Finite element modelling of a two-layer hyperloop model

To find the response of a hyperloop model on discrete periodic supports using both a Matlab and an Ansys model

Faculty of Civil Engineering and Geosciences, Delft University of Technology - June 23, 2025

TUDelft

Finite element modelling of a two-layer hyperloop model

by Group 2:
Menno Marissen, Gabriele Mylonopoulos, Bart Slingerland, Sulongge Sulongge and Jerin Thomas

Student numbers:	5381827, 4807421, 5309913, N/A and 6276423
Period:	2024/2025 Q4
Course:	CIEM5220-U3 - Dynamics of Structures Under Moving Loads
Responsible lecturer:	dr. Z. Yang

Image cover page: concept art of a hyperloop tube with a pod moving inside it. From Zeleros Hyperloop, n.d.

TU Delft

Preface

This report comprises the finite element modeling of a two-layer hyperloop model on discrete periodic supports with concentrated masses at each support, using both Ansys and Matlab code. From both models, a dispersion curve was extracted which was compared with each other.

We wrote this report as part of the Dynamics of Structures Under Moving Loads course that is part of the module Applied Dynamics of Structures (CIEM5220), which is one of six B-modules in the Structural Engineering track of the Master Civil Engineering at Delft University of Technology. The assignment includes this report, as well as a presentation of our findings on 27 June 2025. This report only includes Part B of the assignment; Part A is reported separately.

The report is meant for the lecturers of the entire module and fellow students. As our group had to fulfill five assignments, the work was split among the group members. Gabriele mainly worked on the Matlab part, while Menno did the Ansys part. We wrote this report together.

A special thanks is given to dr. Z. Yang for his support and hints while working with both models.
We hope you enjoy reading this report.

Menno Marissen, Gabriele Mylonopoulos, Bart Slingerland, Sulongge Sulongge and Jerin Thomas (Group 2)

Delft, June 23, 2025

Contents

1 Introduction

When it comes to sustainable transportation of the future, a hyperloop is one of the first types one thinks of: it is very fast and does not need fossil fuels. It could even be faster than airplanes. However, due to high-speed dynamics, it is important to take into account instability issues of the supporting structure and foundation. Intuitively, one can expect very high-amplitude responses in the system with certain velocities, known as resonance. Those so-called critical velocities can be found with computer models, which will be done in this report.

The hyperloop model will be represented by a two-layer model which is supported by periodic discrete supports with concentrated masses on top of them, which are used to model the inertias of the supports. This assignment is limited to a hyperloop model with certain parameters for properties like stiffness, support mass and damping, but one should realize that the steps can be reproduced for different parameters.

In Chapter 2, a model for the structure of a hyperloop transportation system is introduced and its finite element implementation in Matlab is discussed. In the following Chapter 3, the simulation of the finite element model was carried out in Ansys. A comparison of the results of the dynamic behavior of the two models follows. In the last chapter, Chapter 4, the relation between support stiffness and critical velocity is discussed. Finally, the findings are summarized in Chapter 5.

2

Question a: Model description and Matlab model

2.1. Model description

Let us first introduce the given schematization for the infrastructure. The hyperloop structure is modeled as a beam on discrete periodic supports with concentrated masses at each support, as shown in Fig. 2.1. The masses are used to model the inertia of the supports.

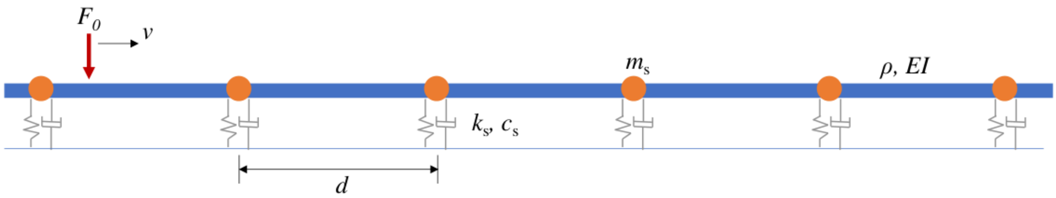

Figure 2.1: Hyperloop Structural Scheme

2.2. Matlab model

The Matlab implementation (`Assignment_problem_2024_Group2_Modified.mlx`), however, is based on a different structural scheme, depicted in Fig. 2.2. The model is therefore adapted to match the dynamic behavior of the desired system. A summary of the correspondence between elements is presented in Tab. 2.1.

