Stimmung und Intonation bei Blechblasinstrumenten

Tuning and intonation of brass instruments

Sideletter #4: Openwind – Python FEM Simulation

Project status 24.11.2024, Revision 20.0

The latest revision of this document can be found at the project site:
http://www.preisl.at/brassissima/

Accompanying documentation of the project / topic.
Development, Work, Calculation and Copyright:

brassissima
The fantastic world of Brass Instruments

(="Brass Instrument Scanning System – Impedance Measurements & Analysis")

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P.S.: If you find systematic errors, nonsense or false claims:

Please don't keep them!!,
but please send me a short message, that helps me a lot, thank you!!

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Openwind

At the end of 2023 I came across a very interesting open source project from France, which on the one hand offers a browser-based online demo and on the other hand can be run as a Python library with scripts. It is described as a "Python library assisting instrument makers", the project is found under https://openwind.inria.fr/

It currently consists of 3 basic modules:

1. Impedance Computation with FEM Finite Element Methode in 1D
   or also TMM Transfer Matrix Methode
   or modal
   for Woodwind and Brassinstruments, open-open tubes can also be simulated, using a “player” source
2. Sound Simulation
3. Instrument Geometry Optimisation

I am absolutely not a Python specialist, nor do I want to delve deeper into it at the moment, the project is also well documented in English and provides example scripts that can be run under Python, and the installation of Python is also explained.

So I installed Python 3.12 (Windows), Anaconda 3 Navigator and Spyder 5 and worked my way through it a bit, the Openwind release used is 0.10.3 (as of December 2023),

Meanwile Version 0.11.1 is available, where the roughness and porosity of the wall can be modeled.
Update: Anaconda, Openwind-Env, updatable, > green arrow next to openwind-env; installs the necessary updates; Spider must then be restarted. (I installed this update on February 24, 2024).

In addition to other functions, it is possible to determine the input impedance from a text file that describes the geometry of an instrument and output the result back to a text file.

However, there are some special features that must be observed:

Python uses the point as a decimal separator
Openwind uses meters as the standard unit of measurement
Temperature is 25 degrees by default
Humidity 50%
The resolution and frequency range can be set
The simulation is not carried out with TMM by default but with FEM
TMM can only be used for cylindrical and conical parts.
Losses are not entered in % or factors (As in ART), there are several “models”.
This models are described here: https://inria.hal.science/hal-02917351

1D Zwikker and Kosten losses with Bessel function model is not compatible with modal method. Consider using lossless (losses=False) or diffusive representation of Zwikker-Kosten model (losses=diffrepr+) instead.

Spherical wave fronts can also be simulated.
The impedance data is output as a frequency with real and imaginary parts.
The amount |Z| and the phase angle can then be determined from this:
Input impedance $|Z|in = \text{root}(Re^2+Im^2)$, phase angle in RAD = arctan(Im/Re).

Impedance peaks can be calculated in different ways, but by default they are only output on the console, not written to a file, so i was able to do this als addition to the script.

The following script.py describes the basic functionality for my experiments, this is opened and executed in Spider:

```
# Copyright (C) 2019-2023, INRIA
# This file is part of Openwind, and edited / extended bei Hermann Preisl – thanks to ChatGpt.

import numpy as np
import matplotlib.pyplot as plt
from openwind import ImpedanceComputation

# %% Basic computation
# Frequencies of interest: 10Hz to 2kHz by steps of 0,333 Hz
fs = np.arange(10.0, 2000, 0.3333333)
geom_filename = 'instrument.txt'

# Find file 'instrument' describing the bore, and compute its impedance
result = ImpedanceComputation(fs, geom_filename)

# you can get the characteristic impedance at the entrance of the instrument
# which can be useful to normalize the impedance
Zc = result.Zc

# you can print the computed impedance in a file.
# It is automatically normalized by Zc
result.write_impedance('computed_impedance.txt')

# %% Der folgende Abschnitt oeffnet die gerade erstellte Datei und ersetzt die
# Punkte als Dezimalzeichen durch Komma und schreibt die Datei neu als txt file

# Einlesen der Textdatei
with open('computed_impedance.txt', 'r') as file:
    lines = file.readlines()
# Ersetzen der Dezimalpunkte durch Kommata
lines = [line.replace('.', ',') for line in lines]
# Schreiben in eine neue Textdatei mit geändertem Dezimalzeichen
with open('result.txt', 'w') as file:
    file.writelines(lines)
```

In order to achieve comparative measurements and compatibility with my existing Excel files, I have to change some standard settings.

I name the geometry file geometry.txt (with a comma as the decimal point)
I use millimeters as the unit of measurement and the diameter (dia) in mm instead of the radius:
The geometry.txt now looks as follows with an example of a standard perturbation length of 1m:

```
! unit = mm             # 1.Zeile! Befehl an ow
! diameter = True       # 2.Zeile! Befehl an ow
#Pos x# Dia y   in mm   Hinweis: rein konische bzw. lineare Teile, Steps bei 490 u 510 mm
0       10
490     10
490     11,0
510     11,0
510     10
1000 10
```

006_script.py sieht nun vorab folgendermassen aus:

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
# Copyright (C) 2019-2023, INRIA
# This file is part of Openwind.

import numpy as np
import matplotlib.pyplot as plt
from openwind import InstrumentGeometry
from openwind.continuous import radiation_model
from openwind import ImpedanceComputation

# %% Der folgende Abschnitt oeffnet die erstellte Datei geometrie.txt und ersetzt die
# Komma als Dezimalzeichen durch Punkte und schreibt die Datei neu als instrument.txt file
# Einlesen der Textdatei
with open('geometrie.txt', 'r') as file:
    lines = file.readlines()
# Ersetzen der Kommata durch Punkte:
lines = [line.replace(',', '.') for line in lines]
# Schreiben in eine neue Textdatei mit geändertem Dezimalzeichen (überschreibt vorhandene)
with open('instrument.txt', 'w') as file:
    file.writelines(lines)

# %% Basic computation
# Frequencies of interest: 10Hz to 2kHz steps of 0,333 Hz instrument mm und Dia statt rad in mm
fs = np.arange(10, 2000, 0.333333)
geom_filename = 'instrument.txt'

# Find file 'instrument.txt' describing the bore, and compute its impedance, set Temp in C, etc.,
Parameter carbon ist Std, Losses = true, Rest der Parameter siehe Beschreibung

result = ImpedanceComputation(fs, geom_filename, temperature=23.0, humidity=0.3,
radiation_category='unflanged', compute_method='FEM', discontinuity_mass=True,
spherical_waves=False, nondim=True )

# you can get the characteristic impedance at the entrance of the instrument
# which can be useful to normalize the impedance
Zc = result.Zc

# you can print the computed impedance in a file.
# It is automatically normalized by Zc
result.write_impedance('computed_impedance.txt')

# %% Der folgende Abschnitt oeffnet die erstellte Datei und ersetzt die
# Punkte als Dezimalzeichen durch Komma und schreibt die Datei neu als spectrum.txt file
# Einlesen der Textdatei
with open('computed_impedance.txt', 'r') as file:
    lines = file.readlines()
# Ersetzen der Dezimalpunkte durch Kommata
lines = [line.replace('.', ',') for line in lines]
# Schreiben in eine neue Textdatei mit geändertem Dezimalzeichen (überschreibt vorhandene)
with open('spectrum.txt', 'w') as file:
    file.writelines(lines)
```

```
#Plot Geometrie of instrument.txt   am Schirm – zur Kontrolle
my_instru_from_files = InstrumentGeometry('instrument.txt')
my_instru_from_files.plot_InstrumentGeometry()
plt.show()

# Display resonance frequencies am Schirm  3.2f bedeuted 3 Vorkomma, 2 Nachkomma, Floating
N = 20 # maximal number of printed frequencies
f, Q, Z = result.resonance_peaks(N)
nb = len(f)
for i in range(0,nb):
   print(f" {i+1:2d} - Resonance frequency : {f[i]:4.2f} Hz, Quality factor : {Q[i]:3.2f}, Scaled
amplitude : {np.abs(Z[i])/result.Zc:3.2f}")

# Plot obtained impedances  am Schirm – zur Kontrolle
fig=plt.figure(1), plt.clf()
result.plot_instrument_geometry(figure=plt.gcf())

fig=plt.figure(2)
plt.clf()
result.plot_impedance(figure=fig)
ax=fig.get_axes()
ax[0].plot(f, 20*np.log10(np.abs(Z/result.Zc)),'r+')
ax[0].legend(['modal computation','modal estimation'])
plt.xlim([fs[0],fs[-1]/2])
ax[1].plot(f, np.angle(Z/result.Zc),'r+')

# Display resonance frequencies  - diese Daten werden als peaks.txt dann ausgegeben
N = 20 # maximal number of printed frequencies
f, Q, Z = result.resonance_peaks(N)
nb = len(f)
print("")
print("")
print("Peak Magnitude Q-Faktor:")
for i in range(0,nb):
   print(f"{f[i]:4.3f} {np.abs(Z[i]):9.0f} {Q[i]:3.2f}")

# Open a file in write mode to save the output mit Punkten als Dezimalzeichen
with open('peaks_out.txt', 'w') as file:
   file.write("Peak Magnitude \n")
   for i in range(0, nb):
      line = f"{f[i]:4.3f} {np.abs(Z[i]):9.0f} \n"
      file.write(line)

# %% Der folgende Abschnitt oeffnet die erstellte Datei und ersetzt die
# Punkte als Dezimalzeichen durch Komma und schreibt die Datei neu als peaks.txt file

