mode complex $k-\omega$ curve

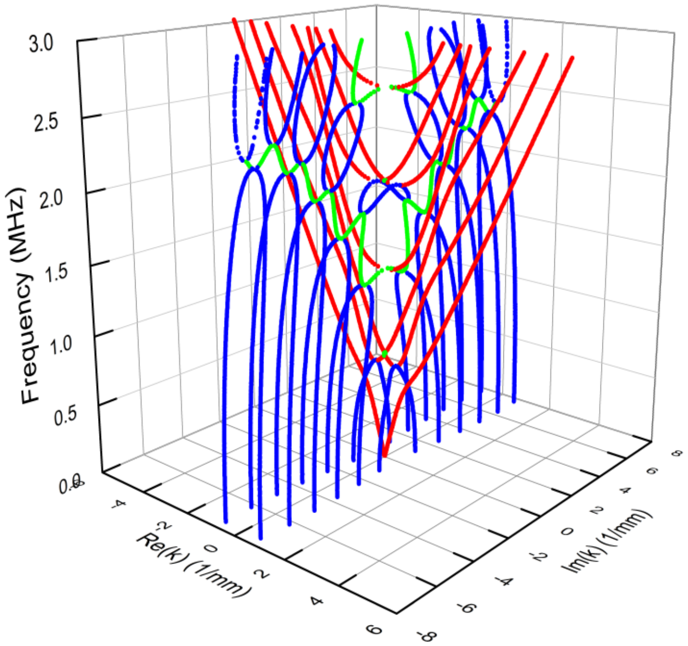
Complex $k-\omega$ curves for undamped waveguide