Two specifications are worthwhile mentioning. Firstly, in the railway model the ballast is rigidly connected to the ground as are the concrete supports for the hyperloop case. Secondly, the rigid connection between rail beam and sleepers (which allows the use of the sleepers to model the supports as masses directly attached to the hyperloop structure) is simulated by increasing the railpads stiffness to a value of $44 \cdot 10^{15} N/m$, hence the absence of a hyperloop counterpart of the railpads.

The Matlab script `get_input_hyper_loop.m` contains all physical features of the system hereby presented, a summary of the parameters is given in Tab. 2.2.

Table 2.1: Rail Model Components and Hyperloop Equivalents

Component CP6	Hyperloop
Rail	Tubular Structure
Sleepers	Concrete Supports (Mass)
Railpad	(None)
Ballast	Concrete Supports (Elasticity, Damping)

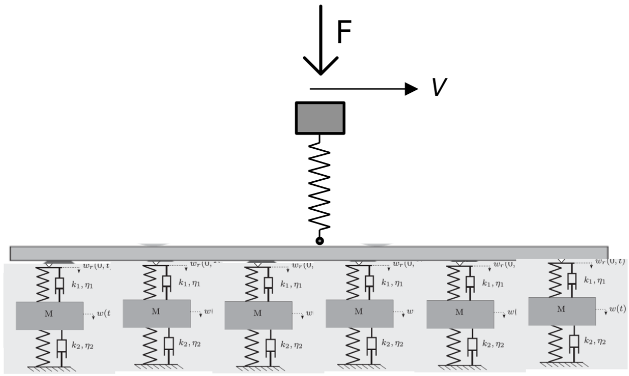

Figure 2.2: Enter Caption

Table 2.2: Parameters for Structural Analysis (Matlab model)

Parameter	Symbol	Value	Unit
Bending stiffness	EI	2.5e10	Nm^2
Mass per unit length	ρ	1330	kg/m
Dead weight	F_0	30e3	N
Support mass	m_S	2330	kg
Support stiffness	k_S	44e7	N/m
Support damping	c_S	10e3	Ns/m
Support spacing	d	16	m

The model is then run performing the following operations:

1. Mesh geometry is created
2. System mass and stiffness matrices are computed
3. An eigenvalue analysis is performed computing natural frequencies and modal shapes
4. Dispersion curves are plotted in the form of a Modal Shape Spectrum 3D plot (Fig. 2.3) and a 2D colorcoded 'heatmap' plot (Fig. 2.4).

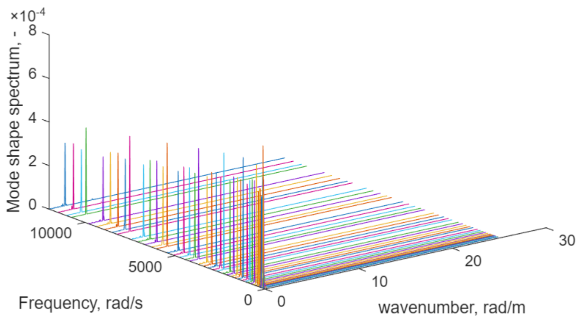

Figure 2.3: Modal Shape Spectrum (Matlab)