# Einlesen der Textdatei
with open('peaks_out.txt', 'r') as file:
   lines = file.readlines()

# Ersetzen der Dezimalpunkte durch Kommata
lines = [line.replace('.', ',') for line in lines]
# Schreiben in eine neue Textdatei mit geändertem Dezimalzeichen
with open('peaks.txt', 'w') as file:
   file.writelines(lines)
print("peaks.txt und spectrum.txt erstellt!")
```

First tests with a closed-open cylinder, lenght 1m, diameter 10mm

23 degrees, 30% humidity, standard CO2 concentration (in room air = 0.042%)** and losses = true = model Zwikker and cost losses with Bessel function model show:

Lower magnitude mode #1 (approx. 10%) than the ART simulation with loss factor 1.1 frequencies and magnitudes determined for the unperturbed cylindrical tube with both FEM and TMM give identical results.

However, the peak frequencies output are not discrete values / rounded values of the spectrum.txt output, because these discrete curve values are interpolated. According to the description, the values in this setting are determined based on the phase zero crossing.

The determined resonance frequency of mode #1 is slightly lower than the ART values (-3 cents), the remaining modes slightly higher than the ART values (+0.6 - 1.9 cents, which is probably related to the different loss model and CO2 content).

The char. impedance is output as 5.229513 megaohms, mathematically I arrived at 5.24 Mohm in Sideletter #2, which is also based on slightly different values for density and speed of sound.

I set the "humidity" parameter to 30% for comparability with ART simulations.

The parameter “Carbon” is standard, although I haven’t found out the value for it yet:

*** The air we breathe is available in a fairly even supply in the homosphere. Its main components are 78% nitrogen (N2), 21% oxygen (O2), water vapor and various noble gases, as well as 0.04% carbon dioxide (CO2). When we breathe in through our nose, this air is additionally moistened with water vapor (which evaporates from the mucous membranes of our nose). Mammals, including humans, convert some of the oxygen in their breath into carbon dioxide during aerobic respiration. The exhaled air still contains 78% nitrogen (N2), but only about 17% oxygen (O2) and about 4% carbon dioxide (CO2) and around 1% other components. The percentages are in percent by volume. The CO2 content in the air is not only given in percent by volume, but often also in ppm. The abbreviation ppm stands for parts per million. A CO2 content of 1000 ppm corresponds to 0.1%. For example, 420 ppm corresponds to 0.042%, etc.*

Exhaled air has a fairly constant value of 4% by volume, i.e. up to about 100 times as much as ambient air. The CO2 concentration in the air is normally 0.04%. Mild consequences such as a lack of concentration can be felt at an increased concentration of 1 to 1.5% - everyone knows what it's like when the air in poorly ventilated or overcrowded rooms feels "used" or stuffy.

