FRANKFURT UNIVERSITY OF APPLIED SCIENCES

SIMULATION METHODS

FACULTY 2, M.SC. PROGRAM HIGH INTEGRITY SYSTEMS

Winter-Semester 2020/2021, Prof. Dr.-Ing. Peter Thoma

CONTENTS OF THIS MODULE

1 INTRODUCTION & EXAMPLE

2 ORDINARY DIFFERENTIAL EQUATIONS

3 SYSTEM SIMULATION

4 FINITE DIFFERENCE METHOD

5 FINITE ELEMENT METHOD

6 OUTLOOK

SUMMARY WHERE WE ARE...

$$\boxed{\frac{\partial^2 u(x,t)}{\partial x^2} - k\,\frac{\partial^2 u(x,t)}{\partial t^2} = 0}$$

Wave Equation

Initial value problem

- Time Domain simulation
- Start from an initial state and simulate how the system behaves as function of time (iterative)
- No further excitation during the simulation

Eigenvalue problem

- Frequency Domain simulation
- Determine natural resonances of a system (solve eigenvalue problem)
- No excitation at all
- Eigenvectors (eigenmodes) describe the shapes of the resonances
- Eigenvalues describe the resonance frequencies

THE FINITE DIFFERENCE METHOD

DRIVEN PROBLEMS

FINITE DIFFERENCE METHOD AGENDA

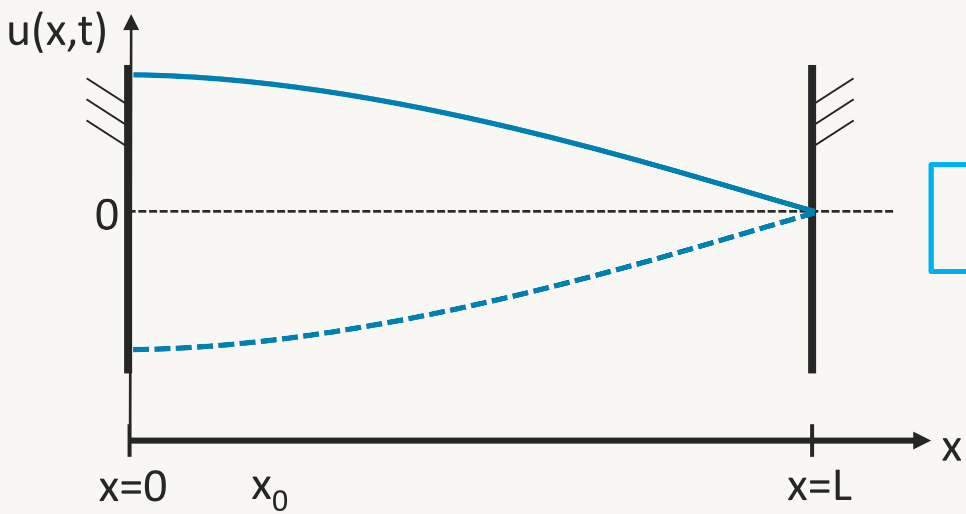
1. Wave equation with excitation
2. Excitation functions
3. Driven problems in Frequency Domain
4. Results in Time and Frequency Domain
5. Solutions of the wave equation
6. Varying material properties
7. Commercial software CST Studio Suite

WAVE EQUATION WITH EXCITATION

SOLUTIONS OF THE WAVE EQUATION

$$\frac{\partial^2 u(x,t)}{\partial x^2} - k\frac{\partial^2 u(x,t)}{\partial t^2} = 0$$

Now we will consider a **driven** problem where we will have an **excitation** at the left end of the string.



$$\boxed{u(x=0,t) = f(t)}$$

BOUNDARY CONDITIONS FOR DIFF. EQUATIONS

TYPES OF BOUNDARY CONDITIONS FOR DIFFERENTIAL EQUATIONS

1. Dirichlet (first-type) boundary condition

Describe the **value** of the solution **at** the **domain boundary**, e.g.

$$u(x = 0, t) = f(t)$$

2. Neumann (second-type) boundary condition

Describe the **derivative** of the solution **normal** to the **domain boundary**, e.g.

$$\left.\frac{\partial u(x,t)}{\partial x}\right|_{x=0} = f(t)$$

3. Robin (third-type) boundary condition

Combination of **Dirichlet** and **Neumann** boundary conditions, e.g.:

$$\alpha \left.\frac{\partial u(x,t)}{\partial x}\right|_{x=0} + \beta\, u(x = 0, t) = f(t)$$

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WAVE EQUATION WITH EXCITATION

TRANSIENT SOLUTION OF THE DRIVEN PROBLEM

$$\frac{\partial^2 u(x,t)}{\partial x^2} - k\frac{\partial^2 u(x,t)}{\partial t^2} = 0$$

Previously we derived the following **transient iteration scheme**:

$$u_{i,j} = cu_{i+1,j-1} + cu_{i-1,j-1} + 2(1-c)u_{i,j-1} - u_{i,j-2} \quad \text{with} \quad c = \frac{\Delta t^2}{k\Delta x^2}$$

Now we assume that the string is **straight** and **at rest** at the **beginning**:

$$\left.\begin{aligned} &u(x,t=0) = 0 \quad \Rightarrow u_{i,0} = 0 \\ &\left.\frac{\partial u(x,t)}{\partial t}\right|_{t=0} = 0 \Rightarrow u_{i,-1} = u_{i,0} = 0 \end{aligned}\right\} \text{Initial conditions}$$

The **end** of the string is still **fixed**, but we apply an **excitation** at the **beginning**:

$$\left.\begin{aligned} &u(0,t) = f(t) \quad \Rightarrow u_{0,j} = f_j \\ &u(L,t) = 0 \qquad \Rightarrow u_{N,j} = 0 \end{aligned}\right\} \text{Boundary conditions (Dirichlet type)}$$

WAVE EQUATION WITH EXCITATION

TRANSIENT SOLUTION OF THE DRIVEN PROBLEM

$$c = \frac{\Delta t^2}{k \Delta x^2}$$

Based on this information, we obtain the following **iteration scheme** in the **same way as before**:

Initialization

$$i = 1, \dots, N-1 \quad : \quad u_{i,0} = 0$$

First step

$$u_{0,1} = f_1$$

$$i = 1, \dots, N-1 \quad : \quad u_{i,1} = c u_{i+1,0} + c u_{i-1,0} + 2(1-c) u_{i,0} - u_{i,0}$$

$$u_{N,1} = 0$$

Iteration

$$j = 2, \dots : \quad u_{0,j} = f_j$$

$$i = 1, \dots, N-1, j = 2, \dots : \quad u_{i,j} = c u_{i+1,j-1} + c u_{i-1,j-1} + 2(1-c) u_{i,j-1} - u_{i,j-2}$$

$$j = 2, \dots : \quad u_{N,j} = 0$$

WAVE EQUATION WITH EXCITATION

TRANSIENT SOLUTION OF THE DRIVEN PROBLEM

$$c = \frac{\Delta t^2}{k \Delta x^2}$$

Based on this information, we obtain the following **iteration scheme** in the **same way as before**:

Initialization

$$i = 1, \dots, N-1 \quad : \quad u_{i,0} = \boxed{0}$$ **Straight line**

First step

$$u_{0,1} = \boxed{f_1}$$ **Excitation**

$$i = 1, \dots, N-1 \quad : \quad u_{i,1} = cu_{i+1,0} + cu_{i-1,0} + 2(1-c)u_{i,0} - u_{i,0}$$

$$u_{N,1} = 0$$

Iteration

$$j = 2, \dots : \quad u_{0,j} = \boxed{f_j}$$ **Excitation**

$$i = 1, \dots, N-1, j = 2, \dots : \quad u_{i,j} = cu_{i+1,j-1} + cu_{i-1,j-1} + 2(1-c)u_{i,j-1} - u_{i,j-2}$$

$$j = 2, \dots : \quad u_{N,j} = 0$$

FINITE DIFFERENCE METHOD AGENDA

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2. Excitation functions
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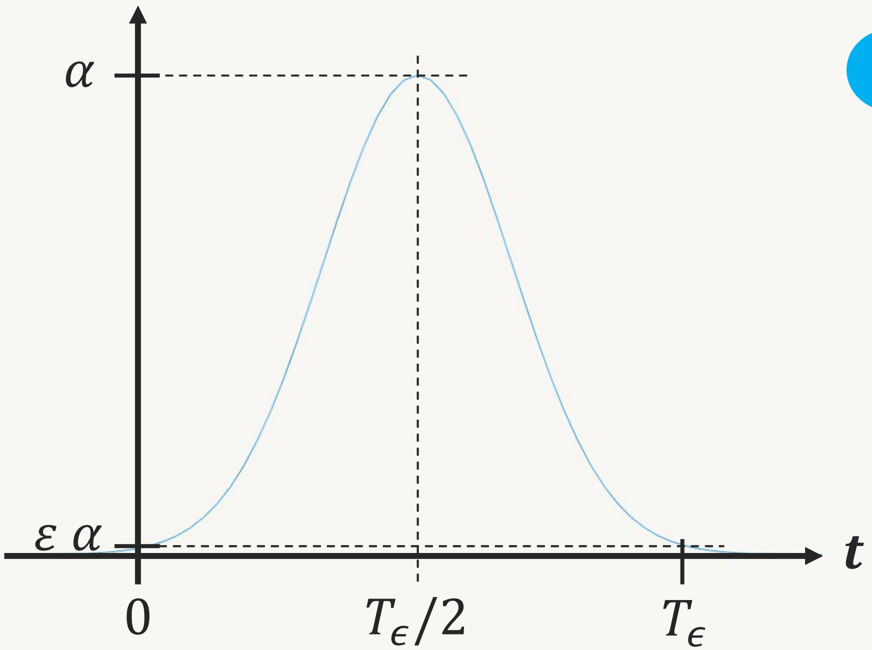
EXCITATION FUNCTIONS