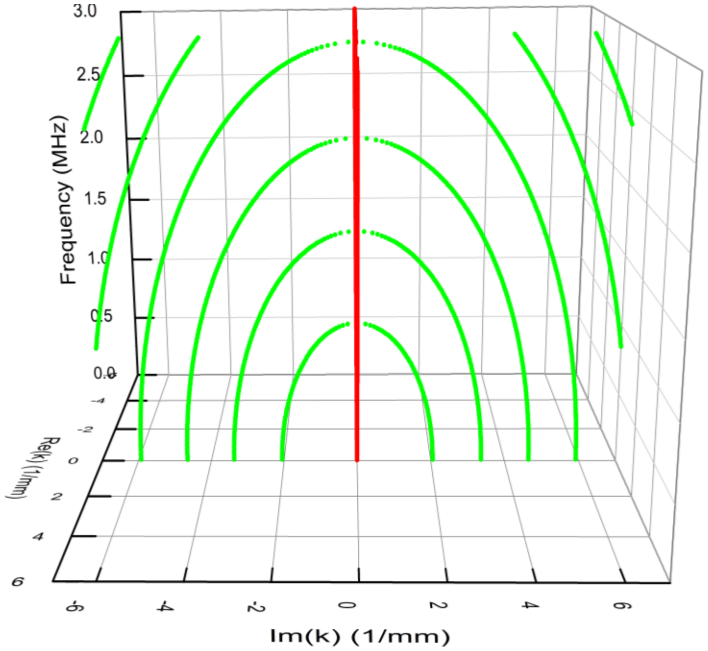
$F(3,m)$ mode complex $k-\omega$ curve

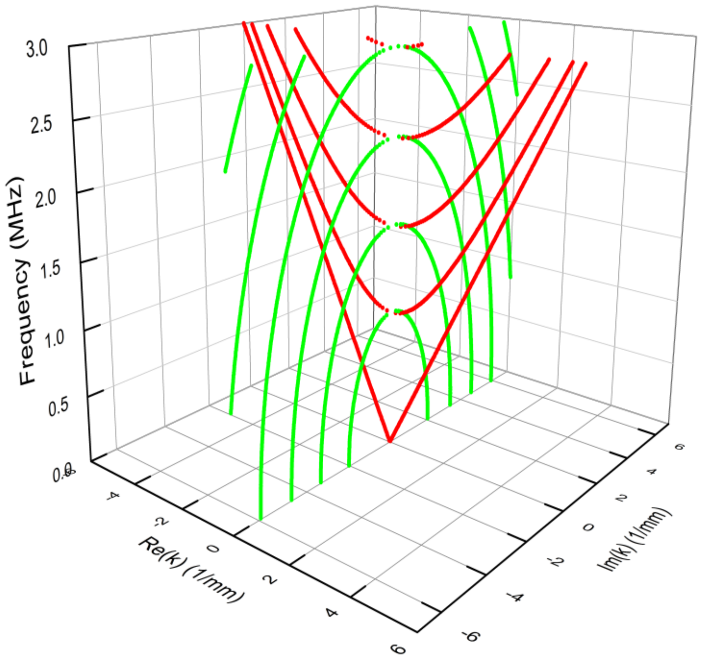




$L(0,m)$ mode complex $k-\omega$ curve

Complex $k-\omega$ curves for undamped waveguide





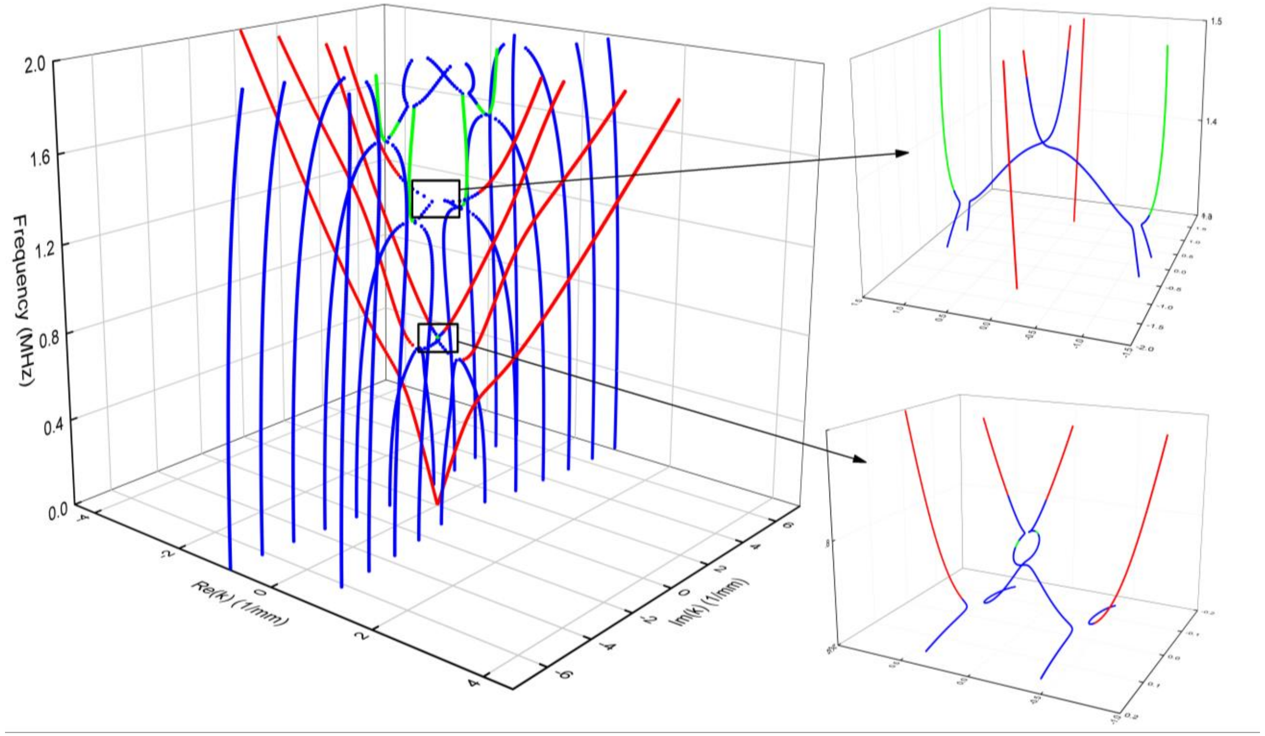
$T(0,m)$ mode complex $k-\omega$ curve

A SAFE method for damped waveguide

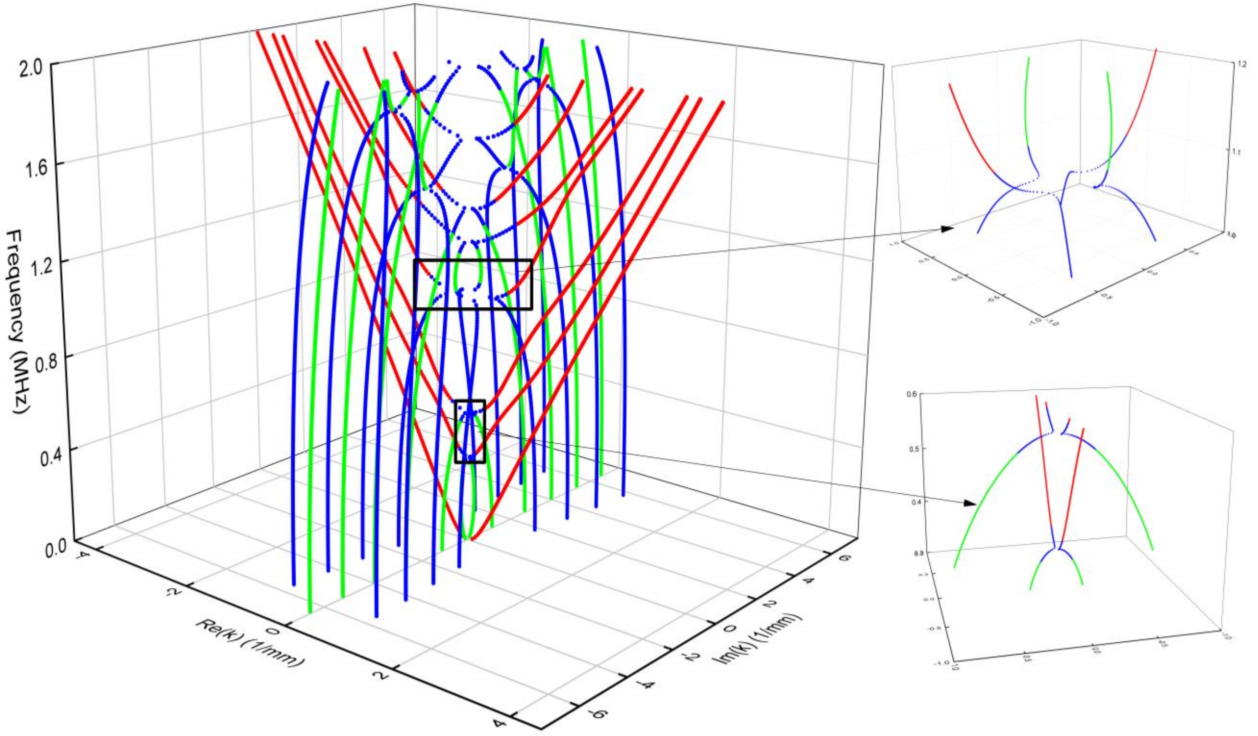
For time-harmonic wave, a linear viscoelastic material model can be simulated by including the imaginary component in the material stiffness matrix