Headaches, tiredness, changes in breathing and reduced hearing begin at a CO2 concentration of around 3%. At 4 to 5%, clear symptoms of poisoning can already be seen and breathing is deeper and faster. At a CO2 concentration of 5 to 10%, things become critical. Breathing becomes very difficult and a loss of judgment sets in. If the CO2 content is over 10%, there is an acute risk to life and unconsciousness can occur within a minute. (Fortunately, exhaled air mixes very quickly with the ambient air.)

The specification of carbon as a factor of 0 -1 in the OpenWind description unfortunately does not provide a conclusive value; I assume that the standard is 0.042. (0.1 as 10% CO2 is given as a “reasonable playing condition” in the examples in the documentation, which would be more than twice as much).

Das Verlustmodell ZK = Zwikker-Kosten

There is a reference to a publication by the physicists, but I do not have access to it.
In 2023, the year of AI, Chat GPT and Google Bard unfortunately do not currently provide any useful results, even to the question of how the impedance magnitudes change due to a disturbance, the AI provides hair-raising answers.

The parameter „acoustic Discontinuity Mass“

include, Standard = True produces small differences:

Without this mass, the potential differences for standard enlargements would be L=20mm, q0=1.1 for magnitudes in the single-digit per mille range, Enl. lower pot, Constr. higher pot.

Pitch pot with enlargements would be ~ 5% stronger = +0.3 cent higher frequency at pressure nodes, at DB same pot. down. Pitch pot with inv. prop. constrictions would be ~ 4% lower, lower frequency at pressure nodes. This parameter is therefore not responsible for the relatively large differences to the ART simulation.

With true, the result is a potential of +6 to -7.25 cents with Std. Pert. and enlargements, which corresponds almost exactly to the found ratio $1/q0^2 = 1.21$. With constrictions, the pot up is identical, but the deepening potential is 1.29 times stronger, i.e. 1.066 times stronger than enlargements.

inkludieren, Standard = True liefert geringe Unterschiede:

The parameters used for all the following experiments, unless otherwise stated:

OpenWind FEM - Tests with closed-open cylindrical tube, physical lenght 1m, inner Dia 10mm
30% Humidity, standard Co2 concentration (in room air = 0.042%)** and
losses = true = Modell Zwikker and Kosten losses with Bessel function model
Radiation Model = unflanged Baffle, Discontinuity Mass = true and temperature 23 Grad Celsius.

Description of the experimental setup and simulation of local perturbations

The test object is a cylindrical pipe that is closed on the left side,
this corresponds to position x = 0 in % of the pipe length, and that is open on the right side x = 100% RL.