EXCITATION FUNCTIONS

The **excitation function** should be zero at the beginning of the simulation.
An often-used smooth excitation function is a shifted **gaussian pulse**:

$$f(t) = \alpha\, e^{-\beta\,(t-\gamma)^2}$$



1. $f(T_\varepsilon/2) = \alpha \Rightarrow \gamma = T_\epsilon/2$
2. $f(T_\varepsilon) = \alpha\, e^{-\beta\,(T_\varepsilon/2)^2} = \varepsilon\,\alpha$

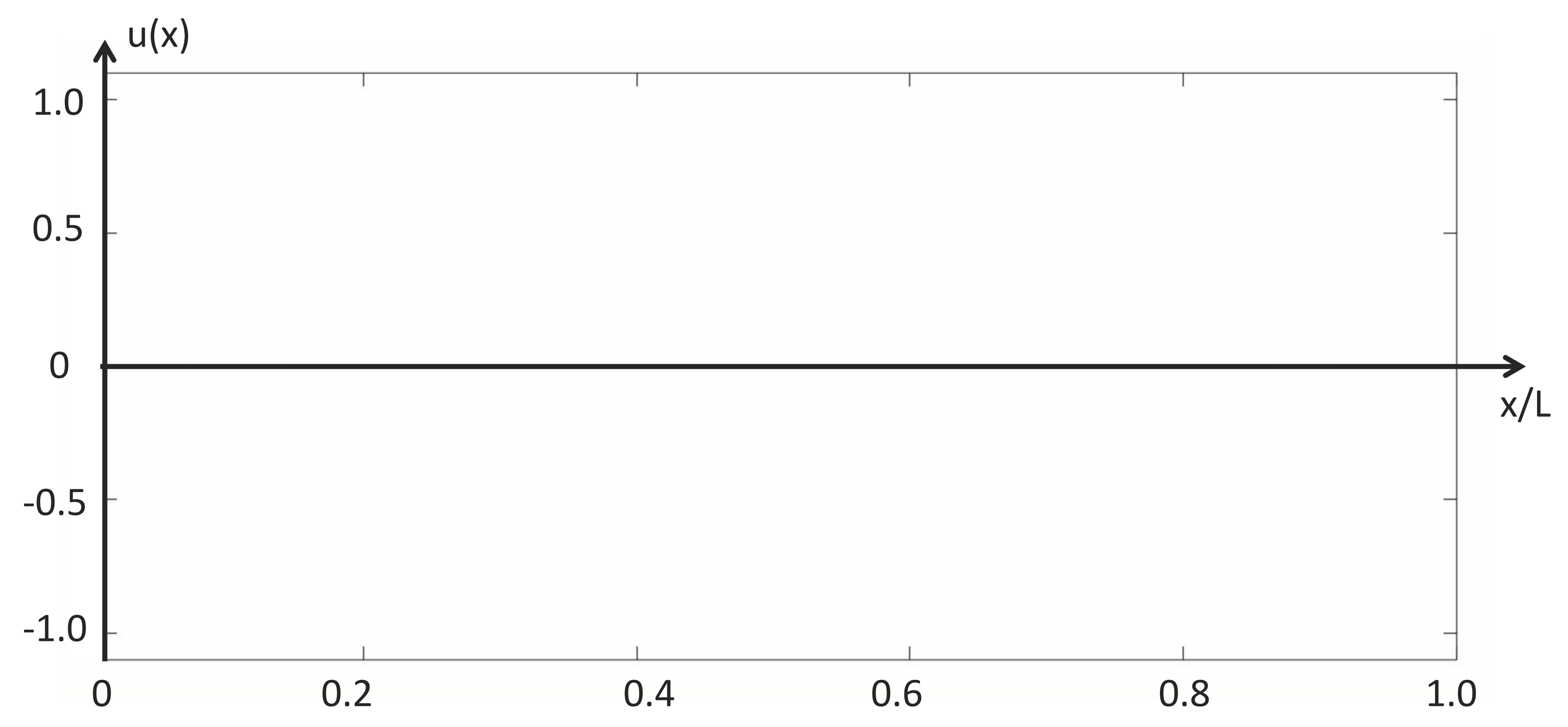
$$\Rightarrow \beta = -\left(\frac{2}{T_\varepsilon}\right)^2 \ln \varepsilon$$

$$\boxed{\begin{aligned} f(t) &= \alpha\, e^{-\beta\,(t-T_\varepsilon/2)^2} \\ \beta &= -\left(\frac{2}{T_\varepsilon}\right)^2 \ln \varepsilon \end{aligned}}$$

Typical value for **sufficient smoothness**: $\varepsilon = 0.001$

EXCITATION FUNCTIONS

Run the transient scheme with **Gaussian excitation** at the left end of the string:



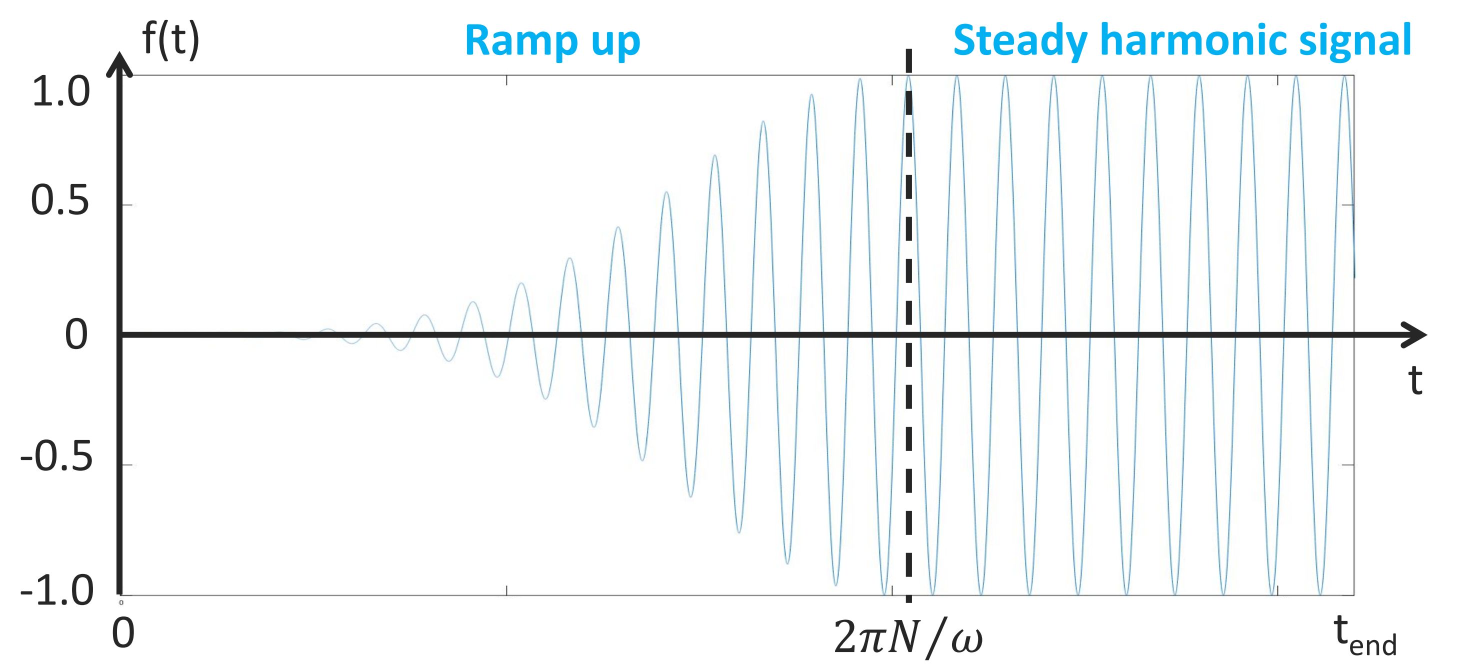
Video: Guitar_string_with_Gaussian_Excitation

EXCITATION FUNCTIONS

As an alternative to a pulse shaped excitation, a ramped up harmonic excitation can be used, too. A **ramped up sinusoidal** excitation function can be defined as follows:

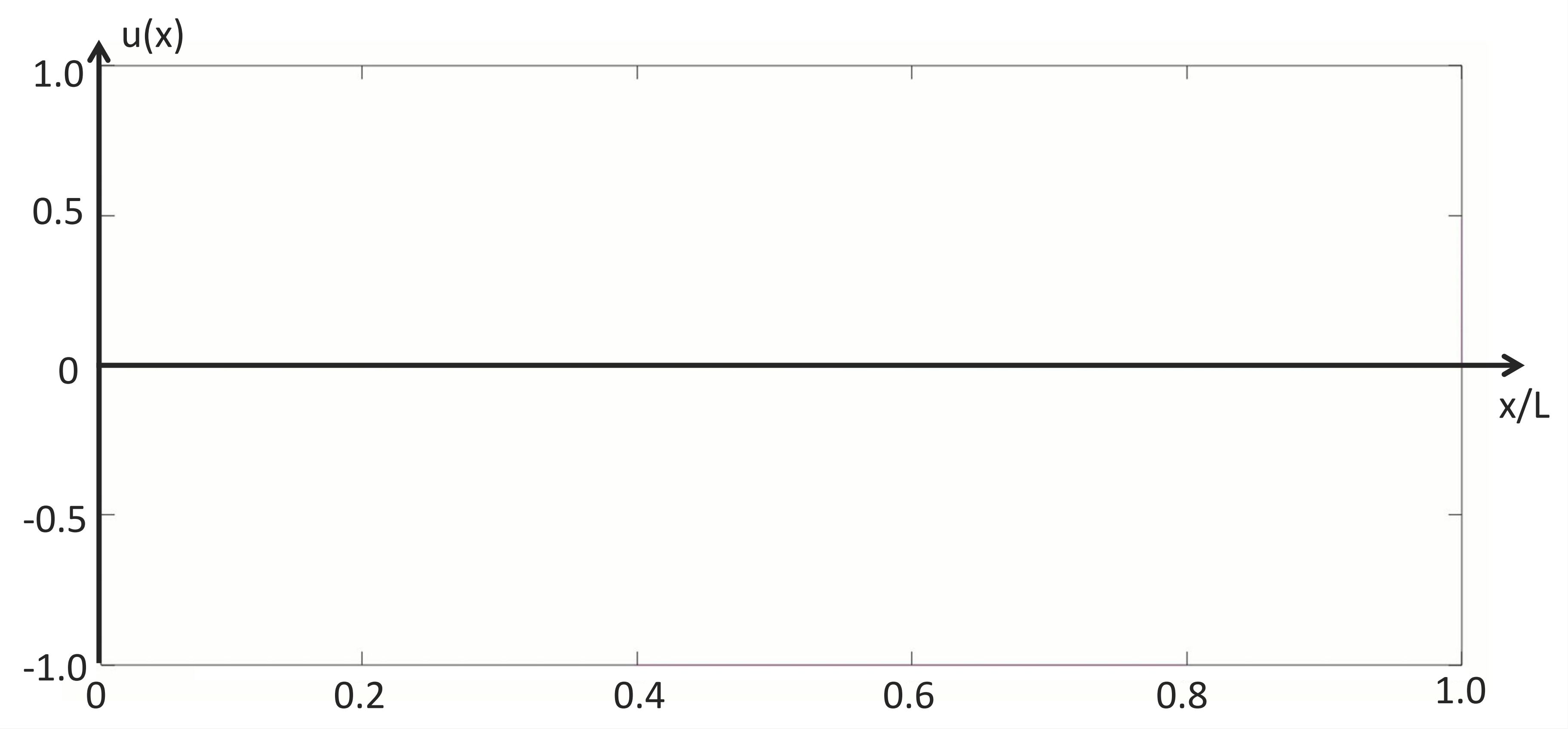
$$f(t) = \begin{cases} e^{\frac{\ln 0.001}{\left(N\frac{2\pi}{\omega}\right)^2}\left(t-N\frac{2\pi}{\omega}\right)^2} \sin(\omega t), & t < 2\pi N/\omega \\ \sin(\omega t) \quad , & t \geq 2\pi N/\omega \end{cases}$$

Ramp up for N periods



EXCITATION FUNCTIONS

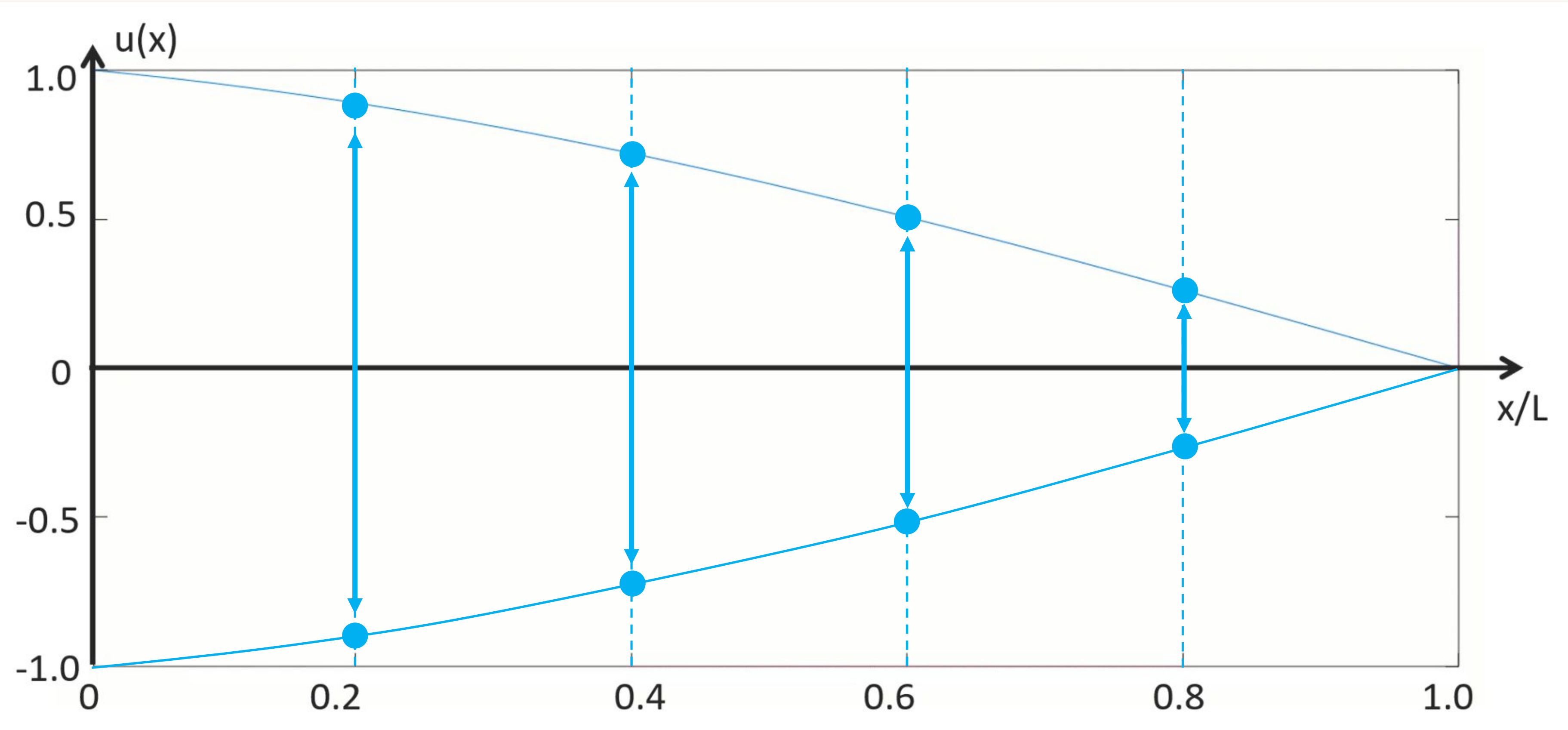
Now run the transient scheme with a **slowly ramped up sinusoidal** excitation at the left end of the string:



Video: Guitar_string_with_harmonic_excitation

EXCITATION FUNCTIONS

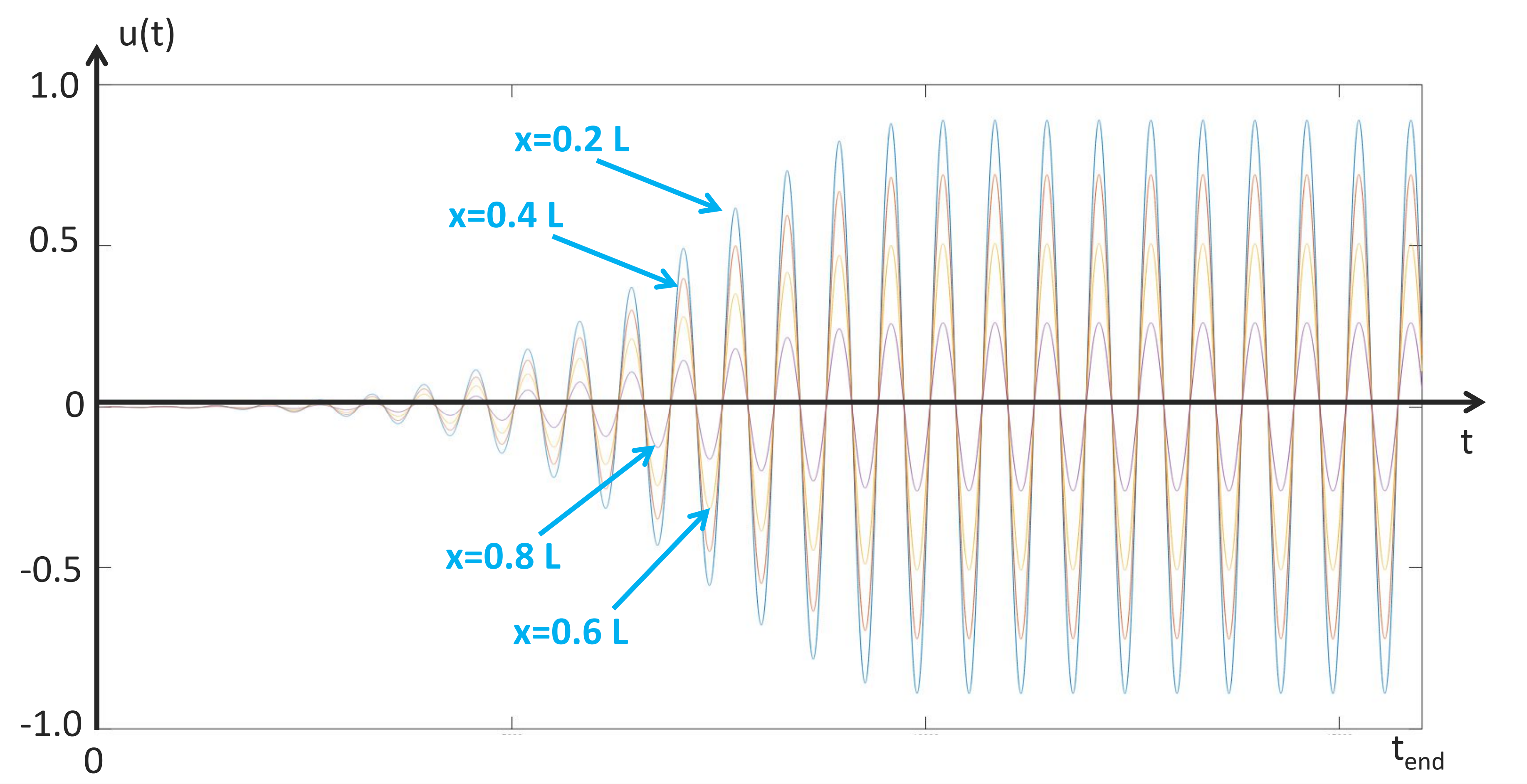
At each **position along the string**, the string performs a **harmonic oscillation** with a **position dependent amplitude**:



Thus, after a while the string performs a **continuous harmonic steady-state oscillation**

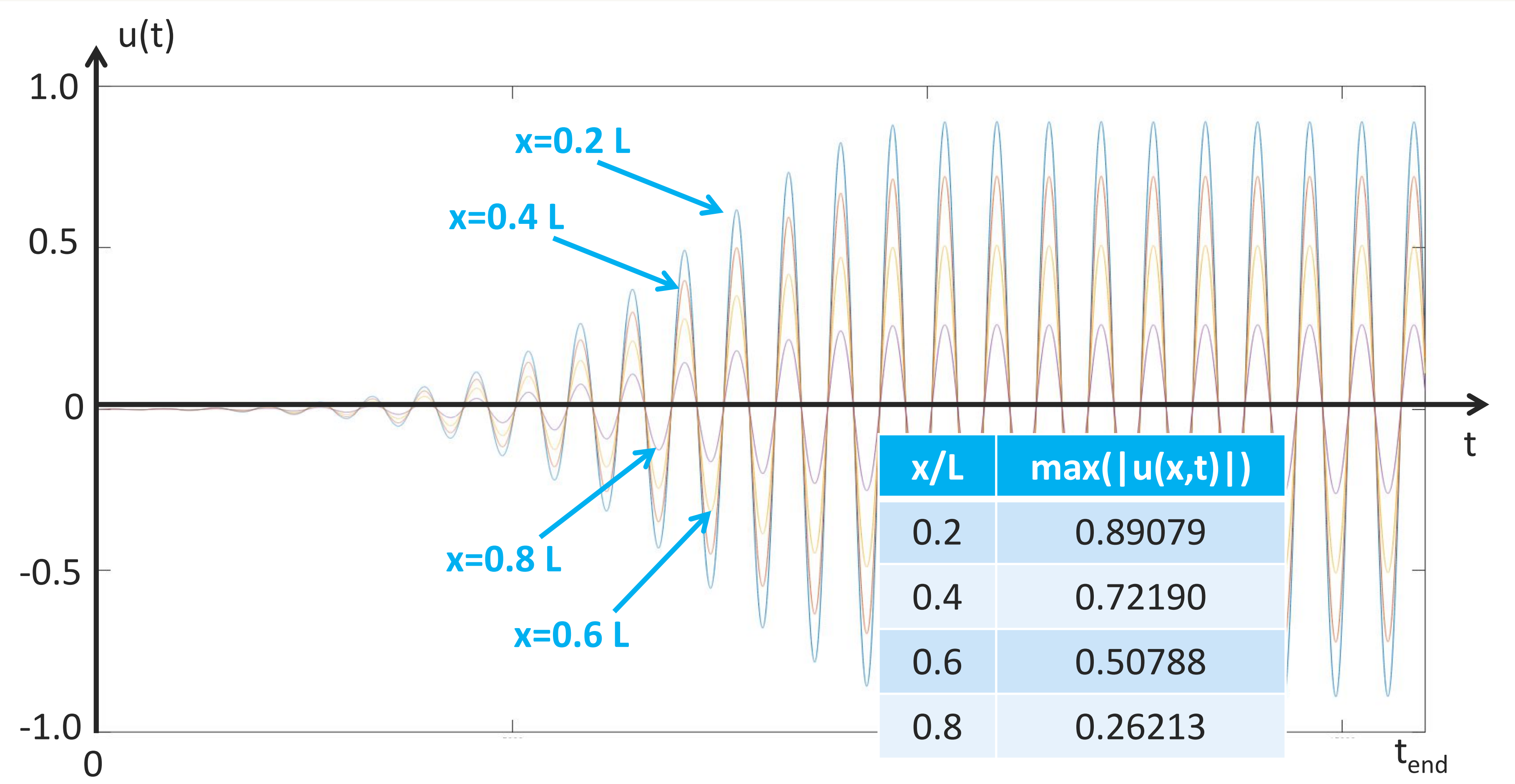
EXCITATION FUNCTIONS

At each **position along the string**, the string performs a **harmonic oscillation** with a **position dependent amplitude**:



EXCITATION FUNCTIONS

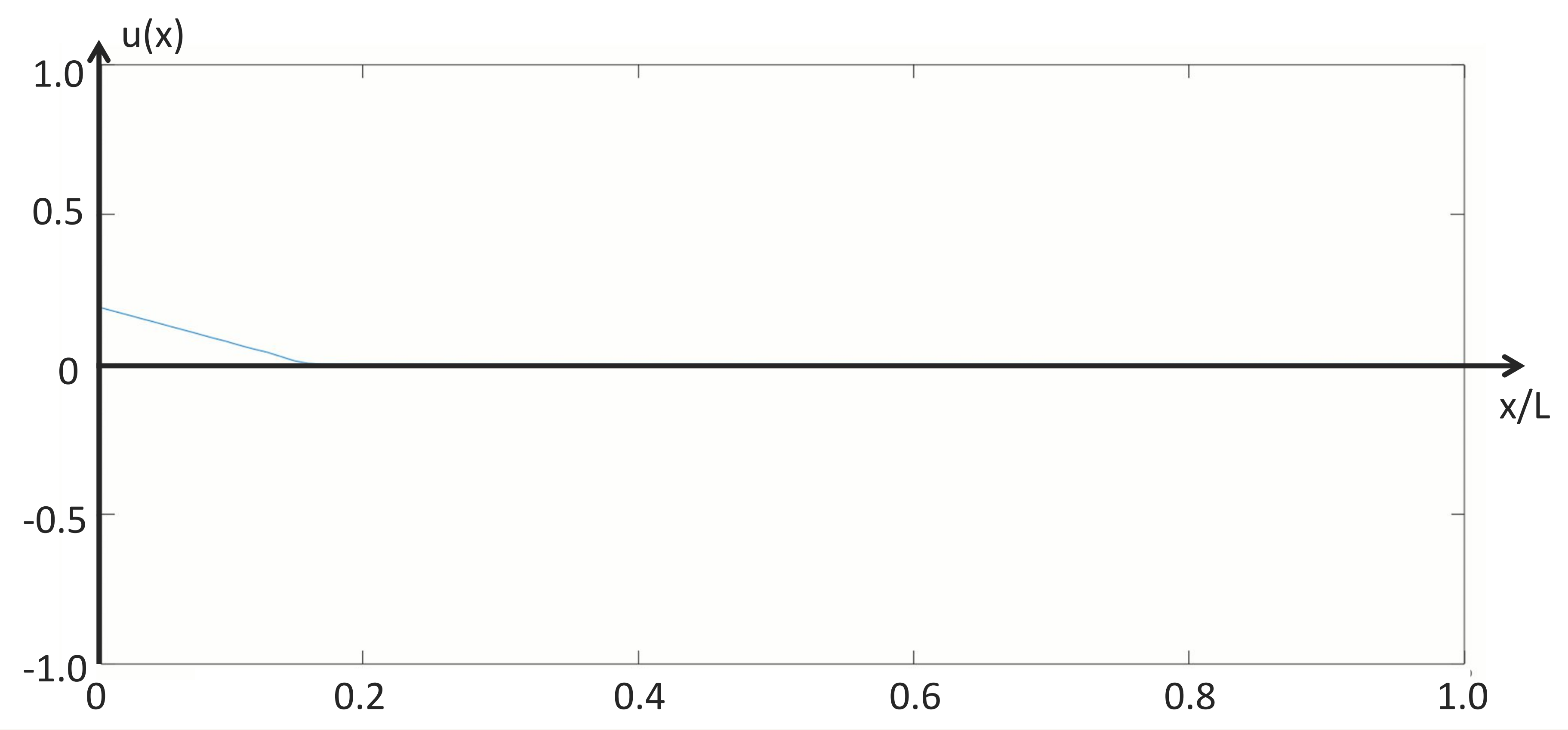
At each **position along the string**, the string performs a **harmonic oscillation** with a **position dependent amplitude**:



x/L	max(|u(x,t)|)
0.2	0.89079
0.4	0.72190
0.6	0.50788
0.8	0.26213

EXCITATION FUNCTIONS

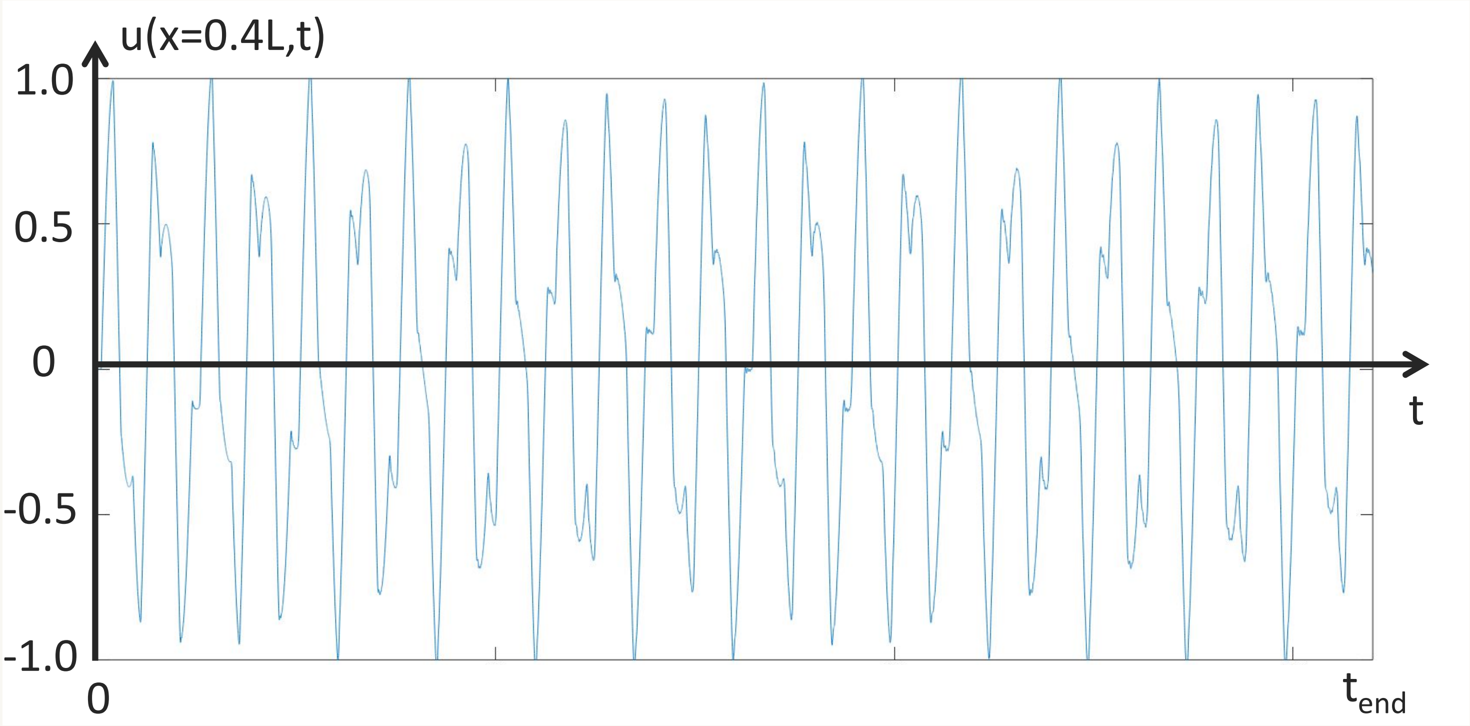
What happens if we switch on the sinus **without ramping up the amplitude**?



Video: Guitar_string_with_step_harmonic_excitation

EXCITATION FUNCTIONS

The **step function type excitation** creates a lot of **high frequency** content stimulating many **higher order modes** which disturb the harmonic solution:



Note: Smooth excitation functions need to be used if **harmonic steady-state** solutions shall be obtained from transient simulations directly

FINITE DIFFERENCE METHOD AGENDA

1. ✓ Wave equation with excitation
2. ✓ Excitation functions
3. Driven problems in Frequency Domain
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DRIVEN PROBLEMS IN FREQUENCY DOMAIN

FREQUENCY DOMAIN SOLUTION OF THE DRIVEN PROBLEM

Time harmonic **steady-state** solutions can be obtained from the **Frequency Domain** formulation:

$$\frac{\partial^2 \underline{u}(x)}{\partial x^2} = -k\,\omega^2\,\underline{u}(x)$$

Applying a spatial discretization (**central difference**) again, we obtain:

$$\frac{\underline{u}_{i+1} - 2\underline{u}_i + \underline{u}_{i-1}}{\Delta x^2} = -k\,\omega^2 \underline{u}_i$$

For the **special case $i = 1$** we get:

$$\frac{\underline{u}_2 - 2\underline{u}_1 + \underline{u}_0}{\Delta x^2} = -k\,\omega^2 \underline{u}_1$$

Our **time harmonic excitation function** defines the value of $\underline{u}_0 = \underline{f}$

$$\frac{\underline{u}_2 - 2\underline{u}_1}{\Delta x^2} = -k\,\omega^2 \underline{u}_1 - \frac{\underline{u}_0}{\Delta x^2}$$

DRIVEN PROBLEMS IN FREQUENCY DOMAIN

FREQUENCY DOMAIN SOLUTION OF THE DRIVEN PROBLEM

In **matrix form**, we can then write (the first row contains the **excitation**):

$$\begin{pmatrix} \ddots & & & & \\ & \ddots & & & \\ & 1 & -2 & 1 & \\ & & & \ddots & \\ & & & & \ddots \end{pmatrix} \begin{pmatrix} \underline{u}_1 \\ \underline{u}_2 \\ \vdots \\ \underline{u}_{N-1} \end{pmatrix} = -k\,\omega^2 \Delta x^2 \begin{pmatrix} \underline{u}_1 \\ \underline{u}_2 \\ \vdots \\ \underline{u}_{N-1} \end{pmatrix} + \begin{pmatrix} -\underline{f} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

Or by **adding the term** $k\,\omega^2 \Delta x^2 \underline{u}$:

$$\underbrace{\begin{pmatrix} \ddots & & & & \\ & \ddots & & & \\ & 1 & k\,\omega^2 \Delta x^2 - 2 & 1 & \\ & & & \ddots & \\ & & & & \ddots \end{pmatrix}}_{M} \underbrace{\begin{pmatrix} \underline{u}_1 \\ \underline{u}_2 \\ \vdots \\ \underline{u}_{N-1} \end{pmatrix}}_{\underline{u}} = \underbrace{\begin{pmatrix} -\underline{f} \\ 0 \\ \vdots \\ 0 \end{pmatrix}}_{b}$$

DRIVEN PROBLEMS IN FREQUENCY DOMAIN

FREQUENCY DOMAIN SOLUTION OF THE DRIVEN PROBLEM

The resulting **equation system** has the form of:

$$M\,\underline{u} = b$$

where b is called the **excitation vector** or often simply **right-hand side**.