$$\boldsymbol{D} = \boldsymbol{D}' - i\boldsymbol{D}''$$

Complex $k-\omega$ curve for damped waveguide



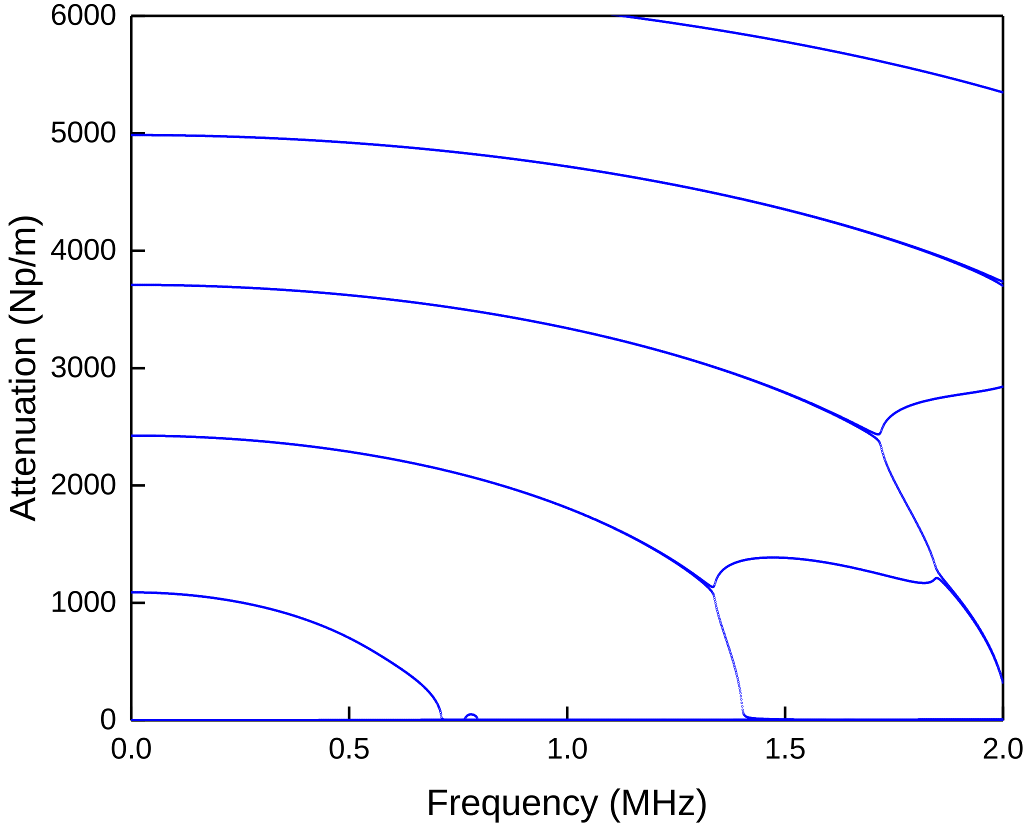
$L_d\left(0,m\right)$



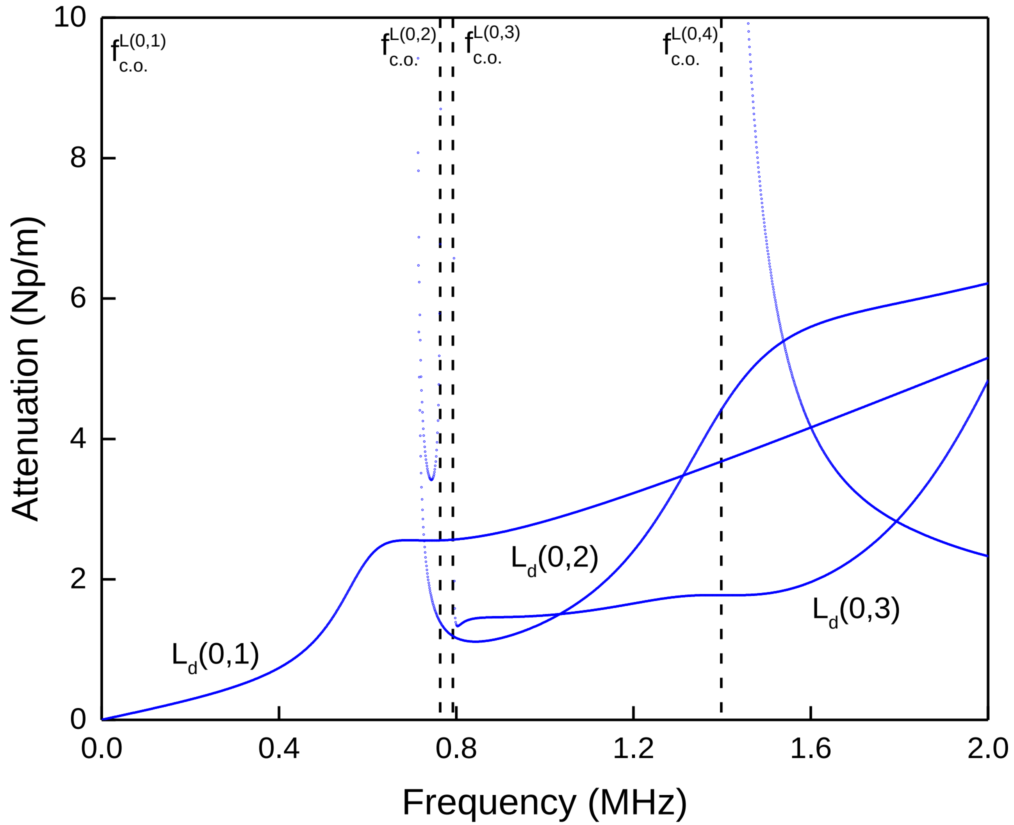
$F_d\left(1,m\right)$

Attenuation curve

$$L_d\left(0, m\right)$$



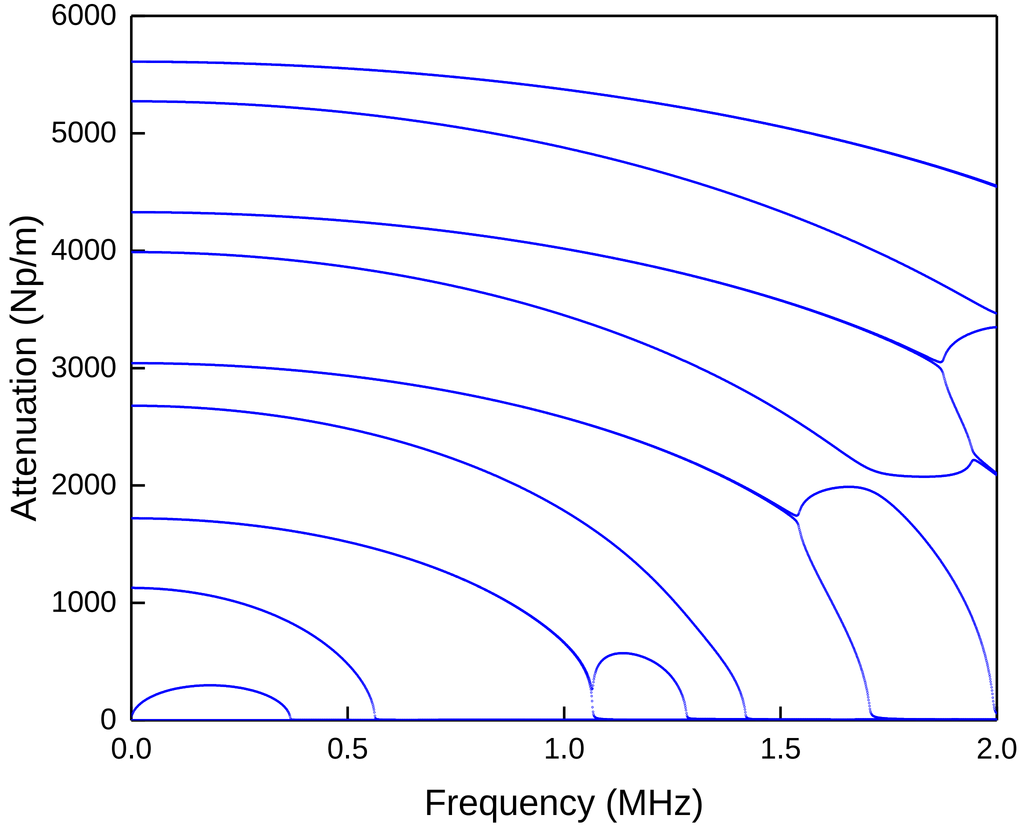
(a) higher value attenuation (0-6000 Np/m)



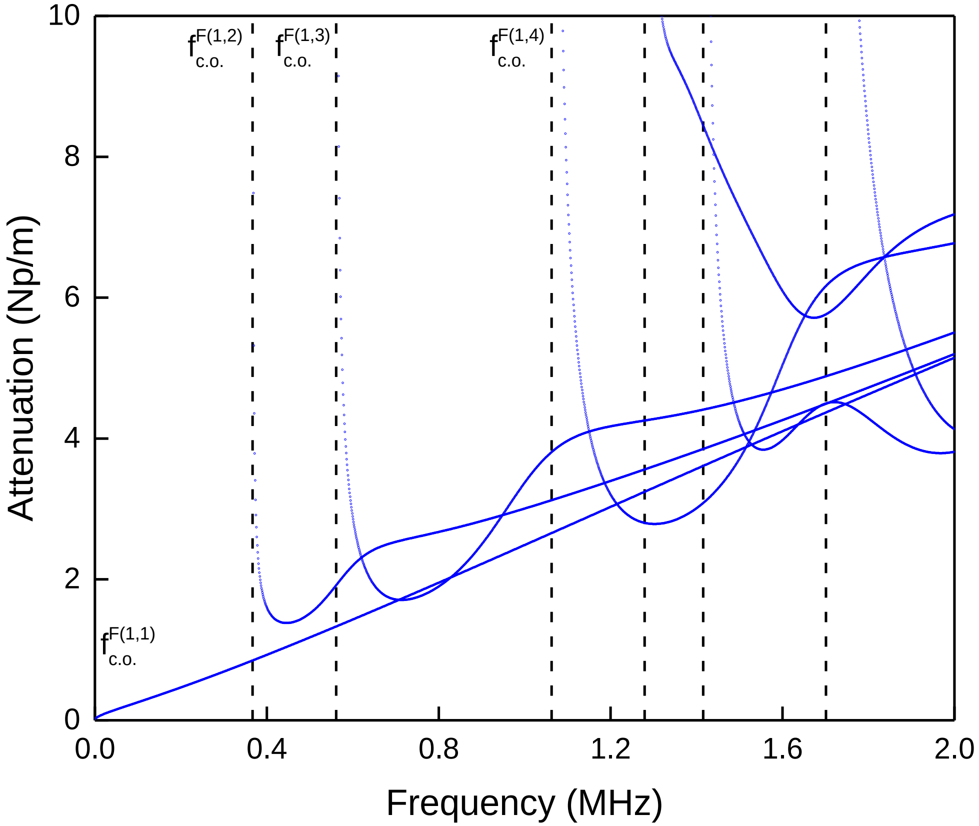
(b) lower value attenuation (0-10 Np/m)

Attenuation curve

$$F_d(1,m)$$



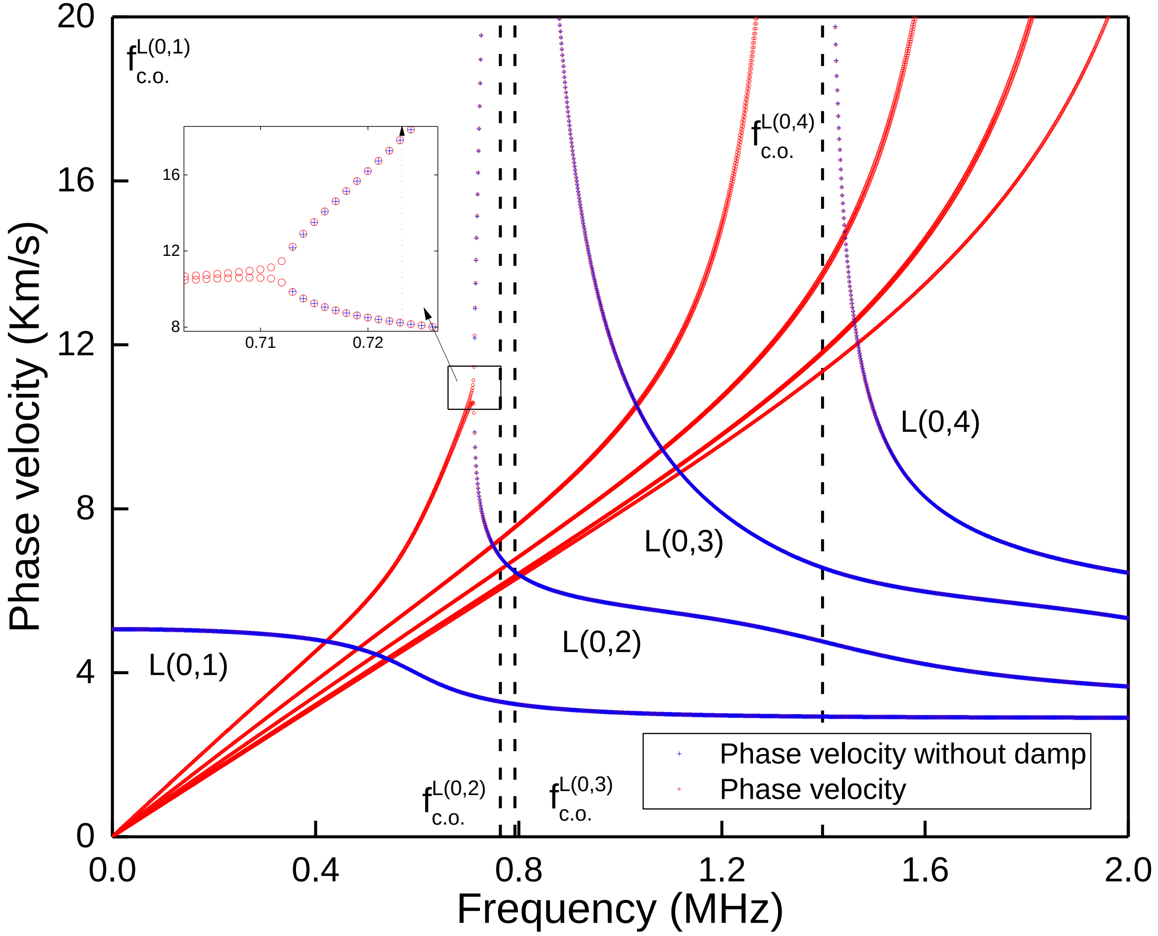
(a) higher value attenuation (0-6000 Np/m)