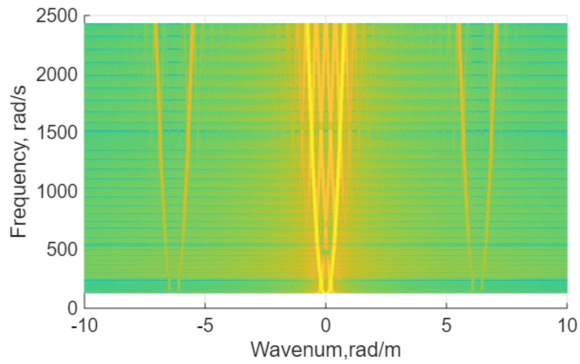

Figure 2.4: 'Heatmap' Dispersion Curve (Matlab)

Figure 2.5: Results from Matlab Model

By close inspection of the latter graph (a zoomed in version is presented in Fig. 2.6) the main features of interest of the system can be extracted. The cut-off frequency, corresponding to the vertex of the parabolic shape, is located approximately at 130 Hz. The figure also portrays a stop-band located

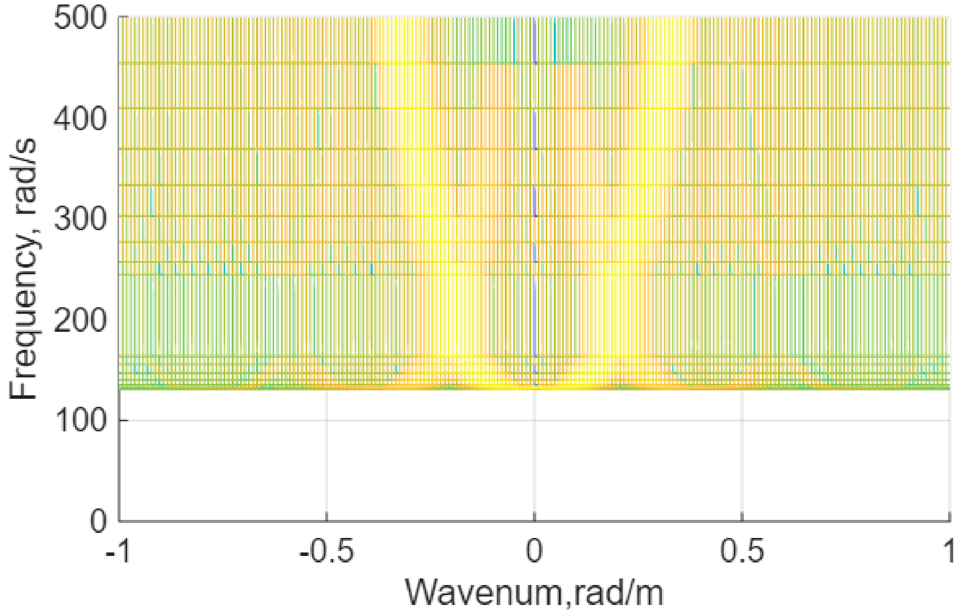

Figure 2.6: Dispersion Curve (Matlab) - Enlargement on first Brillouin zone

between 160 Hz and 245 Hz. Moreover, the critical velocity of a static (i.e. non-oscillating) moving load can be determined as the tangent to the parabolic shape just below the stop band. Performing such a procedure graphically returns a critical velocity of approximately 850 m/s.

3

Question b: Ansys model and comparison

3.1. Ansys model

Similarly to the model in Matlab, the Ansys model is also based on a two-layer system. The same parameter values as in Tab. 2.2 are used, although they are called differently and some properties are added (e.g. Young's modulus and moment of inertia separately instead of their multiplication; the bending stiffness). The full list of parameter values can be seen in Tab. 3.1. It is worth mentioning that railpads in the Ansys model are modeled in the same way as the Matlab model: a very high value of $44 \cdot 10^{15} N/m$ is chosen to represent the rigid connection between the concentrated masses and the hyperloop structure.