Positions x therefore refer to the distance from the closed end unless otherwise stated.
The length of the pipe = RL is 1,0 m unless otherwise stated, the inner diameter, perturbation cross-section factor and length of the simulated perturbation are each stated.

A simulation or measurement of this pipe without perturbations serves as a comparison reference for the evaluations. The temperature was assumed to be 23 °C in the pipe (and outside).

A perturbation is a disturbance of the geometry or cross-sectional area, but each perturbation also has a length = PL and its center then a position x in the pipe.

Local perturbations are either expansions of the cross-section = “Enlargements”, Enl., Gaps, or constrictions, sleeves, “Constricition”, Constr.. These are modeled by 2 abrupt transitions of the pipe cross-section. Boresteps only have 1 abrupt transition. Boresize changes correspond to a complete perturbation with perturbation length = pipe length.

Perturbations result in changes to the input impedance across the frequency axis, here the amount |Z|in referred to as magnitude, whereby resonance frequencies are observed, i.e. the change in the peaks of the impedance maxima and their change in frequency due to the perturbation are compared and evaluated. I refer to the possible extent of the change = difference as potential (Pot.),
there are therefore two quantities: local input magnitude (change) pot. and global pitch (change) pot.

Each complete simulation run contains the change per 1% position increase from the closed pipe end, so it consists of 98 individual simulations, x=1 to x=99. A "disturbance" of the same size is systematically pushed through the pipe, the individual simulations are then lined up, evaluated and displayed in the graphics.

Opposite changes in cross-sectional area - i.e. enlargements versus constrictions - must be inversely proportional to each other in order to be comparable. This is especially true for frequency changes.

I use the following abbreviations and terms:

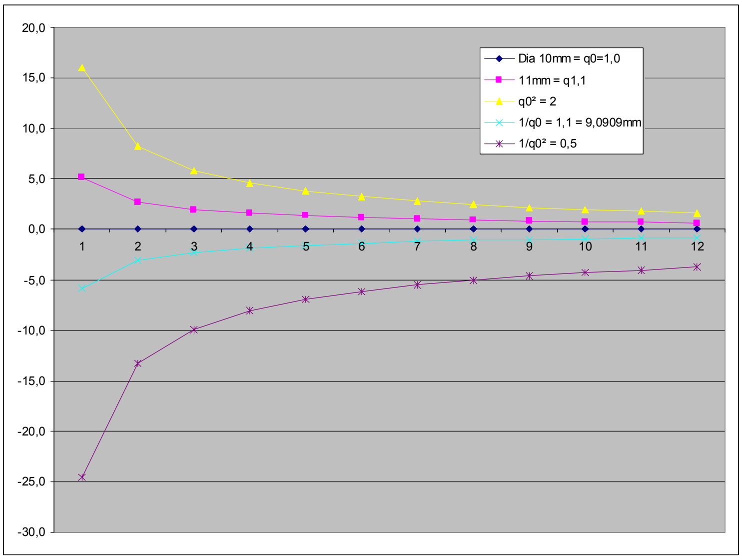
q0=	Ratio	Enlargement to Boresize, Ratio of cross-section (Diameter used)
1/q0=	Ratio	inv. prop. Constriction (Diameter used)
$q0^2$=	Ratio	Cross sectional area of Enlargement to cross sectional area of boresize
$1/q0^2$=	Ratio	Cross sectional area of Constrictions to cross sectional area of boresize
$q0^2$-1=	Xe	= Difference or Change of area, (Enlargement, +) dimensionless
Xe/q0=	Xg	= geometric mean of area difference, dimensionless
Xg/q0=	Xc	= Difference or Change of area (Constriction, -) which is inv proportional to Enlargement e
PL Pot=	Ratio	PL / ¼ Wavelenght of resonant Mode = Proportion of perturbation length to ¼ wave lenght
sin(PL Pot)		the sinus value of angle in radians (PL Pot * Pi/2)
PL =		Perturbation Lenght
DB =		Druckbauch = Pressure Antinode
DK =		Druckknoten = Pressore Node
RL =		Rohrlänge = tube lenght