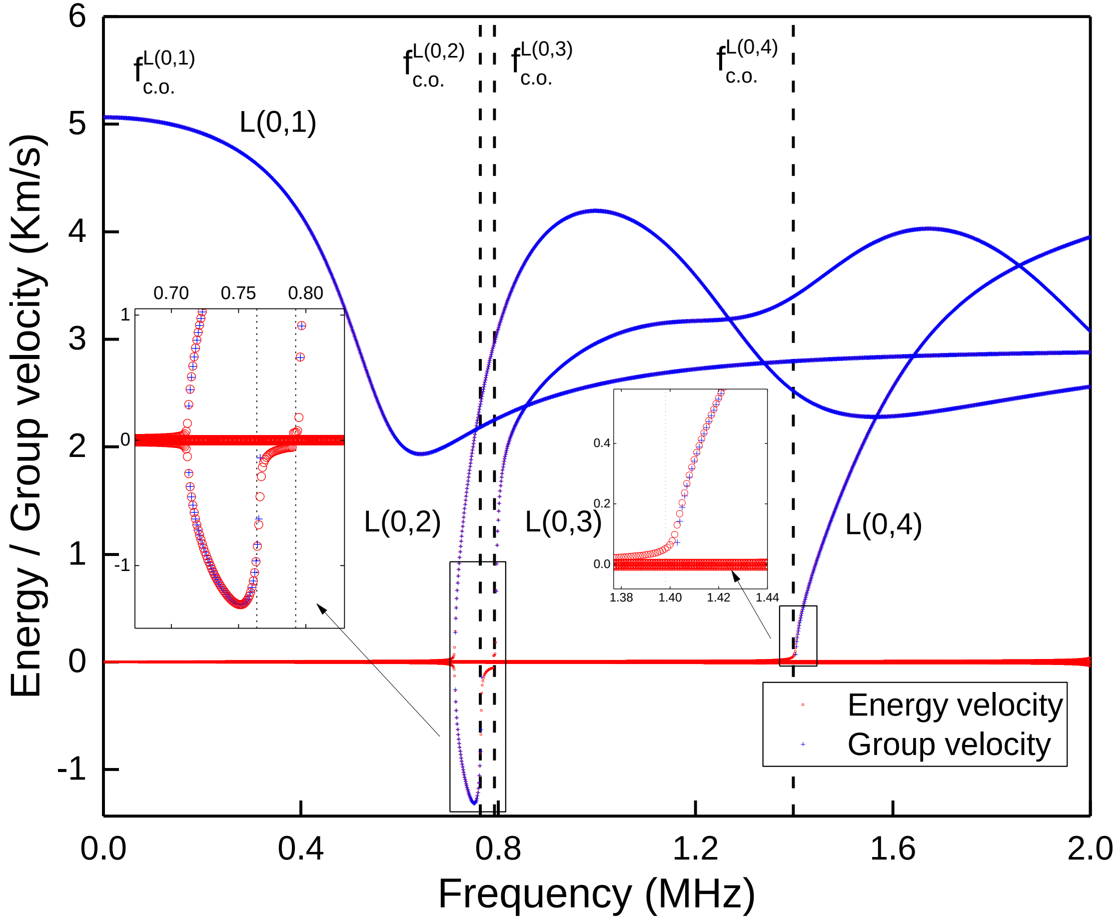
(b) lower value attenuation (0-10 Np/m)

$L(0,m)$ & $L_d(0,m)$ Modal dispersion curves

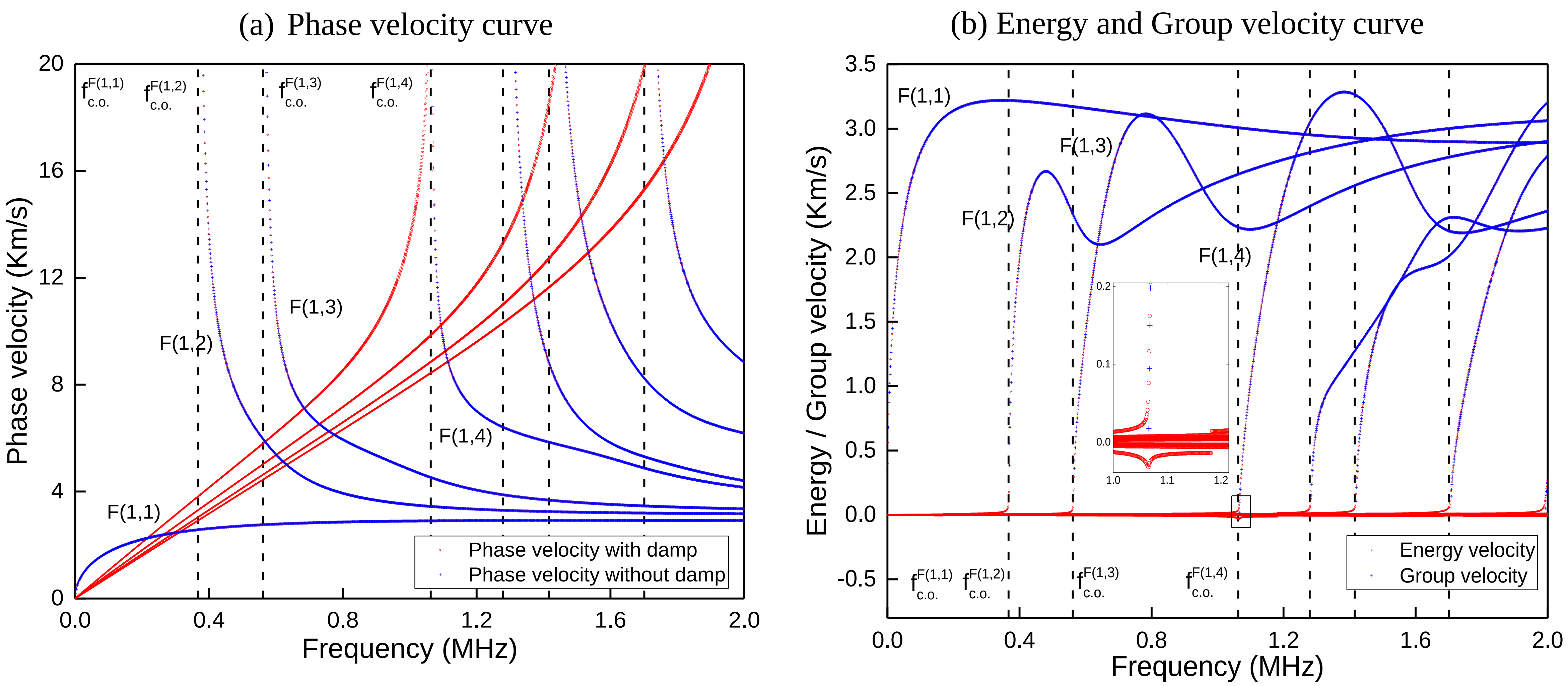
(a) Phase velocity curve



(b) Energy and Group velocity curve



$F(1,m)$ & $F_d(1,m)$ Modal dispersion curves



Influence of initial tensile stress on energy velocity and attenuation

The first equilibrium state is that a single wire is subjected to axial tension to achieve static balance, and the corresponding static virtual work equation is