Table 3.1: Parameters for Structural Analysis (Ansys model)

Parameter	**Value**	**Unit**
Support spacing	16	m
Young's modulus	25	GPa
Moment of inertia	1e8	cm^4
Density	1330	kg/m^3
Poisson's ratio	0.3	[-]
Area	1	m^2
Fastening stiffness	44e9	MN/m
Fastening damping	10	kNs/m
Sleeper mass	2330	kg
Ballast stiffness	440	MN/m
Ballast damping	10	kNs/m

Those parameters were substituted in the given command file that is the input to Ansys, after which the software computes the natural frequencies and modes of vibration. For these steps, the provided manual was used.

To create the dispersion curves, the list of natural frequencies was exported to an Excel file. From here, the natural frequencies corresponding to the so-called fake modes could be removed from this list. After that, the natural angular frequencies (with a multiplication of 2π) could be plotted against the wave numbers that were computed based on the order of the modes: the first mode of this finite model has a wave length of $2L$ with $L = 160$ meter, while the jth mode has a wave length of $2L/j$. From these, the wave numbers can be computed as 2π over the wave length: $k = \frac{2\pi}{\lambda}$. Finally, those wave numbers were plotted against the filtered list of frequencies (multiplied by 2π). The result is visualized in Fig. 3.1.

Multiple stop bands can be seen, which can be recognized by the little jump in angular frequency, for example around $k = 0.2\, m^{-1}$.

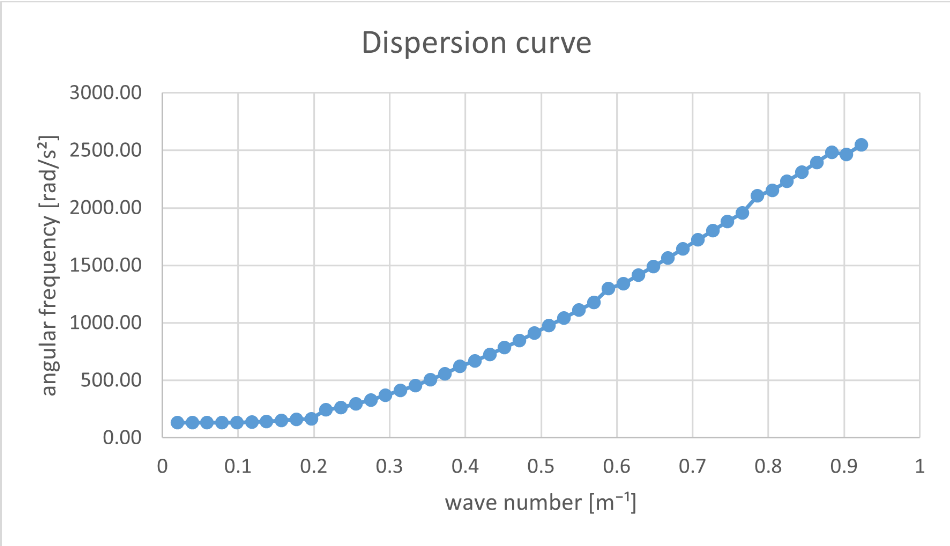

Figure 3.1: Dispersion Curve (Ansys)

In the phase speed plot in Fig. 3.2, it can be seen that the critical velocity is around 900 m/s. To be exact, the lowest dot has a velocity value of 835 m/s. The phase speed was calculated as 2π times the frequency f over the wave number k.

