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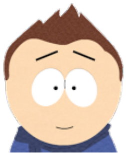

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Abstract

English abstract

Resumé

Danish Abstract

Contents

Curriculum Vitae **iii**

Abstract **v**

Resumé **vii**

Preface **xiii**

I Introduction 1

Introduction **3**

1 History of bowed strings . . . 3
2 To do thingies . . . 3
2.1 Intuition for the frequency dependent damping term $2\sigma_1\partial_t\partial_x^2 u$ . . . 3
3 Notes . . . 5
References . . . 5

II Dynamic Grids 7

Dynamic Grids **9**

4 Introduction . . . 9

Todo list

Preface

As my background does (did) not lie in mathematics, physics or computer science, which – trust me – were three equally crucial components in creating the result of this project, I added a, say, more pedagogical section at the end of this thesis. These tutorials are a result of the things that I learned and (hopefully) explain topics such as *Energy Analysis*, *Stability Analysis*, etc. in a way so that others with the same background will be able to understand what is going on.

Name
Aalborg University, January 14, 2021

Part I

Introduction

Introduction

1 History of bowed strings

In static bow-string-interaction models, the friction force is defined as a function of the relative velocity between the bow and the string only. The first mathematical description of friction was proposed by Coulomb in 1773 [**?**] to which static friction, or *stiction*, was added by Morin in 1833 [**?**] and viscous friction, or velocity-dependent friction, by Reynolds in 1886 [**?**]. In 1902, Stribeck found a smooth transition between the static and the coulomb part of the friction curve now referred to as the Stribeck effect [**?**]. The latter is still the standard for static friction models today.

2 To do thingies

- Think about how to define real-time.
- Create an intuition for different parts of the equation
- Talk about input and output locations and how that affects frequency content (modes).

2.1 Intuition for the frequency dependent damping term $2\sigma_1\partial_t\partial_x^2 u$

Take the frequency independent damping term $-2\sigma_0\partial_t u$. The more positive the velocity $\partial_t u$ is, i.e., the string is moving upwards the more this term applies a negative, or downwards force (/effect) on the string. Vice versa, a more negative velocity will make this term apply a more positive force on the string. As for the frequency dependent damping term, apart from the obvious σ_1, the effect of the term increases with an increase of $\partial_t\partial_x^2 u$ which describes the rate of change of the curvature of the string.

Let's first talk about positive and negative curvature, i.e., when $\partial_x^2 u > 0$ or $\partial_x^2 u < 0$. Counterintuitively, in the positive case, the curve points downwards. Think about the function $f(x) = x^2$. It has a positive curvature (at any point), but has a minimum. We can prove this by taking $x = 0$ and setting grid spacing $h = 1$.

$$
\begin{aligned}
\delta_{xx} f(x) &= \frac{1}{h^2}\left(f(-1) - 2f(0) + f(1)\right), \\
&= \frac{1}{1^2}\left((-1)^2 - 2 \cdot 0^2 + 1^2\right), \\
&= (1 - 0 + 1) = 2.
\end{aligned}
\tag{1}
$$

In other words, the second derivative of the function $f(x) = x^2$ around $x = 0$ is positive.

As our term does not only include a second-order spatial derivative but also a first-order time derivative, we are now talking about a positive or negative *rate of change* of the curvature, i.e., when $\partial_t \partial_x^2 u > 0$ or $\partial_t \partial_x^2 u < 0$. A positive rate of change of curvature means that the string either has a positive curvature and is getting more positive, i.e., the string gets more curved over time, or that the string has a negative curvature and is getting less negative, i.e., the string gets less curved or 'loosens up' over time. In the same way, a negative rate of change of curvature means that the string either has a negative curvature and is getting more negative, or that the string has a positive curvature and is getting less positive.

Let's see some examples. Take the same function described before, but now f changes over time, fx. $f(x,t) = tx^2$. When t increases over time, the curvature gets bigger. Repeating what we did above with $x = 0$ and grid spacing $h = 1$, but now with $t = 2$ and step size $k = 1$, but now with a backwards time derivative we get:

$$
\begin{aligned}
\delta_{t-}\delta_{xx} f(x,t) &= \frac{1}{kh^2}\Bigg(\quad f(-1,2) - 2f(0,2) + f(1,2) \\
&\qquad - \Big(f(-1,1) - 2f(0,1) + f(1,1)\Big)\Bigg), \\
&= \frac{1}{1 \cdot 1^2}\Bigg(2 \cdot (-1)^2 - 2 \cdot 2 \cdot (0)^2 + 2 \cdot 1^2 \\
&\qquad - \Big(1 \cdot (-1)^2 - 2 \cdot 1 \cdot (0) + 1 \cdot (1^2)\Big)\Bigg), \\
&= 2 + 2 - (1 + 1) = 2.
\end{aligned}
$$

So the rate of change of the curvature is positive, i.e., the already positively curved function x^2 gets more curved over time.

If the curvature around a point along a string gets more positive (or less negative) over time, the force applied to that point will be positive. Vice versa, if the curvature around a point along a string gets more negative (or less positive) over time, the force applied will be negative.

The fact the frequency dependent term to be added rather than subtracted to the FDS, is caused by the fact that a positive curvature implies a negative position in the string (think of the function x^2 which has a positive curvature, but the function 'points' downwards). This translated to the force/effect this term has on the scheme means...

3 Notes

One over number $\rightarrow$ reciprocal of number

Example: When the waveform consists entirely of harmonically related frequencies, it will be periodic, with a period equal to the reciprocal of the fundamental frequency (from An Introduction to the Mathematics of Digital Signal Processing Pt 2 by F. R. Moore)

References

References

Part II

Dynamic Grids

Dynamic Grids

4 Introduction