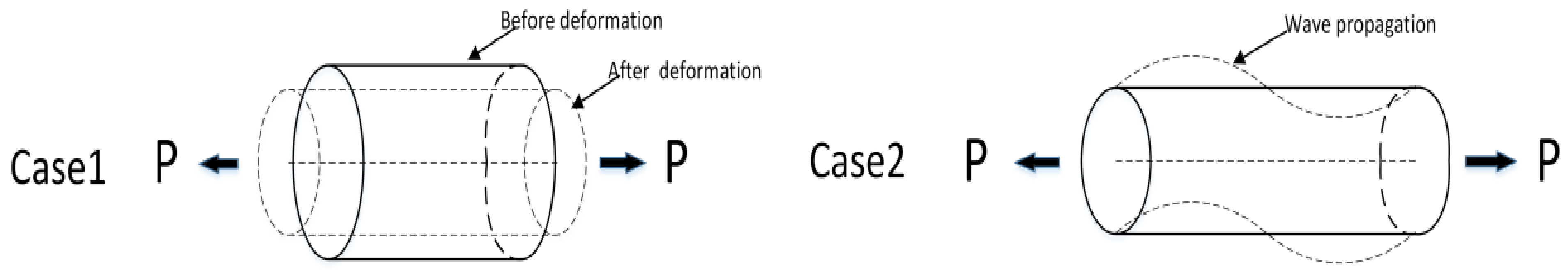
$$\int_V \delta \boldsymbol{\varepsilon}_1{}^T \boldsymbol{\sigma}_0 dV = \int_V \delta \mathbf{u}_1{}^T \boldsymbol{P} dV$$

$$\int_V \delta \boldsymbol{E}_2{}^T (\boldsymbol{\sigma} + \boldsymbol{\sigma}_0) dV + \int_V \delta \mathbf{u}_2{}^T (\rho \ddot{\mathbf{u}}) dV = \int_V \delta \mathbf{u}_2{}^T \boldsymbol{P} dV$$

$$\int_V \delta \mathbf{e}_2^{zT} \boldsymbol{\sigma}_0^z dV = \int_V \delta \left(\frac{1}{2} \left[\left(\frac{\partial u_r}{\partial z} \right)^2 + \left(\frac{\partial u_\theta}{\partial z} \right)^2 + \left(\frac{\partial u_z}{\partial x} \right)^2 \right] \right) \boldsymbol{\sigma}_0^z dV$$

$$\int_{V_j} \delta \mathbf{e}_2^{zT} \boldsymbol{\sigma}_0^z dV = \delta \bar{\boldsymbol{U}}^{j^T} \int_{V_j} k^2 \left(\boldsymbol{N}^{T*} \boldsymbol{N} \right) \boldsymbol{\sigma}_0^z dV \bar{\boldsymbol{U}}^j$$

Two equilibrium states for establishing the virtual work equation



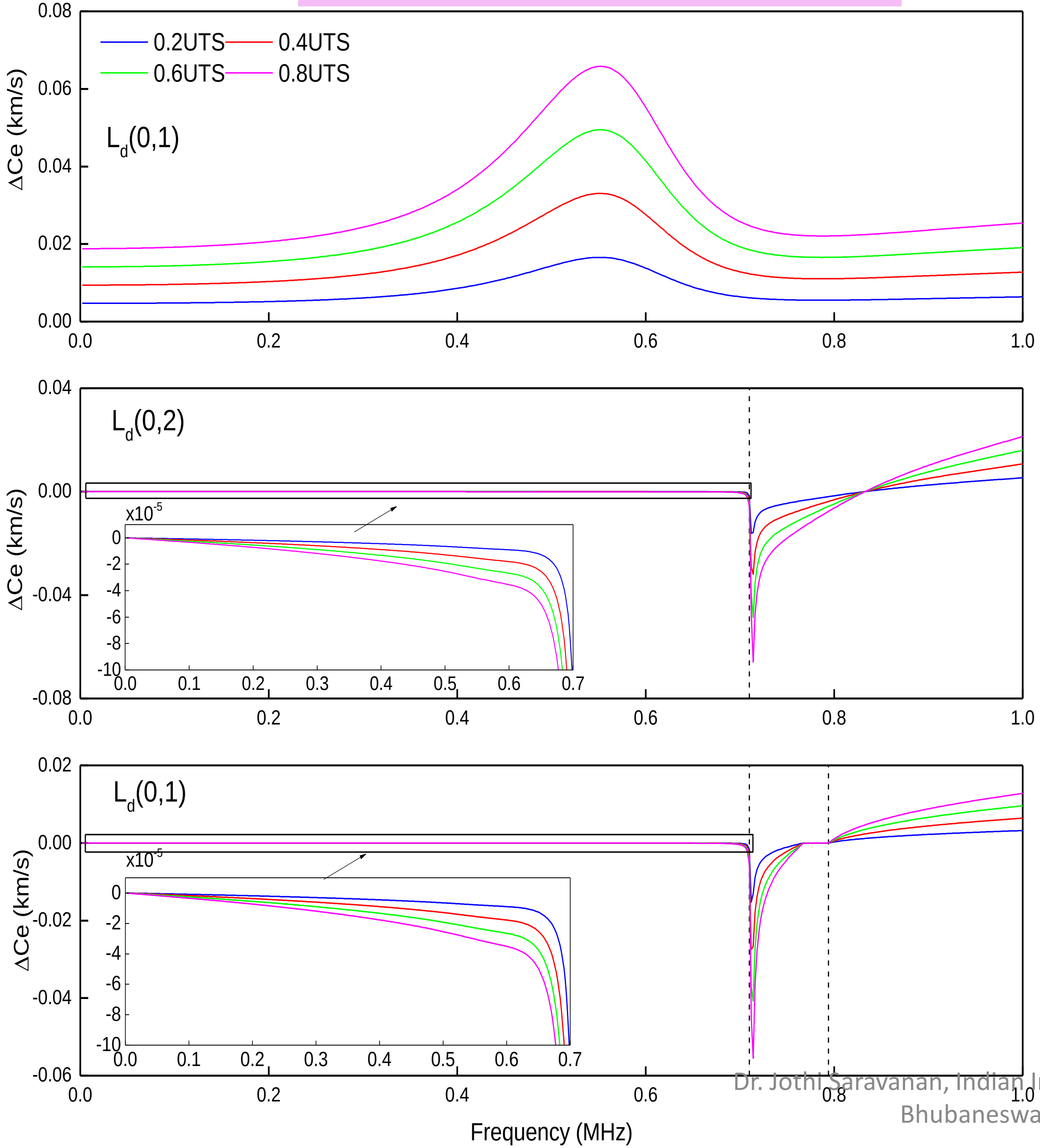
The semi-analytical frequency equation containing the initial stress matrix has

$$\left[\boldsymbol{K}_1 + k\boldsymbol{K}_2 + k^2 \left(\boldsymbol{K}_3 + \boldsymbol{K}_0 \right) - \omega^2 \boldsymbol{M} \right]_M \boldsymbol{U} = 0$$