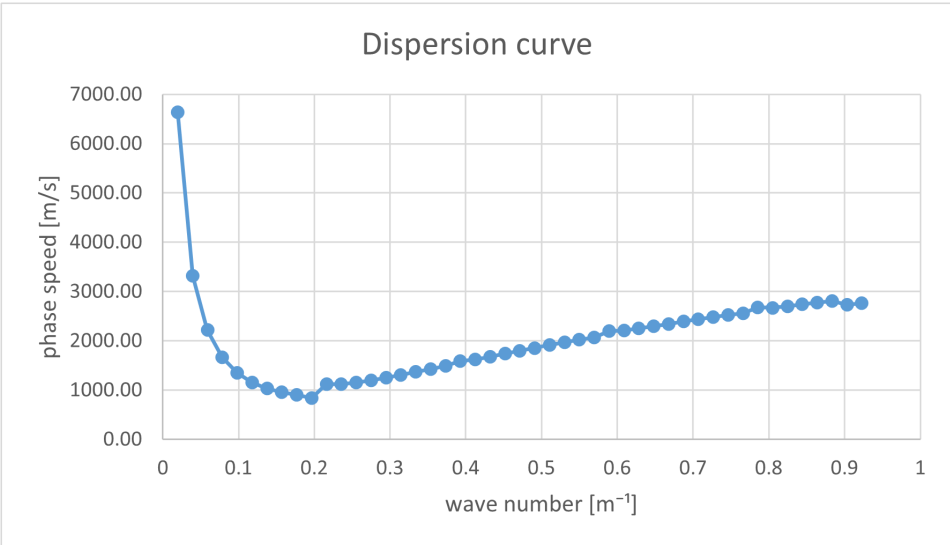

Figure 3.2: Phase Speed Curve (Ansys)

3.2. Comparison

In Fig. 3.3 the natural frequencies and periods resulting from the Ansys model (red line) are overlaid on the Matlab dispersion plot to assess the similarity between the results of the two analysis. On close inspection, see Fig. 3.4, a high degree of correspondence is evident, especially close to the origin. More specifically, the cut-off frequency seen in the graph from Ansys (minimal value of angular frequency) matches the one obtained through Matlab, as well as the coincidence of the discontinuity in the red curve with the stop band from the latter model. The critical velocity from both models is similar: the Matlab model results in a critical velocity of around 850 m/s, while the one derived with Ansys is 835 m/s. Nonetheless, it may be worth noting that a marginal amount of discrepancy can be noticed as the frequency increases.