The system can be solved by calculating the **matrix inverse**

$$\underline{u} = M^{-1}\,b$$

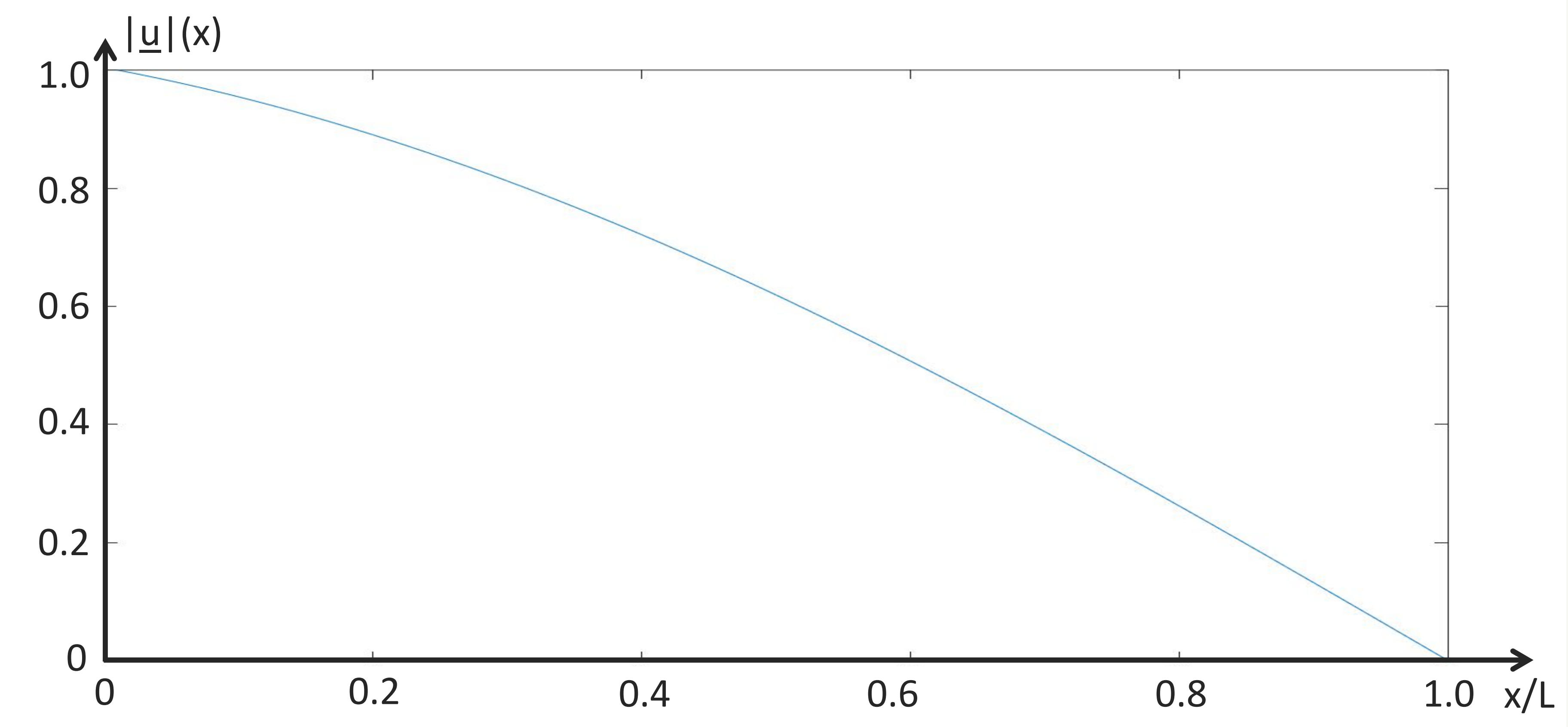
or by applying any algorithm to solve this **linear system of equations**:

1. **Direct methods**, e.g.
   1. Gaussian elimination
   2. Matrix factorization
2. **Iterative methods**, e.g.
   1. Preconditioned Krylow subspace methods (e.g. CG)
   2. Multigrid methods

DRIVEN PROBLEMS IN FREQUENCY DOMAIN

FREQUENCY DOMAIN SOLUTION OF THE DRIVEN PROBLEM

Solving the equation system in MATLAB using **linsolve** yields:



MATLAB: USEFUL TIPS AND TRICKS

SOLVING MATRIX EQUATIONS $M\,u = b$

```
u = inv(M)*b        % or better: u = M\b

u = linsolve(M, b)% direct solution using factorization

% iterative solvers for sparse matrices
S = sparse(M)       % Convert a full matrix into sparse form

u = pcg(S, b)       % preconditioned conjugate gradients method
u = bicg(S,b)       % BiConjugate gradients method
u = bicgstab(S,b)  % BiConjugate gradients stabilized method
u = qmr(S,b)        % Quasi-Minimal Residual (QMR) method
u = tfqmr(S,b)      % Transpose-Free QMR method
```

There is a **large collection** of other solvers and **additional libraries** available for solving **linear equation systems**. **Optimal solver selection** depends on matrix properties and influences **runtime** and **memory** requirements

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RESULTS IN TIME AND FREQUENCY DOMAIN

Comparing the **Time Domain** and **Frequency Domain** results for the harmonic steady-state behavior, we get:

x/L	Transient max(|u(x,t)|)	Frequency Domain |$\underline{u}$(x)|	|Deviation| TD from FD
0.2	0.89079	0.89376	0.33%
0.4	0.72190	0.72787	0.82%
0.6	0.50788	0.51672	1.74%
0.8	0.26213	0.27345	4.14%

Reasons for the differences:

1. Steady-state solution not yet reached in transient simulation
2. Excitation of higher order eigenmodes in transient simulation (smoothness of excitation)
3. Discretization error of the time derivatives (numerical dispersion)
4. Numerical error when solving the linear equation system

Conclusion: It is not straight-forward to compute harmonic steady-state solutions from transient simulations, but possible.

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SOLUTIONS OF THE WAVE EQUATION

$$\frac{\partial^2 u(x,t)}{\partial x^2} - k\frac{\partial^2 u(x,t)}{\partial t^2} = 0$$

Wave Equation

- **Time Domain**
  - **Initial Value Problem**: Weather forecast
  - **Driven Problem**: Automotive suspension dynamics
- **Frequency Domain**
  - **Eigenmode Problem**: Bridge resonance
  - **Driven Problem**: Radiation of Wifi router

SOLUTIONS OF THE WAVE EQUATION

SUMMARY OF FORMULATIONS

1. **Transient**
   - Discretization of **spatial** and **temporal derivatives**
   - Ideally suited for **transient phenomena**
   - **Explicit** scheme, matrix times vector multiplications only
   - Can be **less efficient** for calculating **harmonic steady-state** solutions

2. **Frequency Domain**
   - Transformation into **frequency domain** and discretization of **spatial derivatives**
   - Ideally suited for computing **harmonic steady-state** solutions
   - Requires solutions of **equation system,** either direct or iterative
   - Can be **less efficient** for calculating **transient solutions** due to large number of required frequency samples

3. **Eigenmode**
   - Special variant of the **frequency domain** formulation **without excitation**
   - Ideally suited for computing the **eigenmodes** (resonances) of a system

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VARYING MATERIAL PROPERTIES

MATERIAL PROPERTIES

So far, we have solved the wave equation for **constant** k:

$$\frac{\partial^2 u(x,t)}{\partial x^2} - k\frac{\partial^2 u(x,t)}{\partial t^2} = 0$$

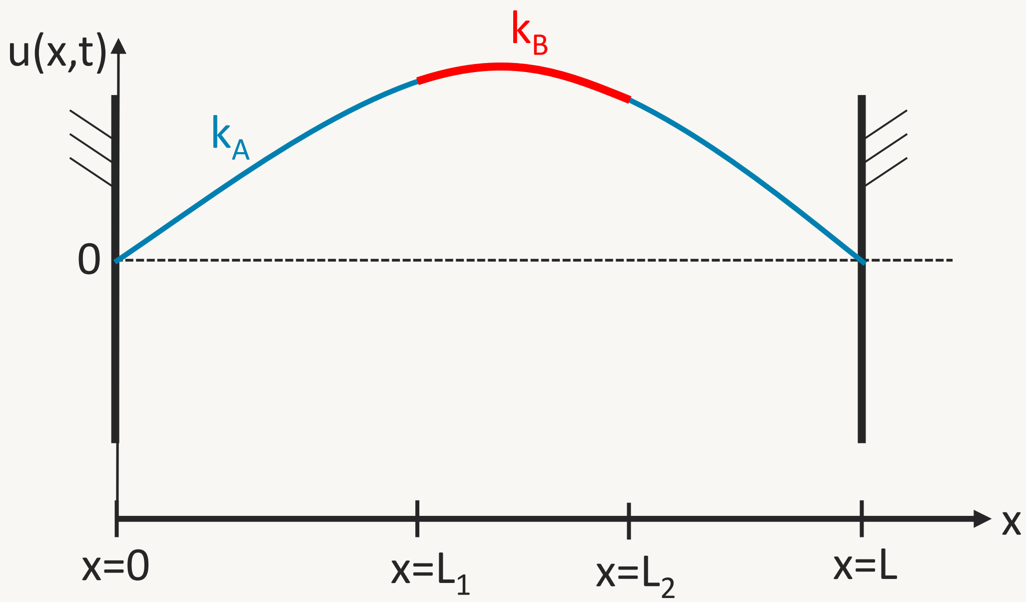
The parameter k describes the **speed** of the spatial **wave propagation** and is determined by the **properties of the materials** in which the wave propagates

In our example, it is described by the **stiffness of the string**

What happens if the string contains a segment with a **different stiffness**?