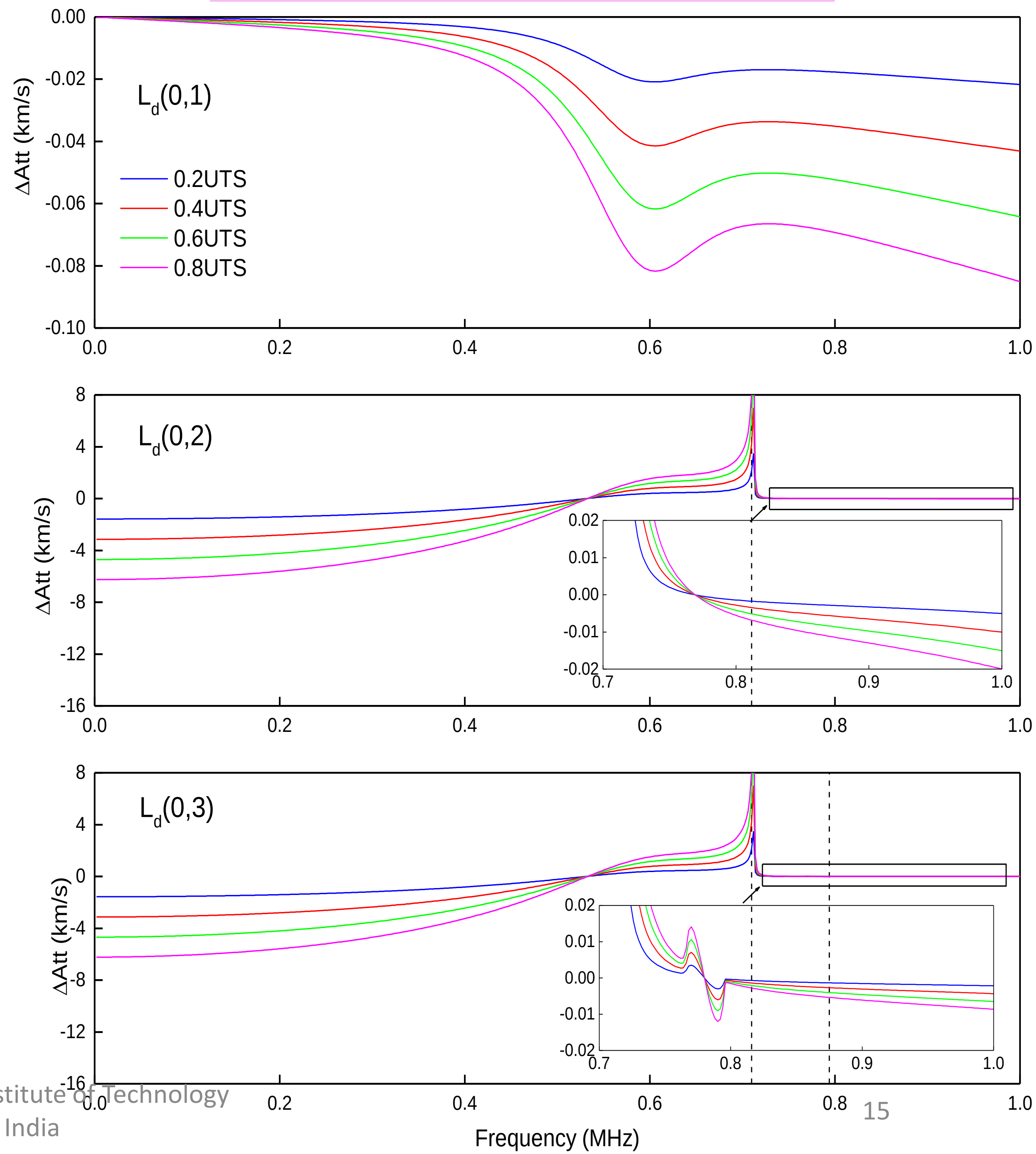
Numerical investigation

- Influence of tensile stress on energy velocity and attenuation is discussed
- The ultimate tensile stress (UTS) of high-strength steel wire is 1860 MPa, and the stress on the cable is generally 0.3 ~ 0.4 of the UTS.
- The comparative analysis of initial stress uses 0.0, 0.2, 0.4, 0.6, and 0.8 times the UTS values to explore the effect of stress on wave propagation characteristics.