Magnitude changes |Z|in are given as % Diff. (y-axis) unless otherwise stated.
Frequency changes are given as cents unless otherwise stated =Log(Frequ.Ratio;2)*1200

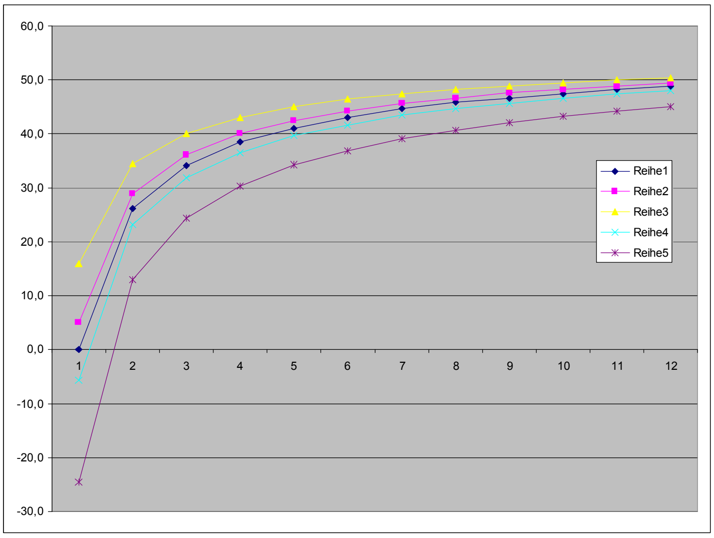
There are already numerous simulations available, including with the A.R.T. = Acoustical Research Toolkit, but also with other simulation software, and physical impedance measurements have also been carried out. Sideletters #2 and #3 describe a large number of effects using ART results. Openwind results are partly in between; here is a review of these results with comparative values from the ART simulations.

The separate sideletter #5 reviews the differences found between OpenWind simulation and my physical impedance measurements as a consequence of local pertubations of the bore.

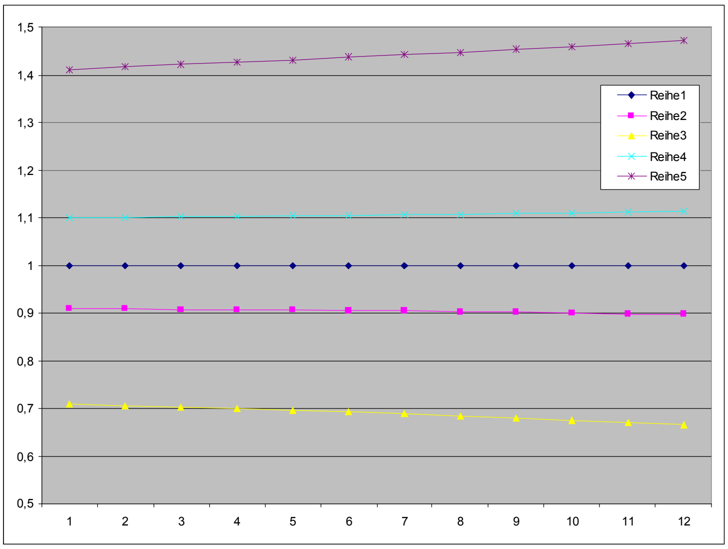
Boresize – Changes q0, results OW:



Change of Harmonicity versus Boresize Diameter q0=1,0 = 10mm.
-24 Cent to +16 Cent with half/double Area, Mode#1



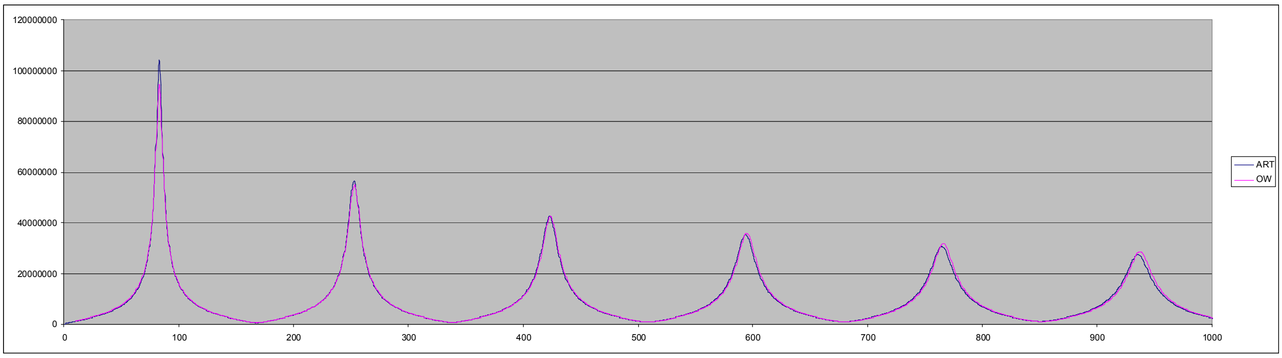
Harmonicity in cents to Mode #1



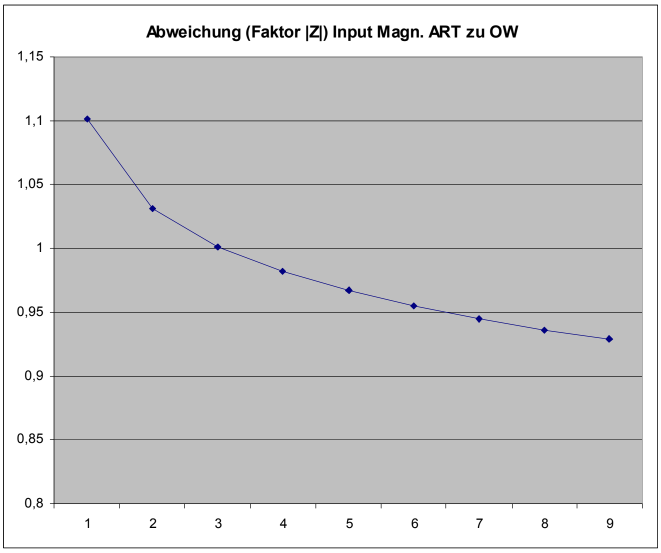
Factor change magnitude |Z|in, high modes are changed more strongly, corresponds to ART / Sideletter #2.

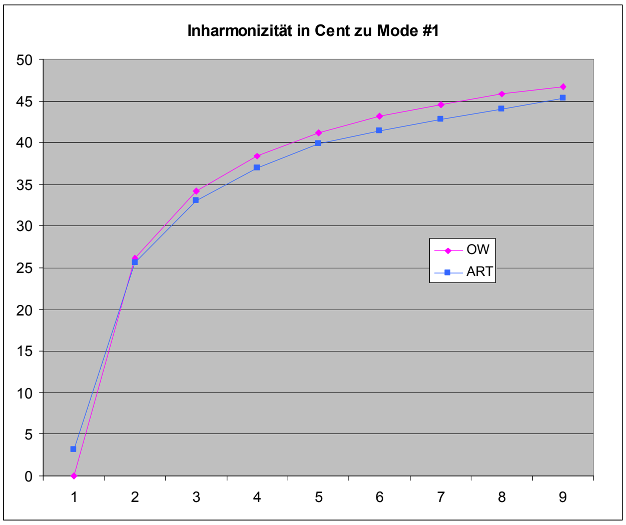
Comparison of the results of FEM OpenWind (OW) to TMM Acoustical Research Tool (ART):

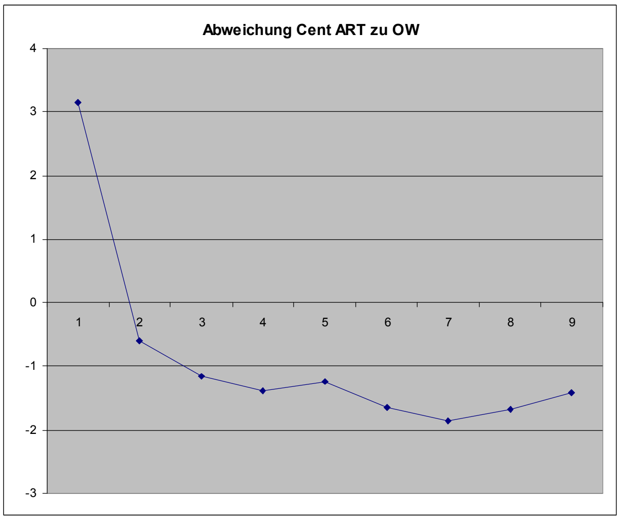
Cylinder, closed – open, lenght 1000mm, Diameter 10mm, 23 Grad C



Peak Magnitudes Mode #1 and #2 are lower with OW compared to ART simulation.

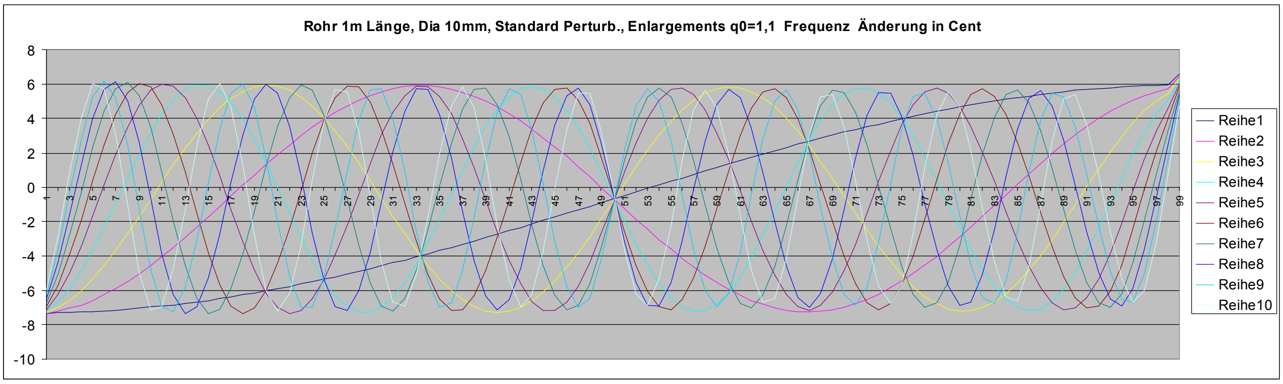




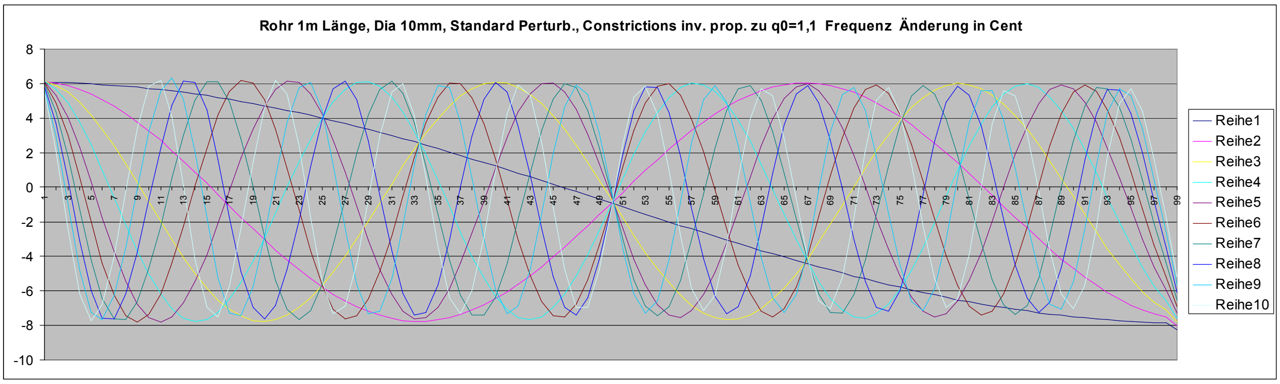


Overall, OW delivers a stronger inharmonicity. OW delivers 82.772 Hz for Peak #1, ART: 83.17 Hz.

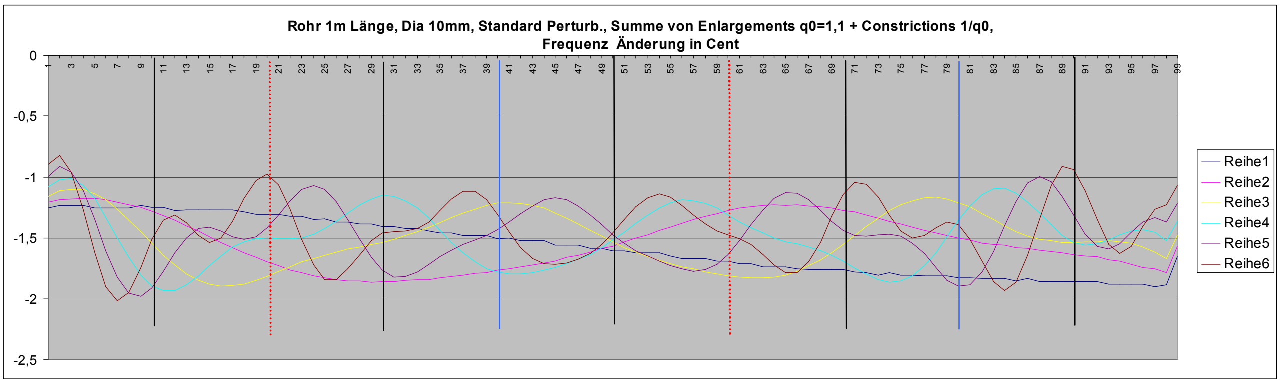
Pitch Potential of local perturbations, OpenWind:



+6,0 to – 7,3 Cent with Standard Perturbation, PL=2% RL



+6,0 to – 7,7 Cent with standard perturbation, PL=2% RL



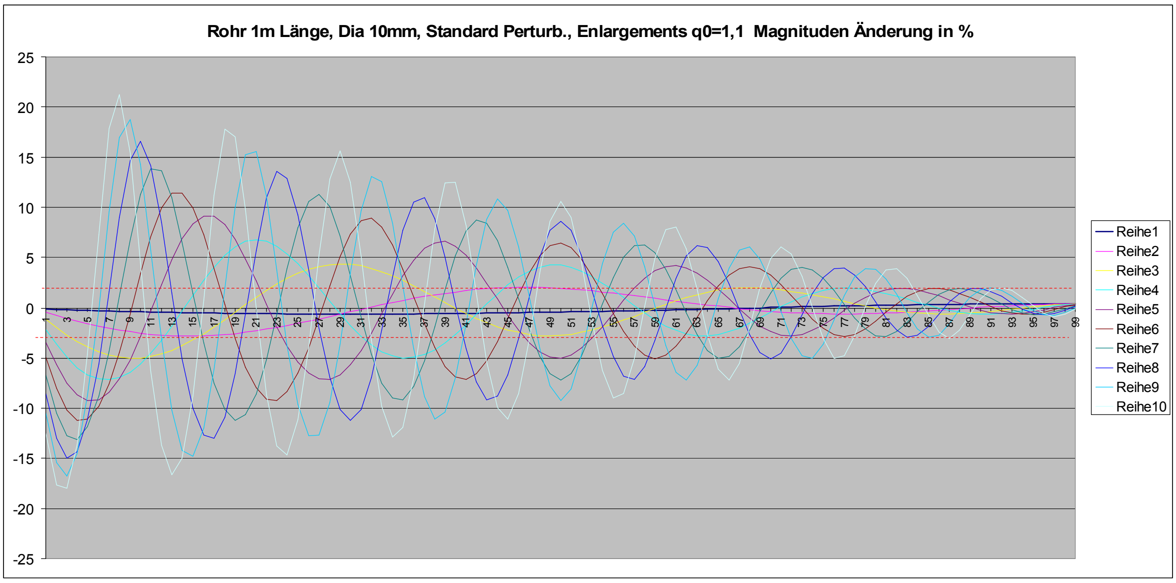
Pitch-Potential Offset dn Mode #1 – Mode #6, inserted marker lines for Mode #3 (yellow curve) are:
red = pressure node positions, blue = Pressure Antinode positions
black = 1/8 WL in between; Pitch Nodes with offset down.
Unfortunately, there is no logical symmetry; the greatest deviations occur on the flanks, and not exactly on the pressure nodes and pressure nodules.

It looks as if deviations downwards from the center of the pipe are offset towards the ends of the pipe, but deviations upwards are offset towards the center of the pipe.

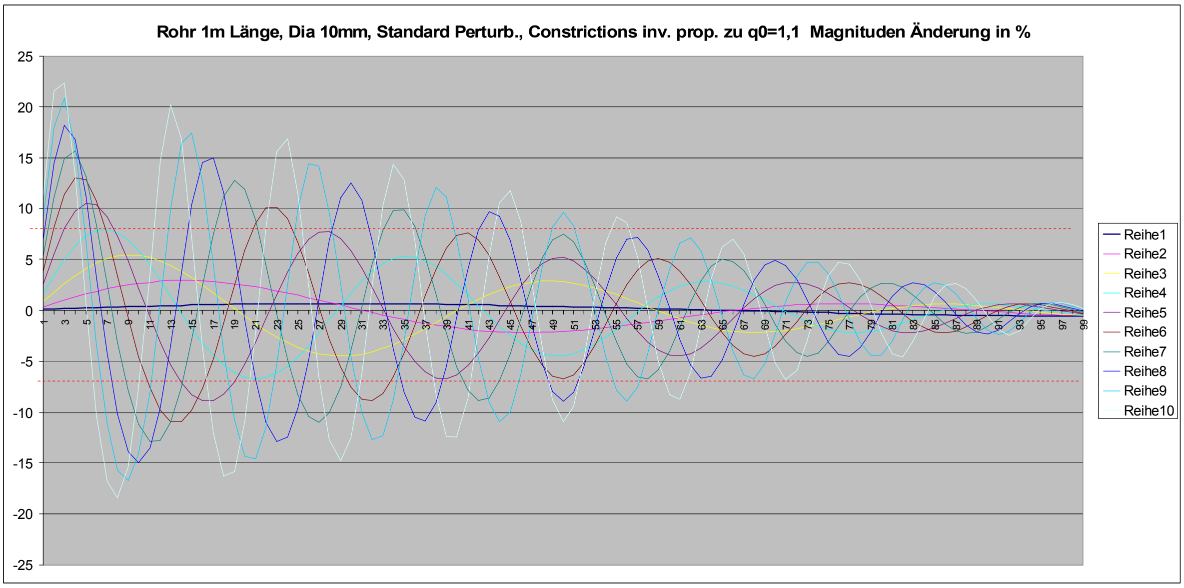
Approximation cross-section dependence, with q0 < 1,15:			See separate section: q0-Faktor/Pitch.
Enlargements up:	Xc	Constrictions up:	~Xc
Enlargements dn:	$Xc*q0^2=Xe$	Constrictions dn:	Xc * [1+ $(Xe*q0^2)$] (stronger than $q0^2$)

Approximation cross-section dependence, with q0 > 1,15:			
Enlargements up:	Xc *0,95	Constrictions up:	~Xc