VARYING MATERIAL PROPERTIES

MATERIAL PROPERTIES



VARYING MATERIAL PROPERTIES

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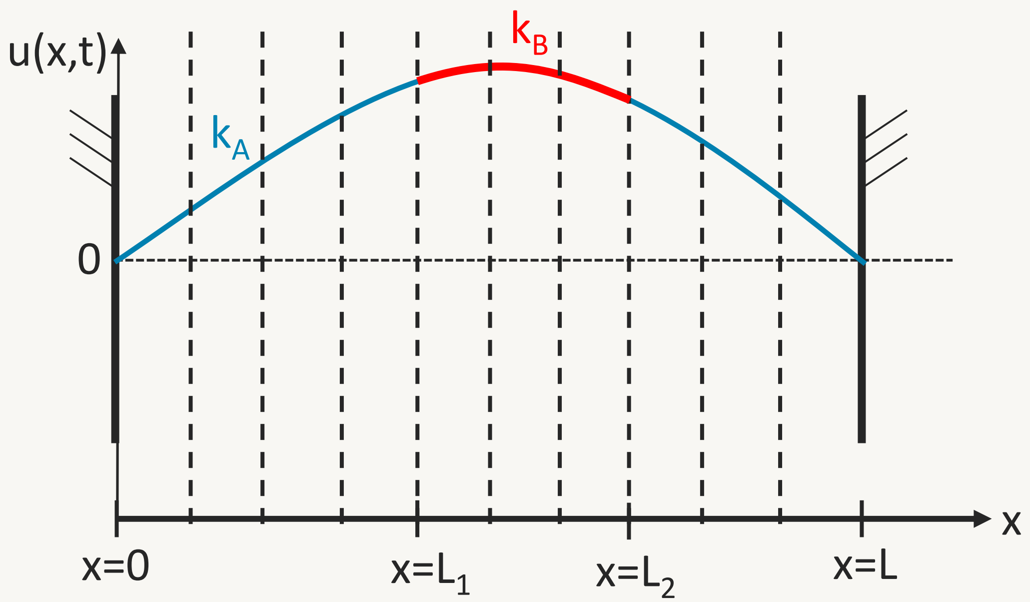


1. Perform a **spatial discretization** of the string as before
2. Apply a **specific value** of k for each segment (instead of using a constant k):

$$\frac{\underline{u}_{i+1} - 2\underline{u}_i + \underline{u}_{i-1}}{\Delta x^2} = -\boldsymbol{k_i}\,\omega^2 \underline{u}_i$$

VARYING MATERIAL PROPERTIES

EXAMPLE: TRANSIENT SOLUTION OF THE DRIVEN PROBLEM

Based on this approach, we obtain the following **iteration scheme**: $c_i = \frac{\Delta t^2}{k_i \Delta x^2}$

$$i = 1, \dots, N-1 \quad : \quad u_{i,0} = 0$$

Initialization

$$u_{1,1} = f_1$$

$$i = 2, \dots, N-1 \quad : \quad u_{i,1} = c_i \left(u_{i+1,0} + u_{i-1,0} - 2u_{i,0}\right) + u_{i,0}$$

First step

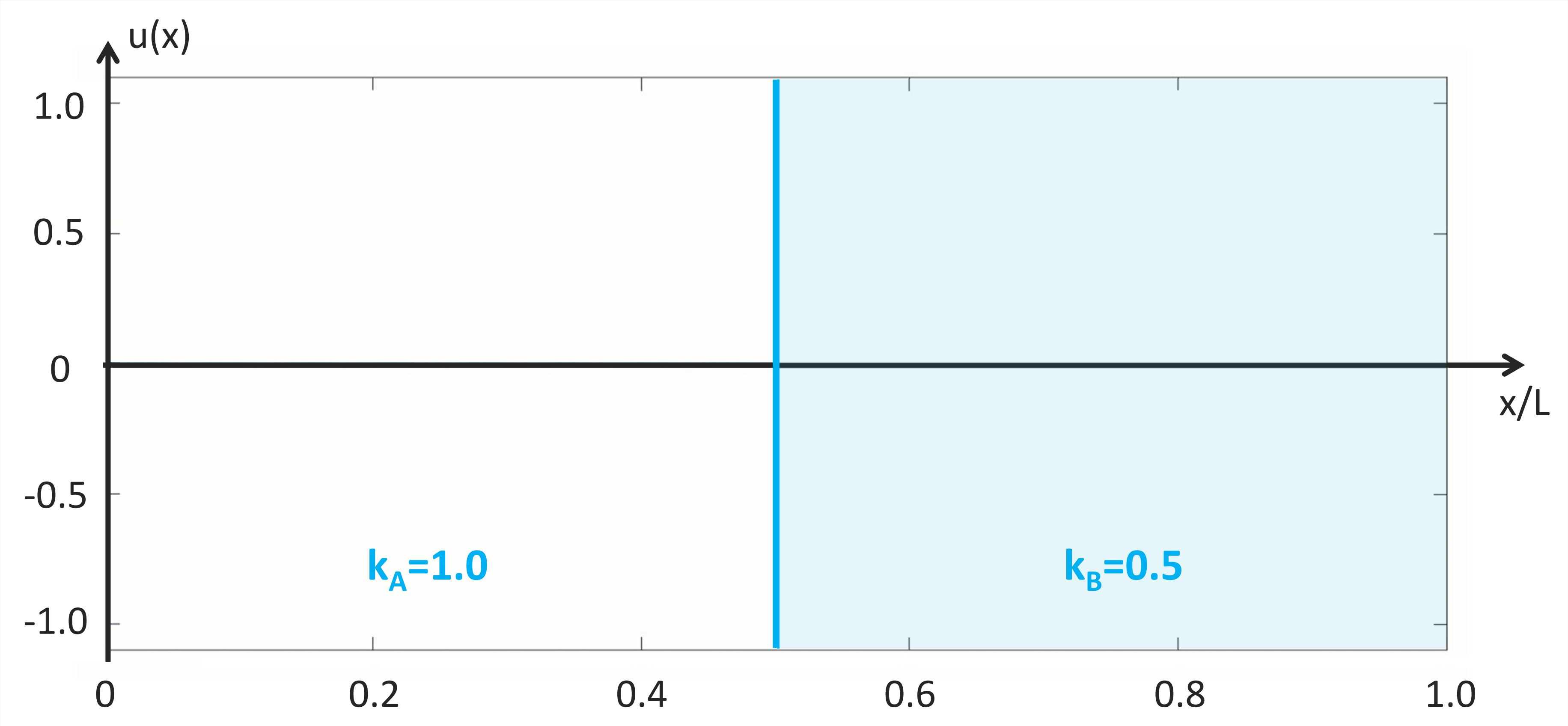
$$j = 2, \dots : \quad u_{1,j} = f_j$$

$$i = 2, \dots, N-1, j = 2, \dots : \quad u_{i,j} = c_i \left(u_{i+1,j-1} + u_{i-1,j-1} - 2u_{i,j-1}\right) + 2u_{i,j-1} - u_{i,j-2}$$

Iteration

VARYING MATERIAL PROPERTIES

Run the transient scheme with **Gaussian** excitation at the left end of the string and **two different values for the string stiffness**:



Video: Guitar_string_with_two_materials

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COMMERCIAL SOFTWARE CST STUDIO SUITE

CST Studio Suite® is a high-performance **3D Electromagnetic and Thermal analysis** software package for designing, analyzing and optimizing components and systems. Next week, we will start using this commercial software package to run some simulations

A **academic version** is available in the computer rooms at the university

However, due to the current restrictions it is **highly recommended** (but optional) that you install a student edition of the software on your own computer

Since the confirmation of your registration will take a **few days**, please go ahead and download and install the software **as soon as possible**

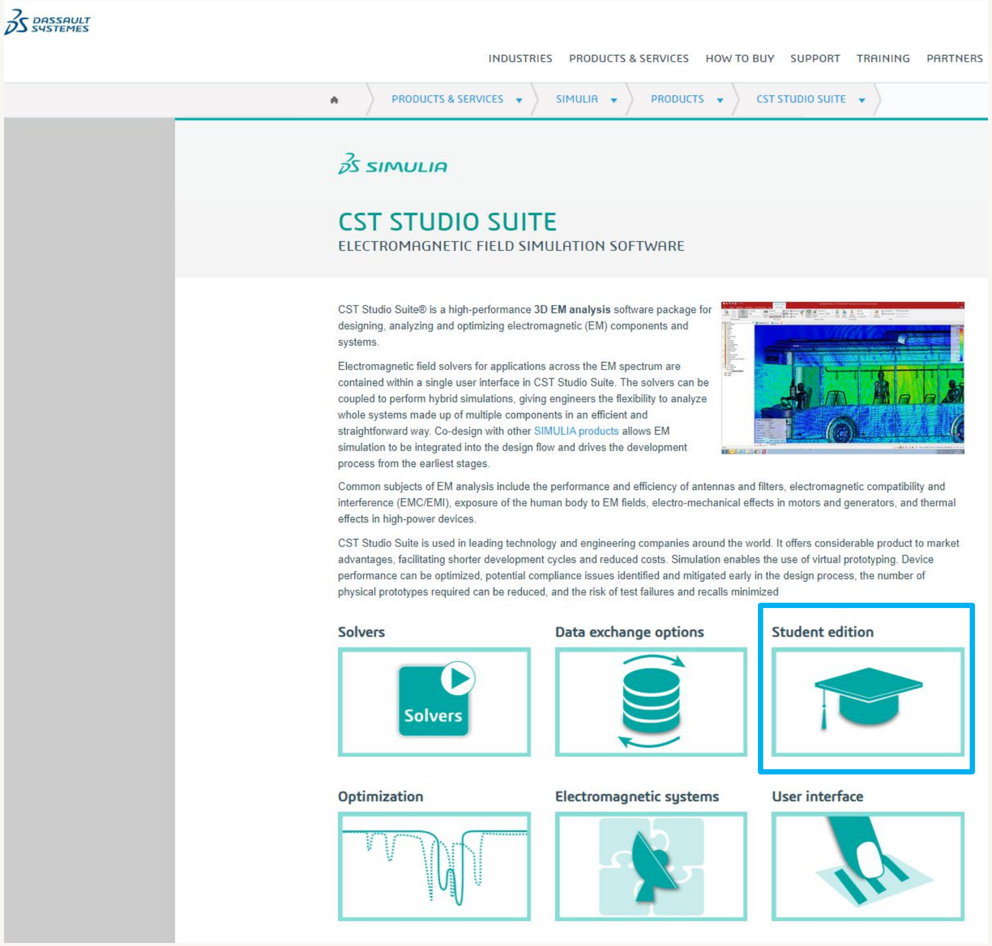
The Student Edition can be downloaded free of charge from

https://www.3ds.com/products-services/simulia/products/cst-studio-suite

The following slides will explain how to **install the student edition** on your own computer