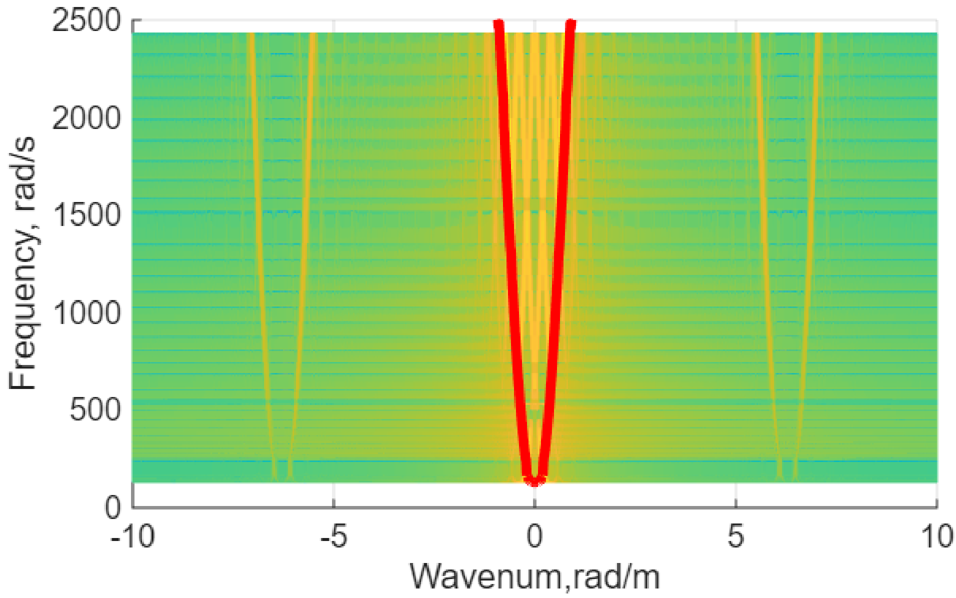

Figure 3.3: Dispersion Curve Comparison

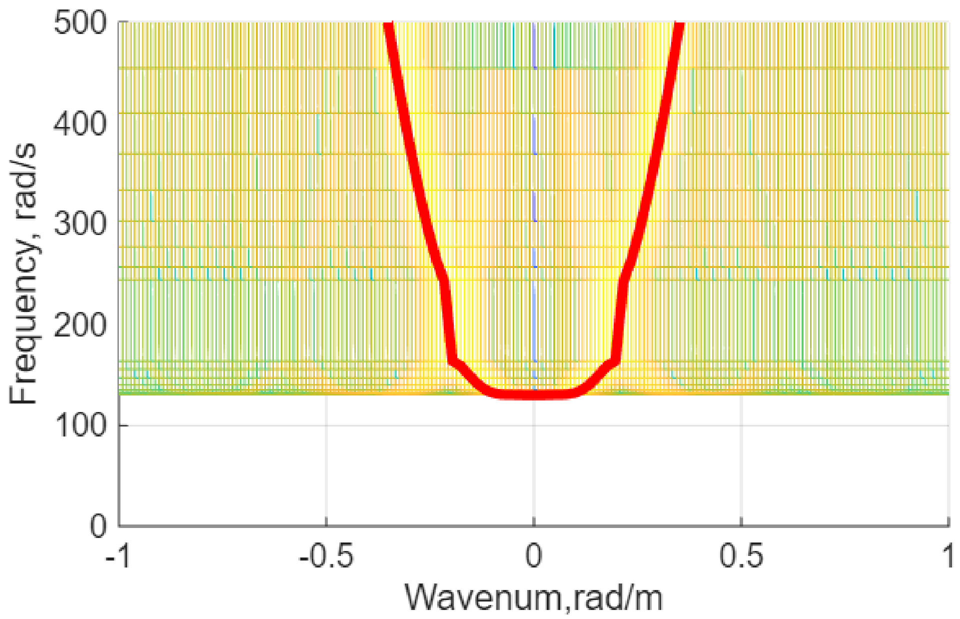

Figure 3.4: Dispersion Curve Comparison - Enlargement on first Brillouin zone

4 Question c: Critical velocity

In order to assess the relation between support stiffness and critical velocity two more sets of simulations are run in Matlab, as that process is faster and less prone to human errors. The ballast stiffness is first decreased by one order of magnitude (Fig. 4.1 and then increased by one order of magnitude (Fig. 4.2). It is apparent how the lower stiffness model undoubtedly returns a lower critical velocity of approximately 490 m/s, which was visually deducted from the graph. The reduced stiffness decreases the cut-off frequency, which results in a less steep tangent. Oppositely, stiffer supports increase the cut-off frequency of the system. However, it also intensifies the effect of reflected waves on supports, visualised by the kink in the graph. Still, the critical velocity of the part below the kink remains close to the critical velocity reported in Chapter 2, with a value of 880 m/s.