Enlargements dn:	$Xc*q0^2=Xe$	Constrictions dn:	Xc * $q0^2$ * 1,1 (stronger than $q0^2$)

|Z|in Input Magnitude (Change-) Potential with local perturbations, OpenWind



PL=2% RL, Mode #1-Mode #10



PL=2% RL, Mode #1-Mode #10

At center position 50% of pipe length, even # modes have inverse magnitude pot., (with constrictions = dn)
This potential can be assigned to a specific wavelength, namely the distance to the open end in 1/8 wavelengths, the number of 1/8 WL is = (Mode # *2) -1, 1/8 WL = 0.5*RL / (Mode # *2) -1.
Mode #2 therefore has 3/8 WL magnitude pot., Mode #4 has 7/8 WL magnitude pot., etc.

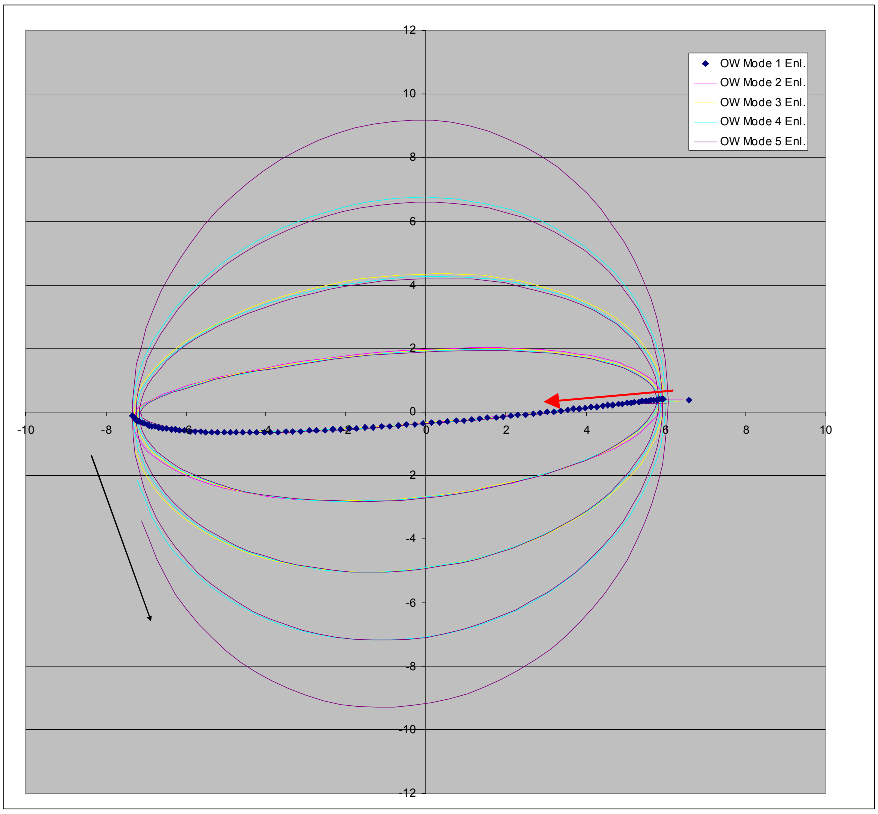
At position 50% of pipe length, odd # modes do not have inverse magnitude pot., (with constrictions = up)
Mode #3 therefore has 5/8 WL magnitude pot., Mode #5 has 9/8 WL magnitude pot., etc.

It can be seen that in the simulation every mode has this same pot. with this number 1/8 WL from the open end results.

The magnitude potential has in the simulation system, see the following perturbation spirals.

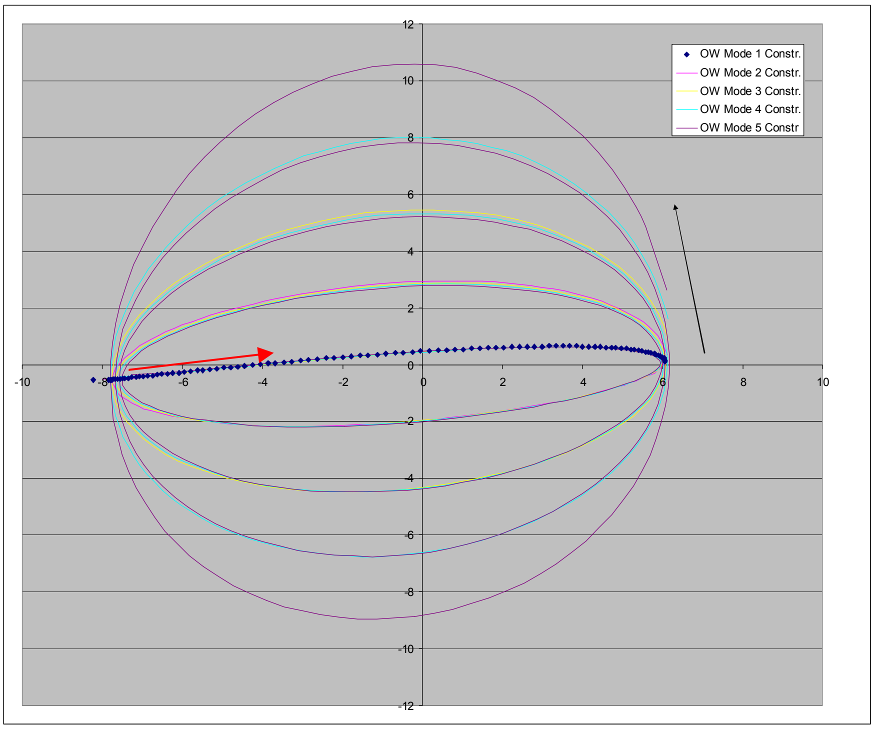
OW: Potential of local perturbations, perturbation-spiral diagrams

closed-open Cyl., L=1000mm, Dia=10mm



All modes follow the pattern of the last ¼ wavelength also with OW, and are so a continuation of the behavior on the last ¼ wavelength, viewed from the open to the closed end (red arrow towards closed end)

Enlargements, PL= 20mm (=2% RL), q0=1,1 black starting arrow at Pos 1% in direction to the open end.

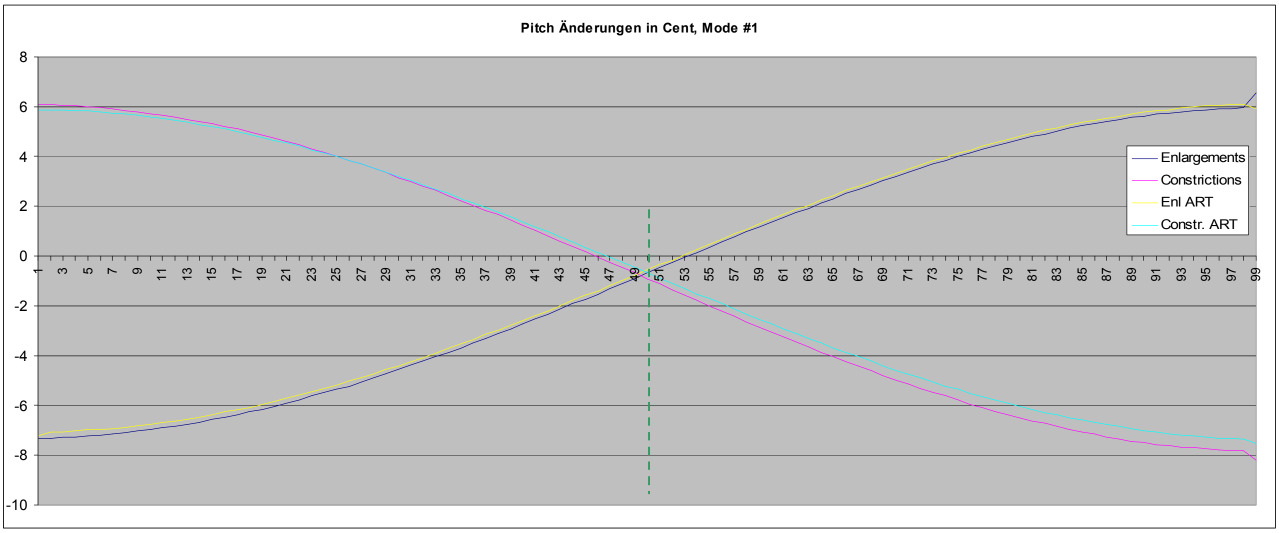


Constrictions, L 20mm (2% RL), inv. prop. Constr. 1/q0= 0,90909
y-Axis= Magn. Change in %, x-Axis= Pitch Change in Cent

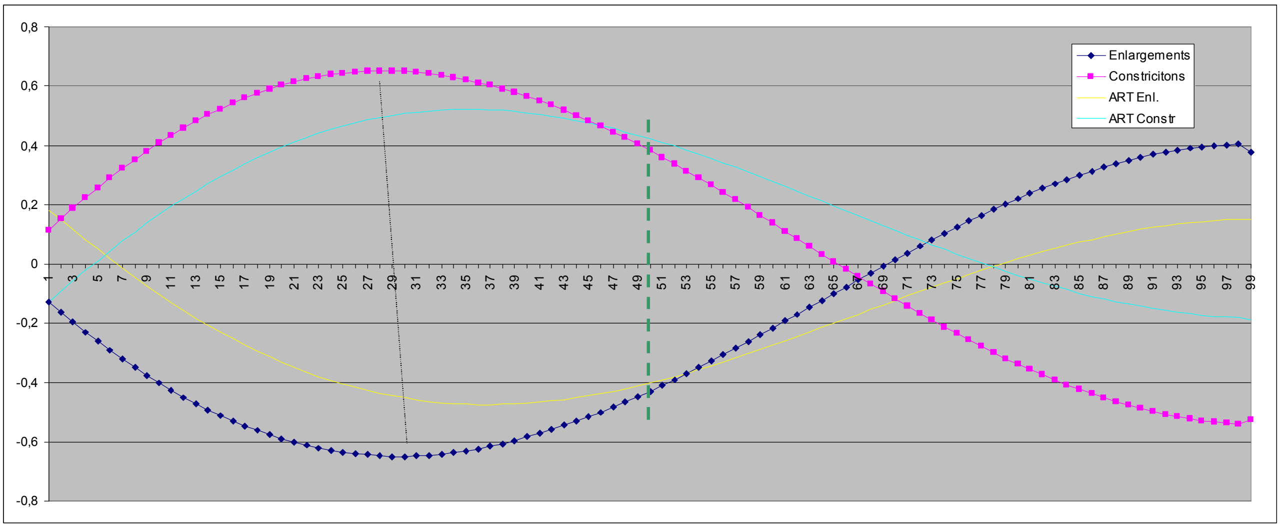
Magnituden Potential with local perturbations, OpenWind Mode #1

Results OW and comparision with ART Simulation results.

Local perturbations: Enlargements = Lenght 20mm, q0=1,1, inv. prop. Constr. 1/q0= 0,90909



Pitch Pot with Constrictions at pressure nodes (DK) dn is stronger than q0² (+6,6%).
The rest of the pitch pot comparable. Shared XM Pitch Node is at 50% RL, Pitch-Offset down is comparable.



x = Position centered Perturbations at % der Rohrlänge, y: % Änderung Magnitude |Z|in

The last ¼ wavelength shows significant differences; potential much stronger at Mode #1, pot. does not start inverse, magnitude node at ~ 33% before the open end (instead of ~22%).

Towards the closed end there is almost the same potential for enlargements to constrictions, the max. pot is around 30% in the center position, at the open end constrictions are less weakened, so a "shared" magnitude node is now at OW results with an offset down (and earlier).

Only at around 50% RL does the Magn. Pot. briefly match ART, otherwise it is much stronger, at the open end around a factor of 2.5 stronger, Inv. prop. Constrictions have around 35% more potential here than enlargements.

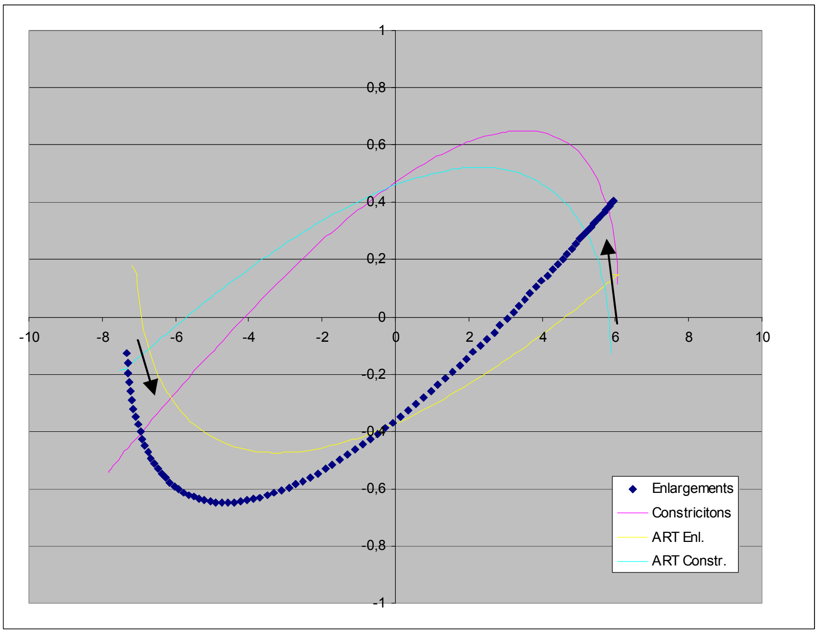