COMMERCIAL SOFTWARE CST STUDIO SUITE

Visit the webpage:
https://www.3ds.com/products-services/simulia/products/cst-studio-suite



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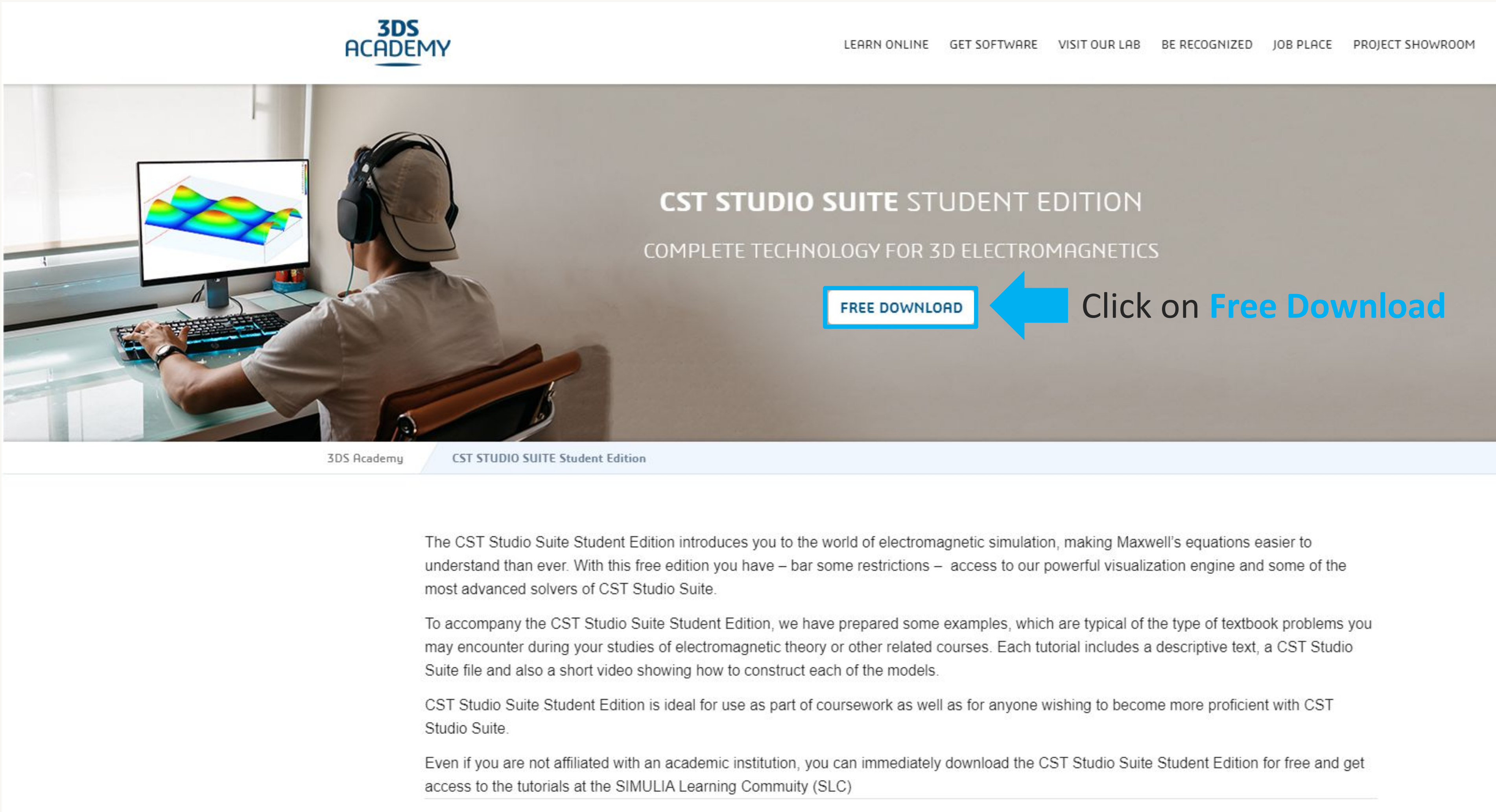
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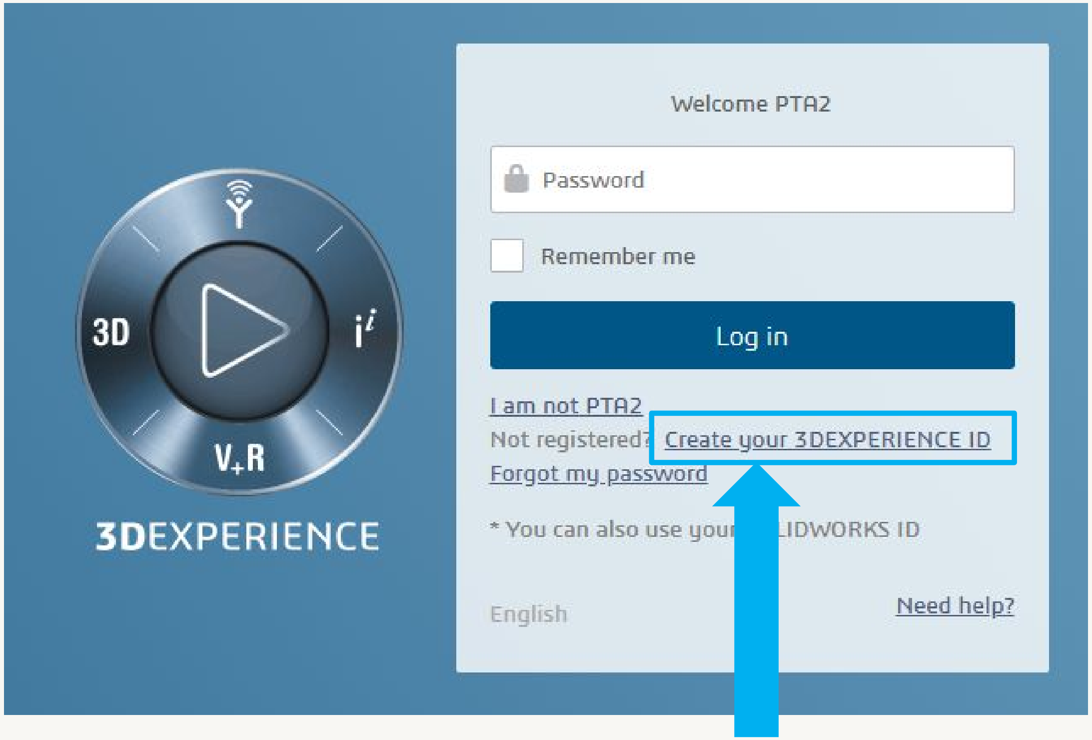
CST Studio Suite Student Edition is ideal for use as part of coursework as well as for anyone wishing to become more proficient with CST Studio Suite.

Even if you are not affiliated with an academic institution, you can immediately download the CST Studio Suite Student Edition for free and get access to the tutorials at the SIMULIA Learning Community (SLC)

COMMERCIAL SOFTWARE CST STUDIO SUITE



You need to **create an account** to be able to download the software

The video contains introductions about **how to create an account** (starting at 0:15):

https://youtu.be/Z8cMPTVeWsI

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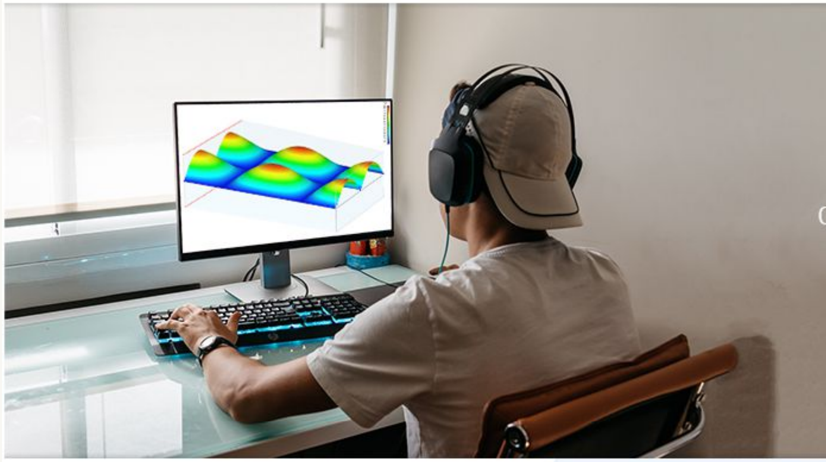

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FINITE DIFFERENCE METHOD AGENDA

✓ 1. Wave equation with excitation
✓ 2. Excitation functions
✓ 3. Driven problems in Frequency Domain
✓ 4. Results in Time and Frequency Domain
✓ 5. Solutions of the wave equation
✓ 6. Varying material properties
✓ 7. Commercial software CST Studio Suite

THANK YOU!

See you in the exercise!