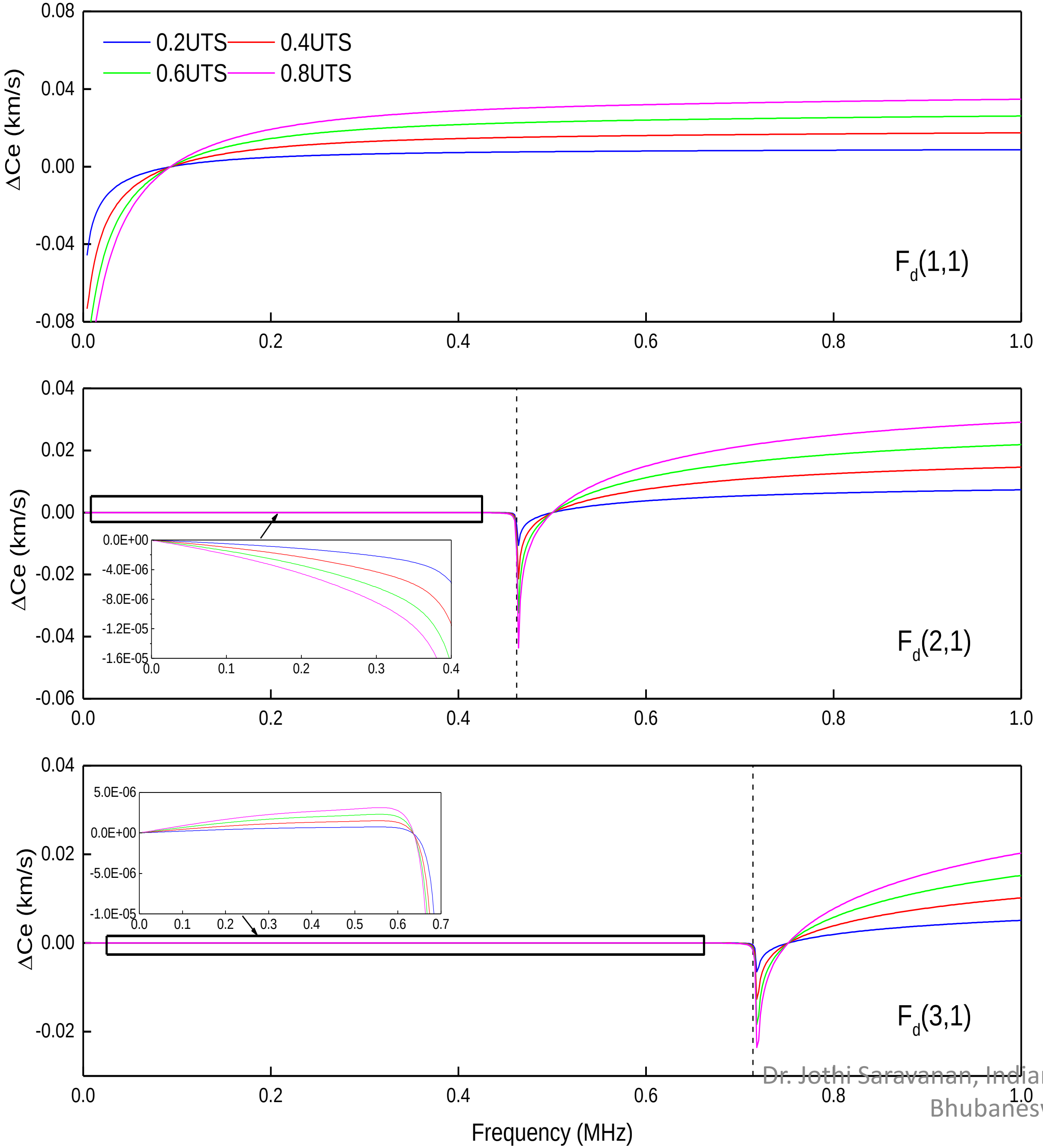
(a) ΔC_e variation for $L_d(0,m)$ mode



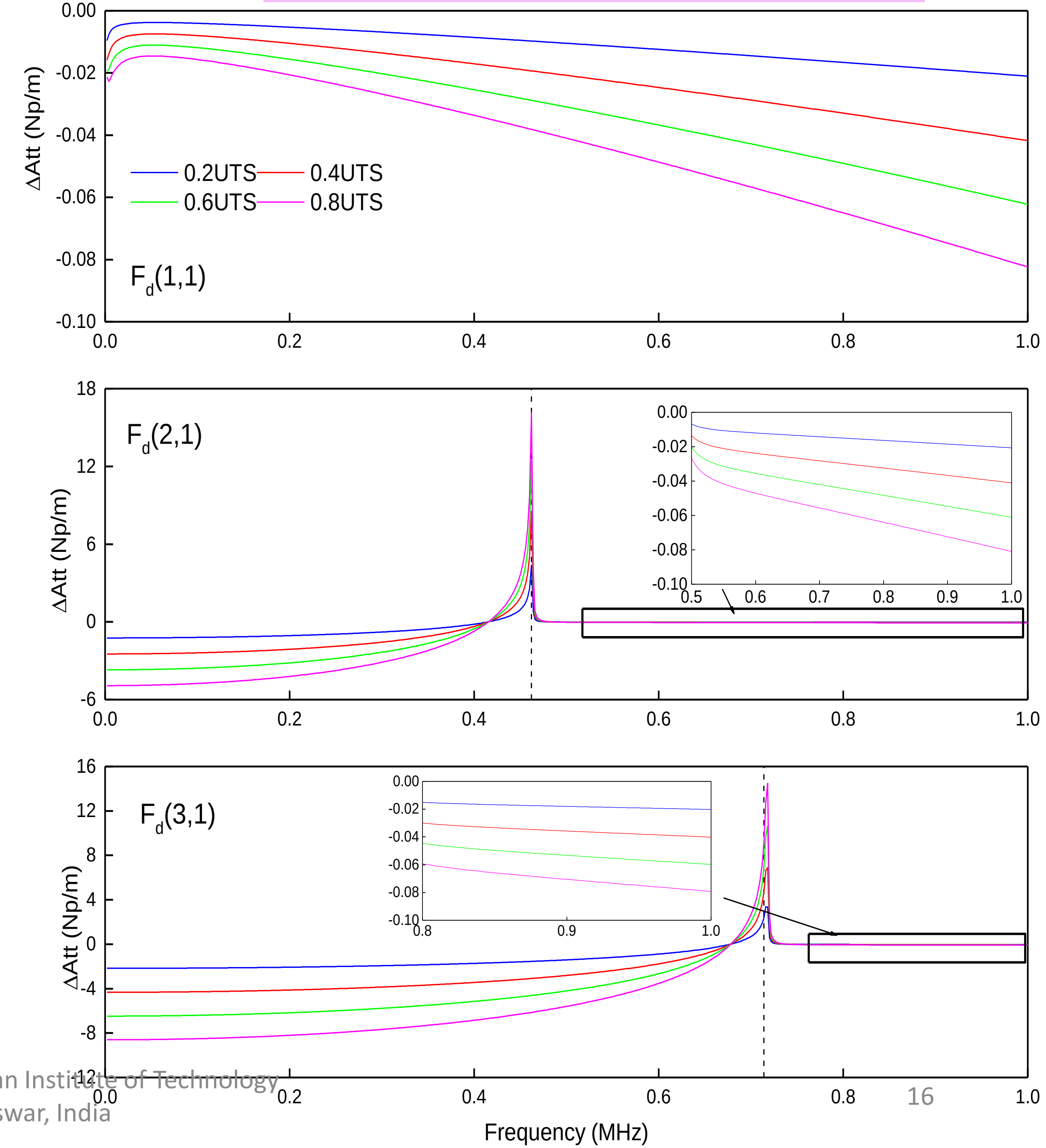
(b) ΔAtt variation for $L_d(0,m)$ mode



(c) ΔC_e variation for $F_d(n,1)$ mode

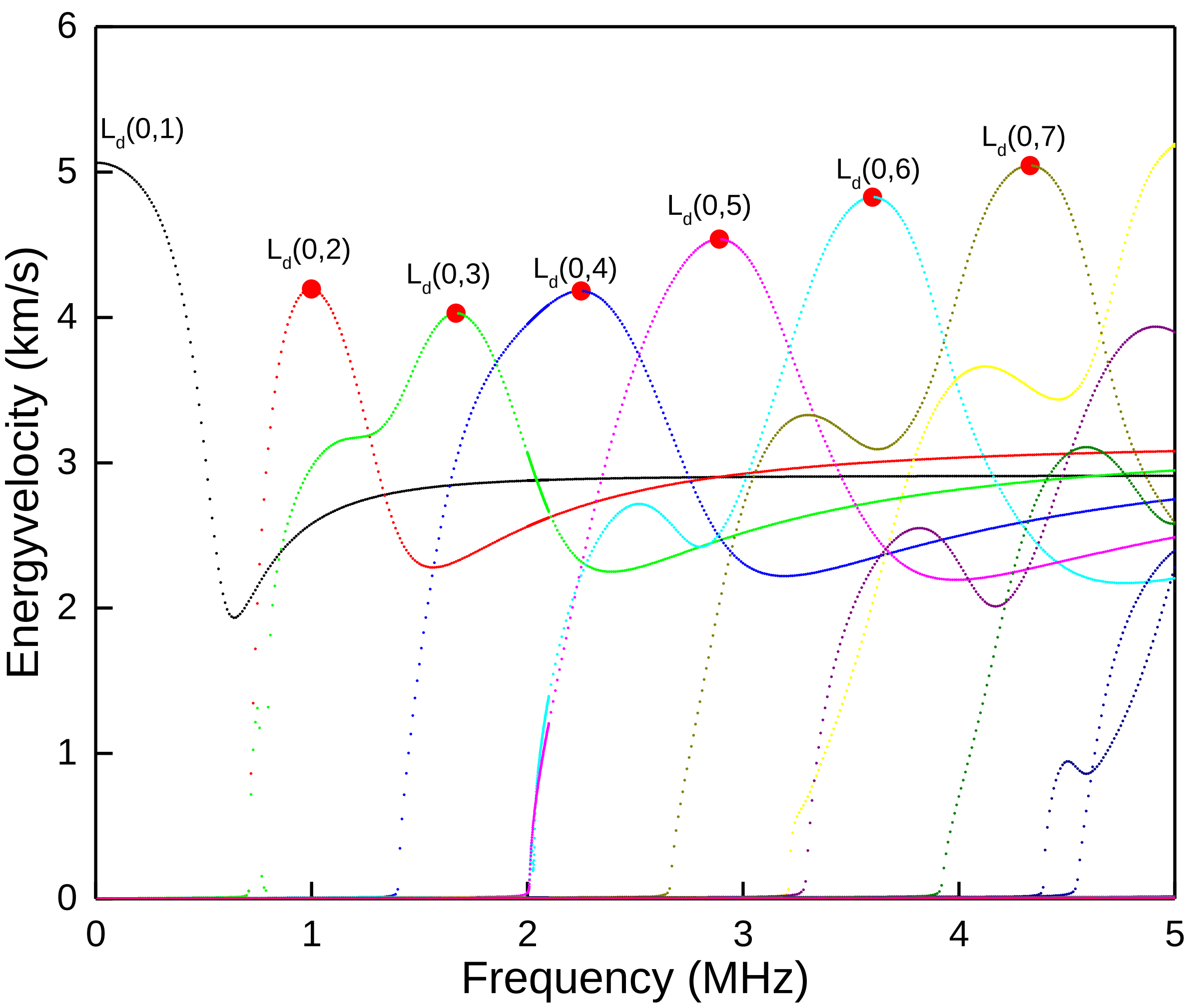


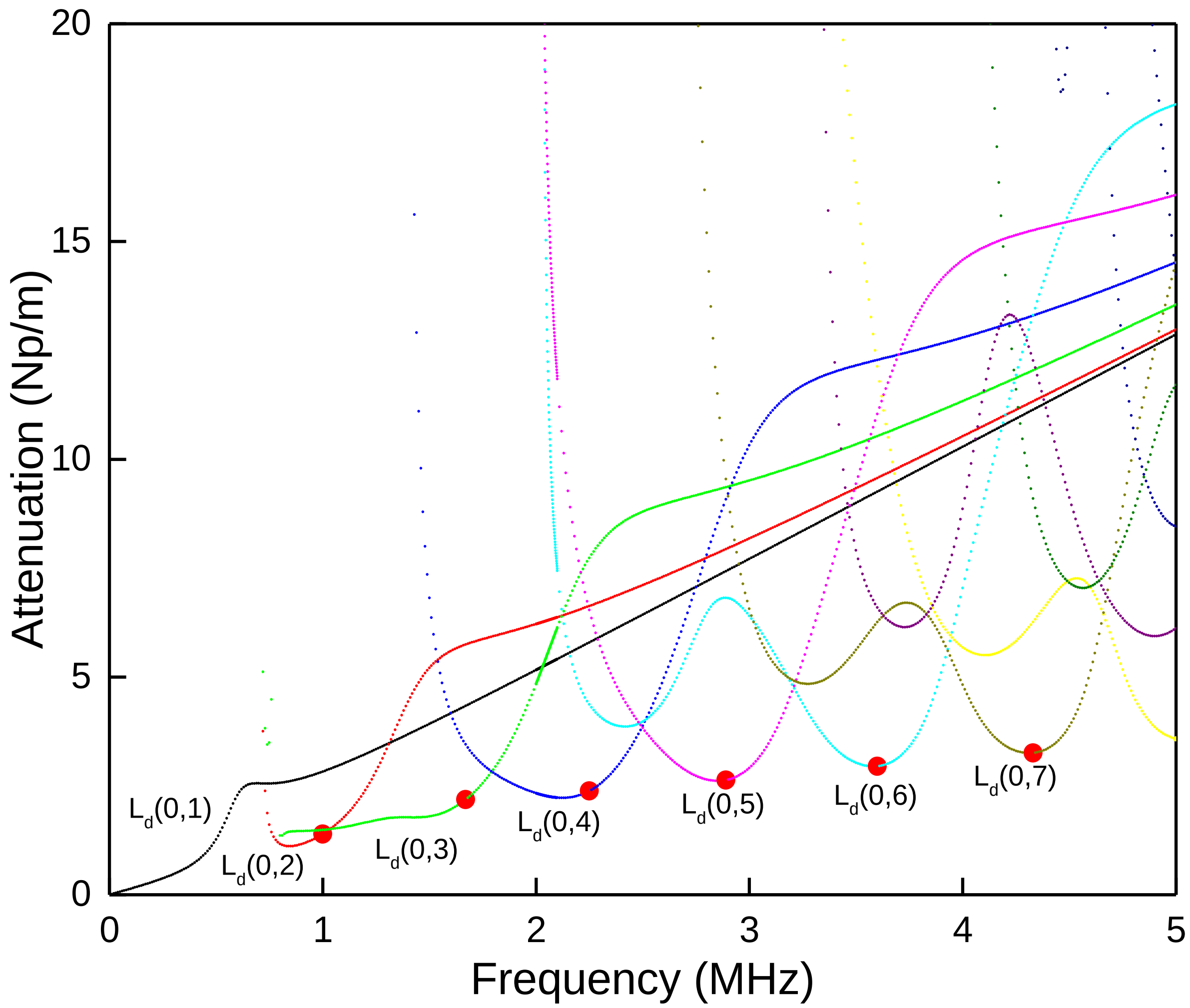
(d) ΔAtt variation for $F_d(n,1)$ mode



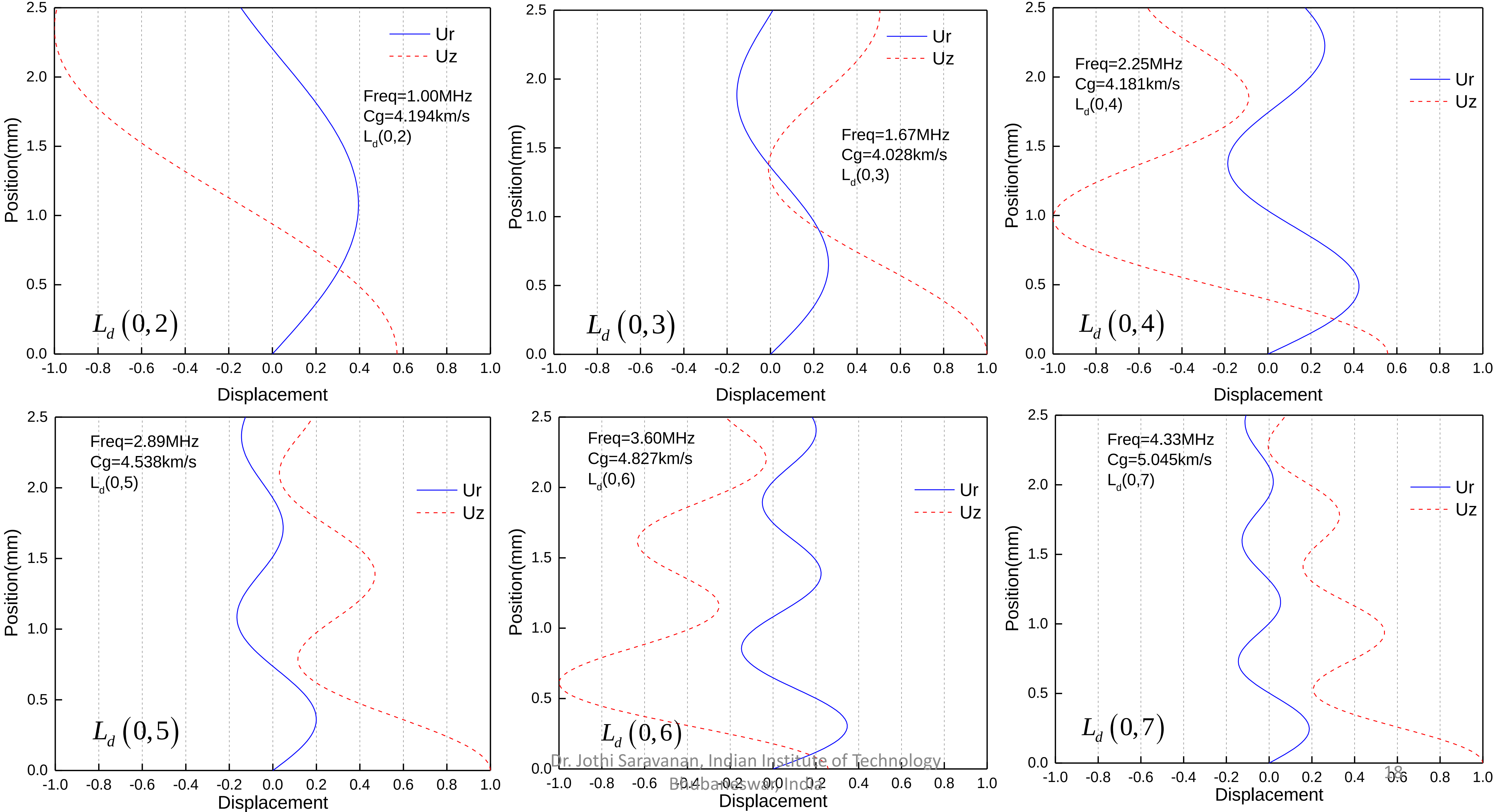
Modal selection for AE monitoring

Longitudinal mode dispersion curve for damped waveguide





Longitudinal mode at maximum energy velocity for damped waveguide



Conclusions

- ✓ A method to calculate the characteristics of guided waves in a steel wire, with the motivation of applications to Acoustic Emissions (AE) monitoring.
- ✓ The initial tensile stress can be calculated and analyzed by the semi-analytical stiffness matrix in the form of a geometric stiffness matrix.
- ✓ Without considering the effects of other stress fields and other deformation, the 0.2, 0.4, 0.6, and 0.8 times, UTS are analyzed for the effect of initial stress conditions.
- ✓ It can be found that for propagating waves above the cut-off frequency, the initial tensile stress can slightly increase the energy velocity and reduce the attenuation factor.
- ✓ The longitudinal wave modes considered in the high-frequency region are suitable for AE monitoring as it has low attenuation factor and relatively small external surface vibration.

Thank you for your kind attention