But keep in mind: There is only a maximum of 0.65% magnitude change with the standard perturbation, so a size that is (remains) practically negligible.

Perturbation spiral, peak mode #1 = the last quaterlenght

Perturbation spirals show the change in the resonance peak based on the perturbation position in the pipe.

Each point corresponds to +1% of the pipe length, respective center position, starting at the closed end, black arrow shows the direction to the open end.

Local enlargements start west, constrictions start east, each counterclockwise.



x= Pitch Cent (logarithmic), y = % Change Magnitude |Z|in

At the last centered perturbation at 99% RL there was an error in the modeled geometry at OW, so it is not displayed. Here it is definitely the same as a bore step at 98% pipe length, and position 1 is also a negative bore step at 2% RL. This means that bore steps must also have a different effect with OW than determined by ART.

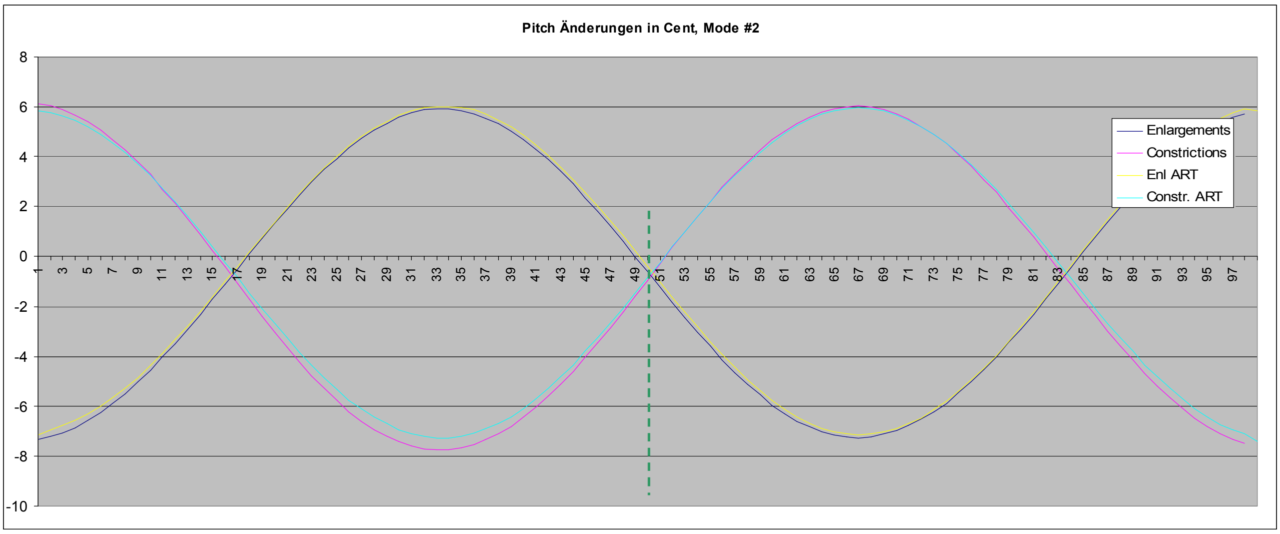
Behavior at higher modes:

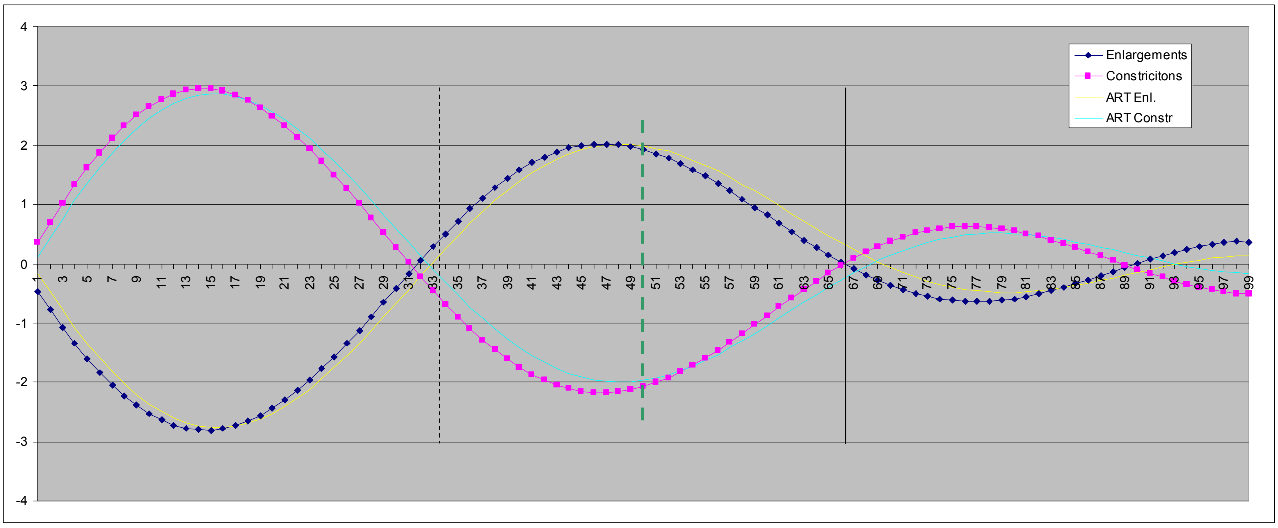
The behavior of mode #1 in ART corresponds to the last ¼ wavelength of all remaining modes before the open end. In ART, the penultimate magnitude node is offset towards the open end (or the inverse start and node at ~ 6% RL); at pressure nodes there are also magnitude nodes without offset, at DB they are offset from this.

With OW, the penultimate magnitude node is at the last pressure antinode, and the remaining magnitude nodes are also at pressure antinodes (DB), but they are offset from pressure nodes. After the last pressure antinode, at approximately 66% of a ¼ WL there is the advanced last magnitude node, which we would actually expect at the open end...

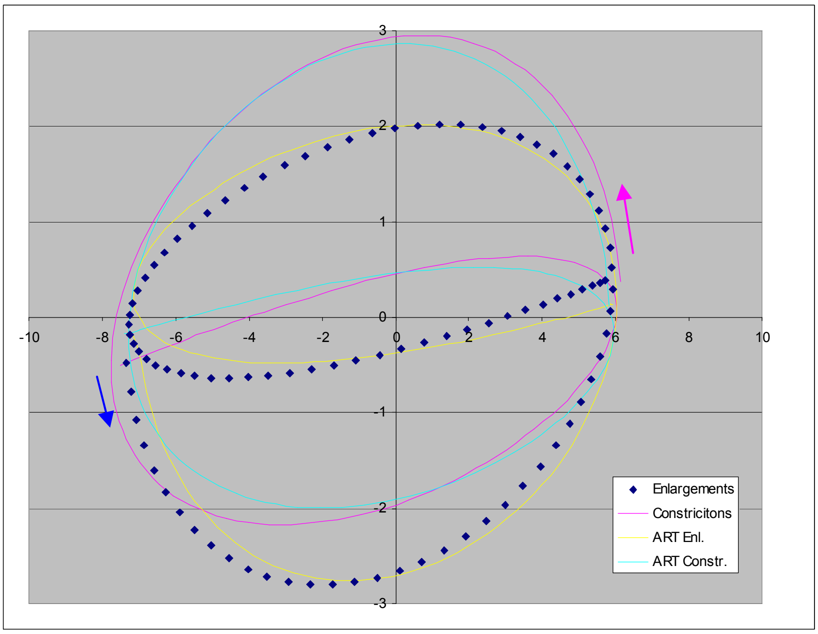
The following applies to the following graphics:
dashed black: expected pressure nodes, solid black: expected pressure antinodes
dashed green: 50% pipe length

Mode #2:

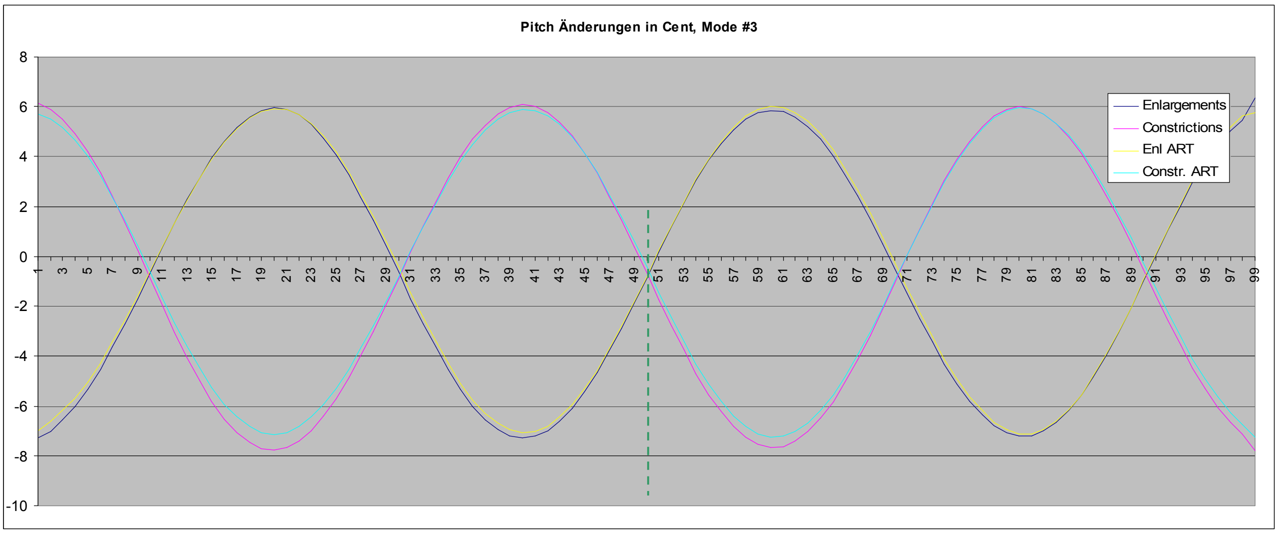


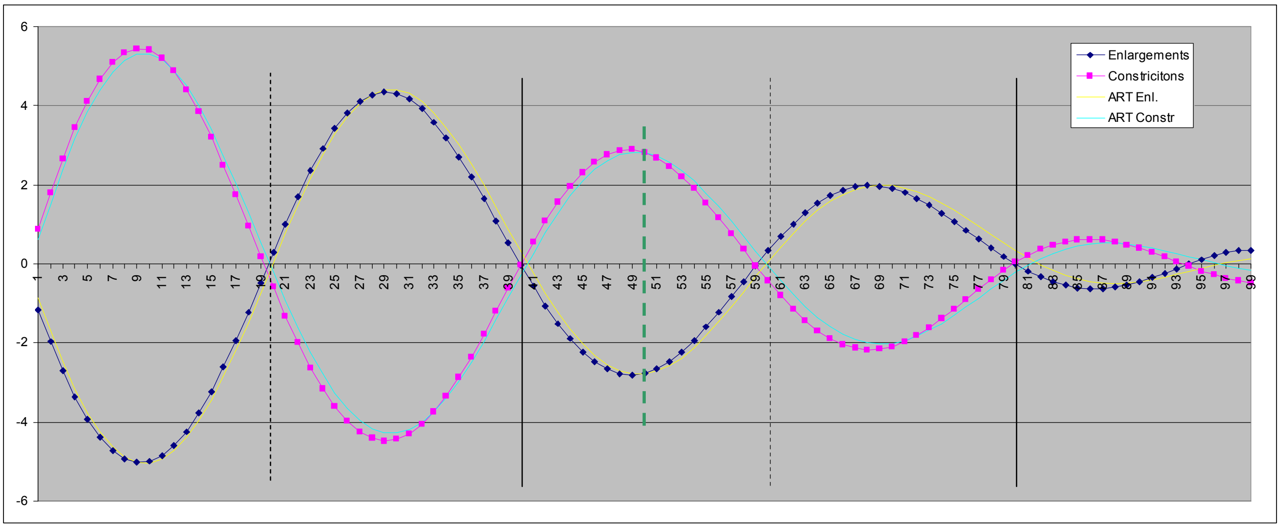


Input magnitude changes, Magn. Pot dn with Enl. is lower, or also lower overall. 1. Magn. Node in front of a (single) DK at presumed 33.33% in the pipe, the max. magnitude pot. is offset in the direction to the closed end.

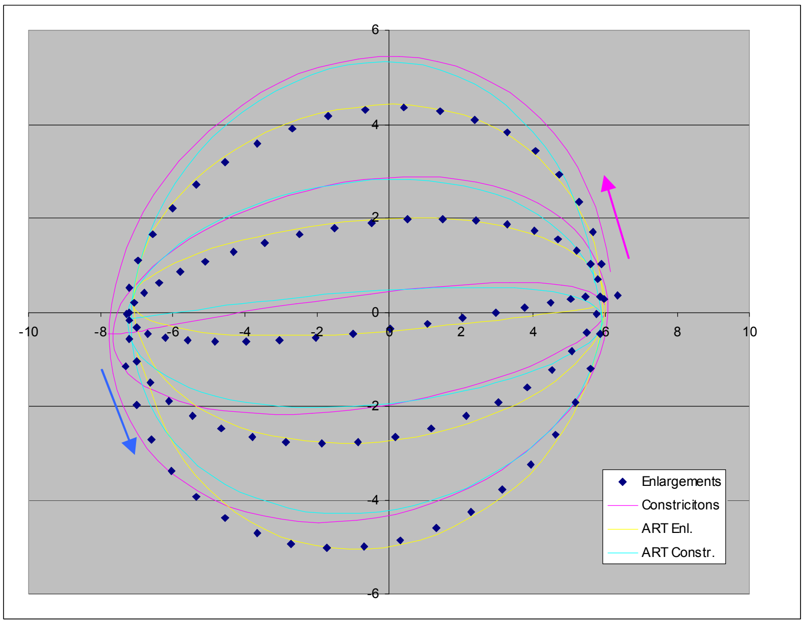


Mode #3:



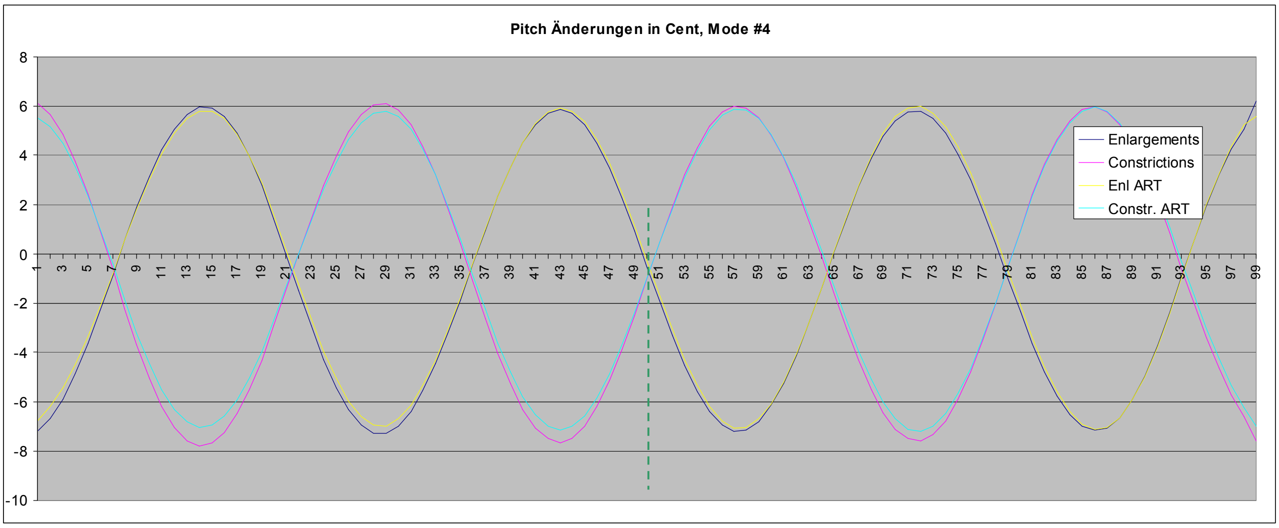


Magn. Pot. Change
From Mode #3 onwards there is only a deviation from the magn. node to the pressure node before the last pressure node. -1% RL

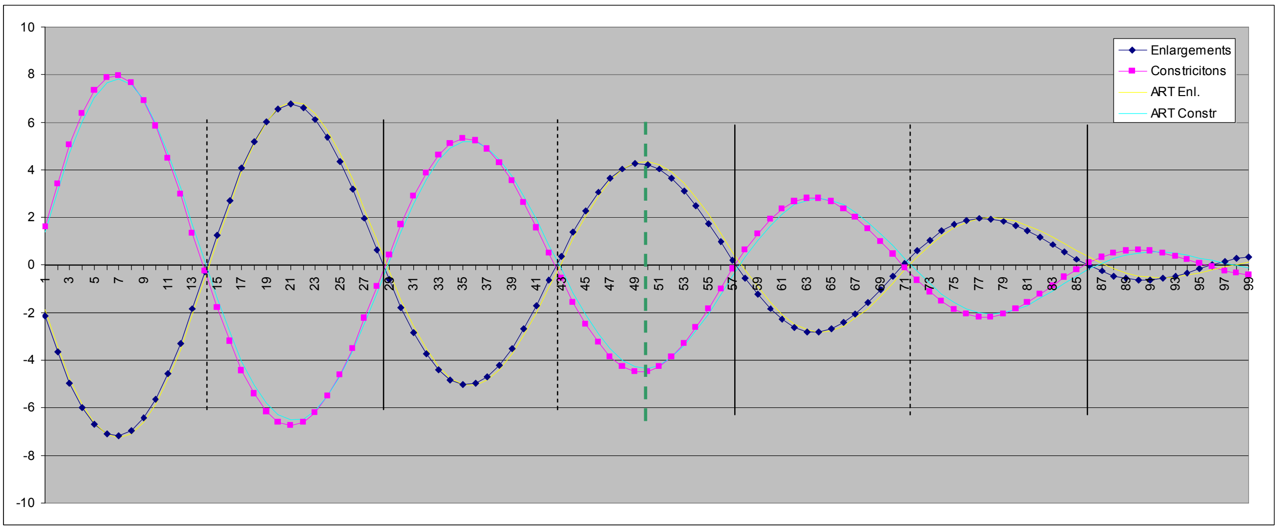


more Pitch Pot dn with constr. found by OW.

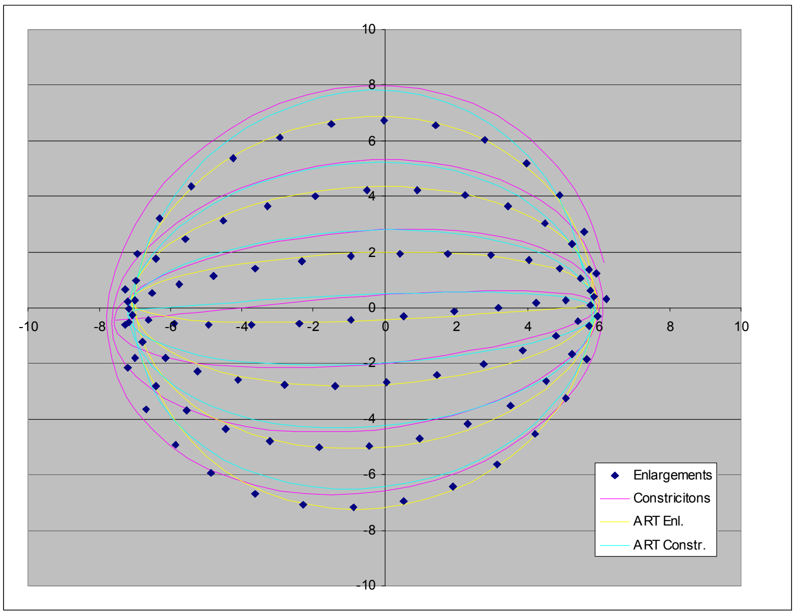
Mode #4:



ART: Pitch Pot increases towards the open end; OW: is already stronger at the beginning, no increase.

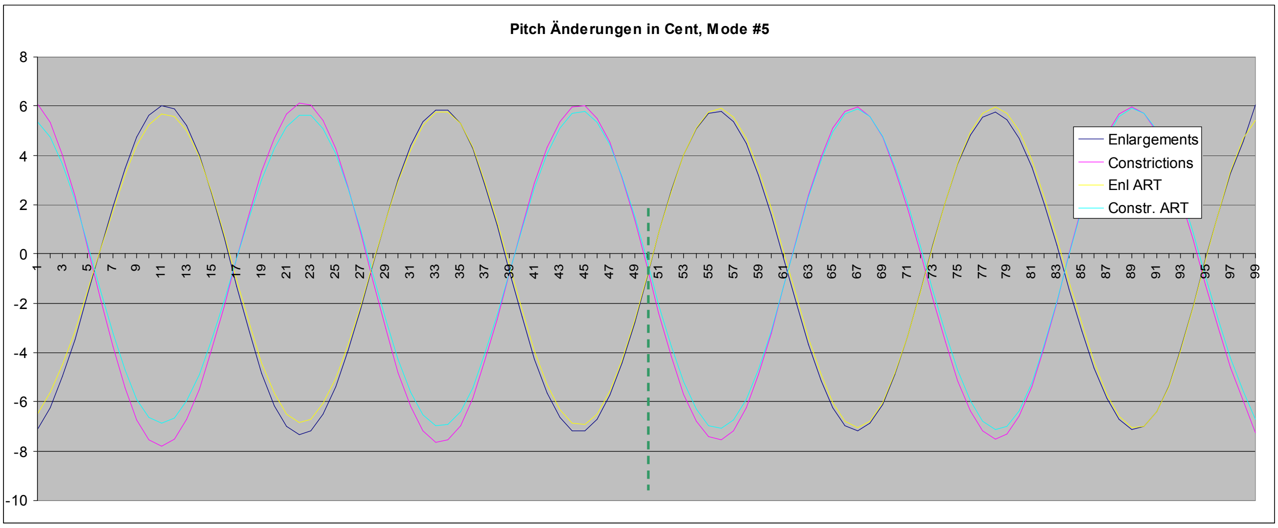


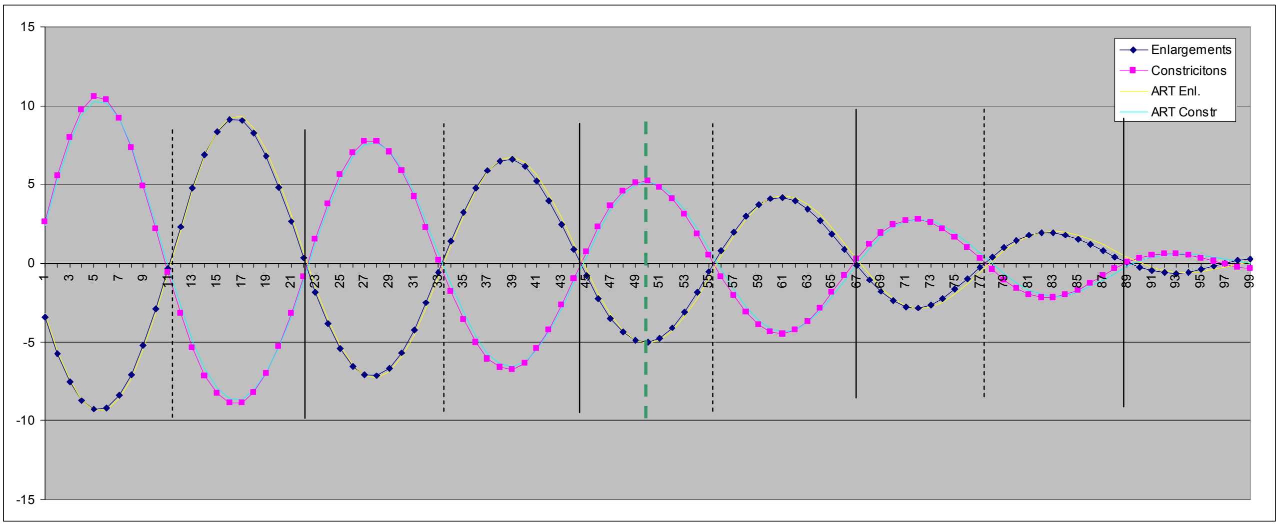
Magn. Pot Change; Magn. Node is just before the last pressure node, otherwise negligible, also Pot.