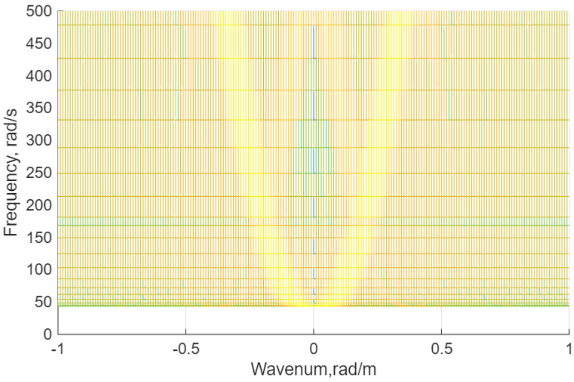

Figure 4.1: Reduced Stiffness

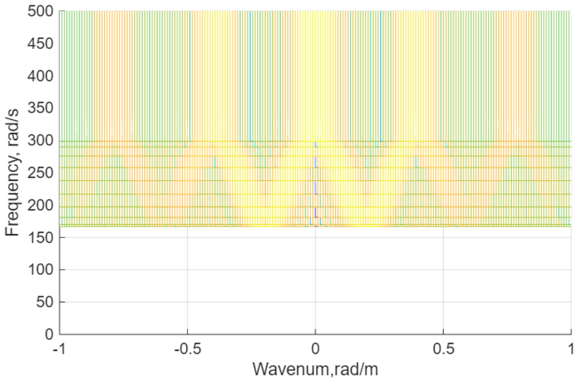

Figure 4.2: Increased Stiffness

Figure 4.3: Variation of Support Stiffness - 10x decr/incr

While being a good showcase of the relation between stiffness and cut-off frequency, this simulation is deemed unrealistic as a tenfold reduction/increase in the mechanical properties is a drastic change in the system characteristics. A final simulation is run with a modifier of 1.5 to the stiffness, results are presented in Fig. 4.6. The computed critical velocities are approximately 740 m/s and 900 m/s.

When performing a transient analysis with this velocity in Ansys, using the second manual provided, it was unfortunately not possible to reproduce the resonance. Velocities of 835 and 850 m/s were tested, without fastening and ballast damping. The time history of different nodes in the hyperloop did not show very high amplitudes.

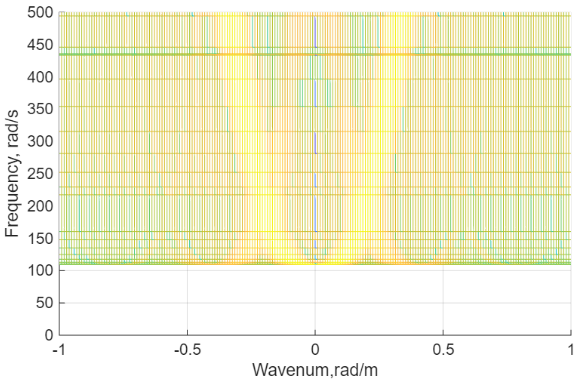

Figure 4.4: Reduced Stiffness

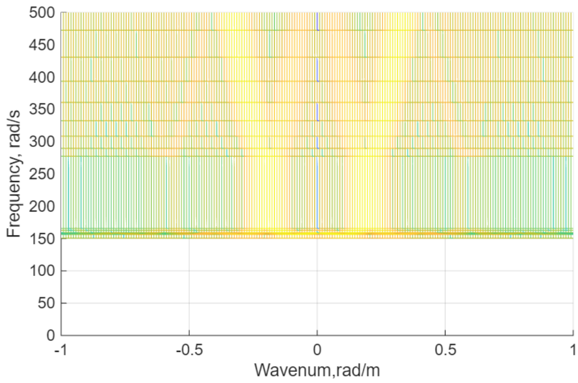

Figure 4.5: Increased Stiffness

Figure 4.6: Variation of Support Stiffness - 1.5x decr/incr

5 Conclusion

It can be concluded that both finite element models produce the same dispersion curve for specific parameter values. The ones from the Matlab model contain more information: it is also able to show the different Brillouin zones. Values like the cut-off frequency and critical velocity are also (nearly) identical.

The hyperloop model that was analyzed has a critical velocity of around 835 m/s, which is around 3000 km/h. For now, that is far beyond the velocities that are considered for hypothetical hyperloops, so a hyperloop structure with the coefficients as analyzed in this assignment will not be faced with resonances as long as the speed remains below what is reasonably possible.

Bibliography

Zeleros Hyperloop. (n.d.). Front page image [Photograph]. https://www.railway-technology.com/features/timeline-tracing-evolution-hyperloop-rail-technology/