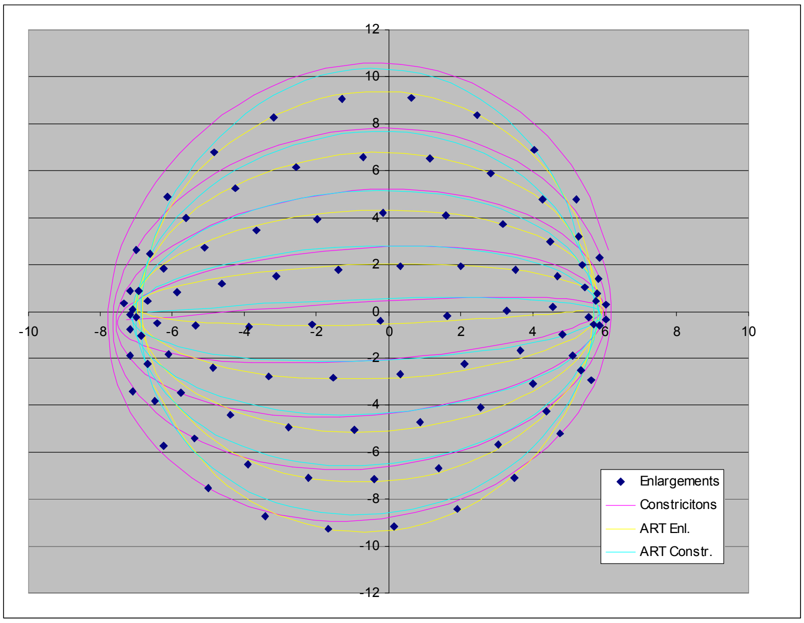
more Pitch Pot dn with Constr found by OW.

Mode #5:





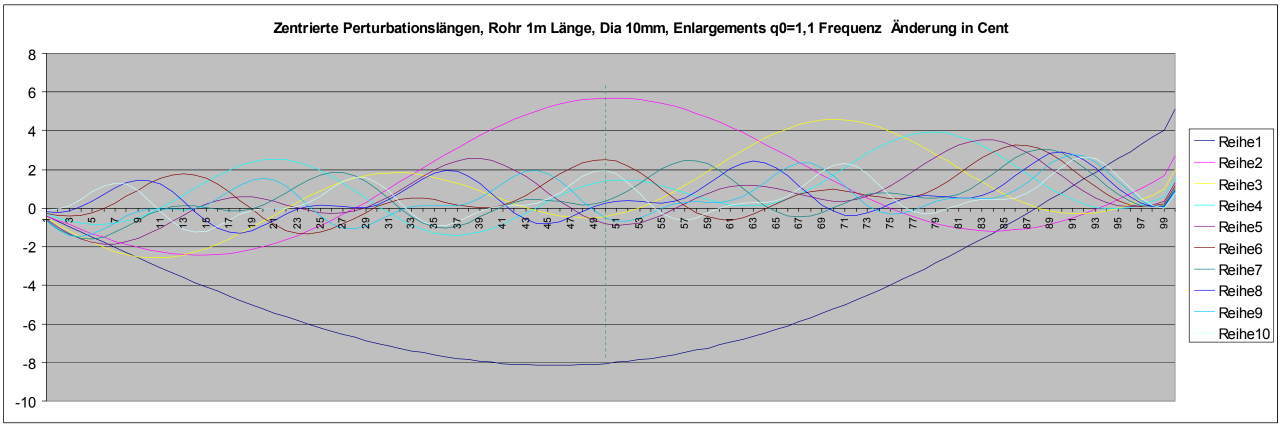
Magn. Pot. Change – at higher Modes very similar to ART



more Pitch Pot dn with Constricitons found by OW.

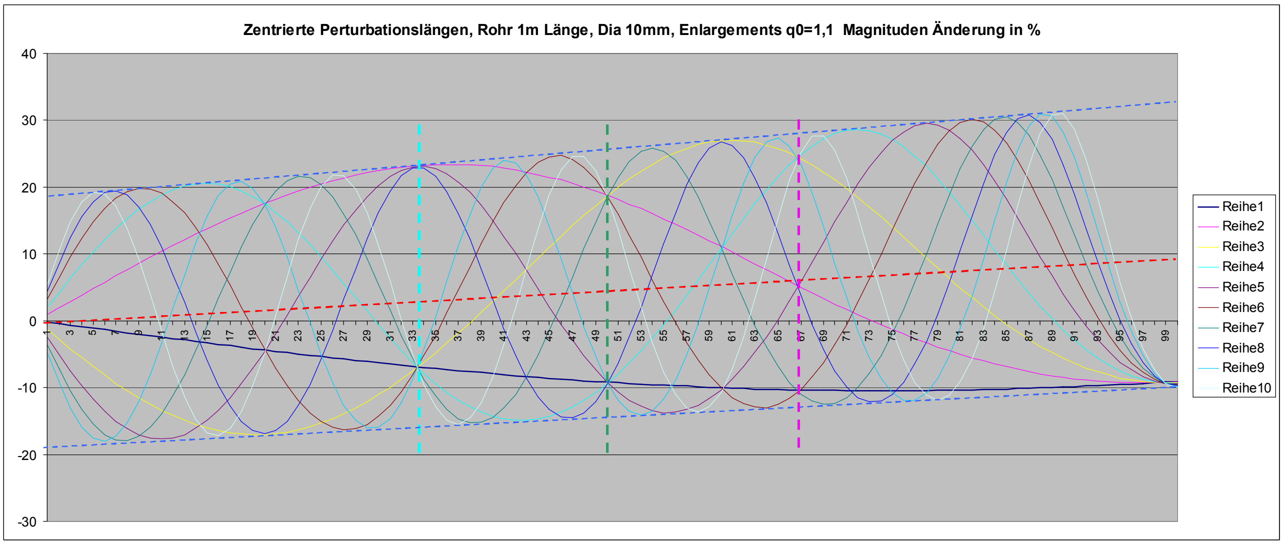
Centered perturbations – Perturb. Length share of ¼ WL or pipe length, Open Wind:

Centered Enlargements (OW, FEM):



x= Perturbation length in percent of pipe length (not position!), perturbations always remain centered at 50% RL
If the perturbation length is very small (approx. under 5% RL, then there is a pitch node at 50% RL (with offset down).

Mode 1 has 1x ¼ WL a 1,00m bzw. 2x 1/8 WL a 0,50 m pert. ~1/8, unpert. ~1/8 =max. inv.Pitch Pot.
Mode 2 has 3x ¼ WL a 0,33m bzw. 6x 1/8 WL a 0,166m pert. 3/8, unpert. 3/8 =max. Pitch Pot.
Mode 3 has 5x 1/4WL a 0,2m bzw. 10x 1/8 WL a 0,10 m pert. 7/8, unpert. 3/8 =max. Pitch Pot.
Mode 4 has 7x ¼ WL a 0,142m bzw. 14x 1/8 WL a 0,071m pert.11/8, unpert. 3/8 =max. Pitch Pot.
etc, with ~1/8 WL Restlänge unperturbated, each Mode has inverse Pitch Pot, but only with
Mode #1 this is pronounced and corresponds to 2x the inv. pot. compared to bore size change. (-8 Cent to +4 Cent).
With a unperturbated remaining lenght of 1/8 tube lenght = 1/32 WL of Mode #1 a „Pitch Node“
Remark: With a single Borestep at 50% ist the pitch pot of Mode #1 is >100 Cent!

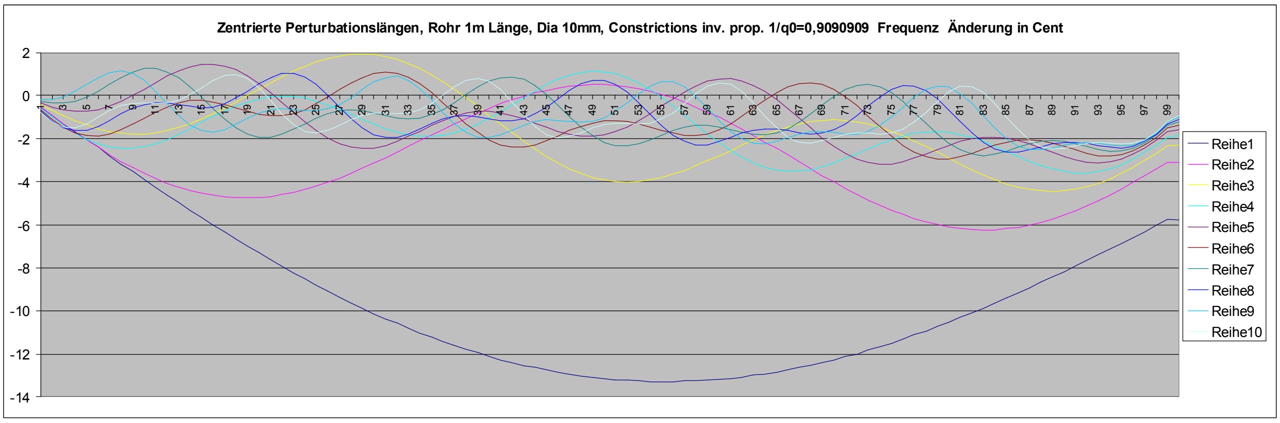


with a centered perturbation length = 100% RL this corresponds to a complete bore size extension,
q0= 1,1 and q0²=1, 21 Xe=0,21. The magnitudes are reduced by 1/q0 = -9,09%.
With higher modes there are slight deviations and the inharmonicity changes slightly.
Red dashed line: Modes and positions that cross this line are pressure antinodes!
Blue dashed lines: Modes meet this line exactly at pressure nodes.

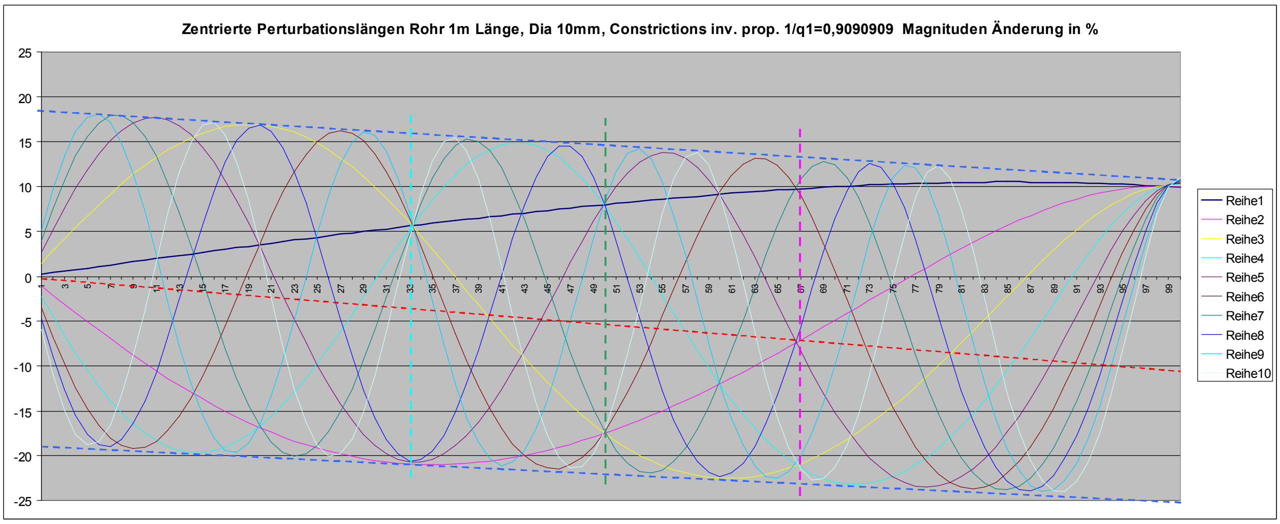
Centered perturbation length 33%: means 33% unpert. before and after the perturbation.
Modes 2,5,8 have ¼, 3/4, 5/4 unpert. / pert. / unperturbed here. The resulting magn. pot is inverse.
the remaining modes have exactly the same magnitude pot as mode #1, ~ Xc /2 = ~-8%
at 50% RL, mode 1, 4, 5, 8, 9 pot is the same as mode #1 =-xhc/2, the inv. pot of the remaining modes is ~ Xg 19%
the (envelope) pot downwards is around -xg to -xhc/2, the inv. pot upwards +xg to around +33%
the red line has a gradient from 0 to + inv +Xhc/2 ~ +9%. Xhc/2 = 1-(1/q0)

¼ WL centered Pert. has max. pot for now, but centered PL = pipe length -2/4 WL has max. increased inverse pot.
At 2/4 WL the changes do not cancel, the red line shows the inverse "residual/overpotential" on pressure antinodes!
Mode #1 has no inverse pot, but already at 50% PL Pot 1/q0, max. overpot at 75% (ar. mean) to 100% PL.

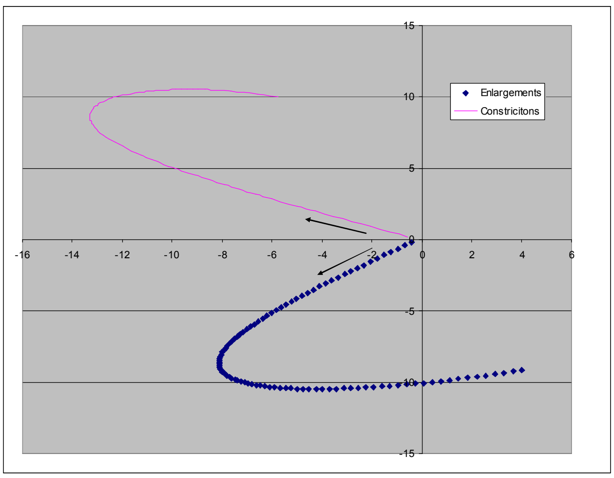
Centered Constrictions (OW, FEM):



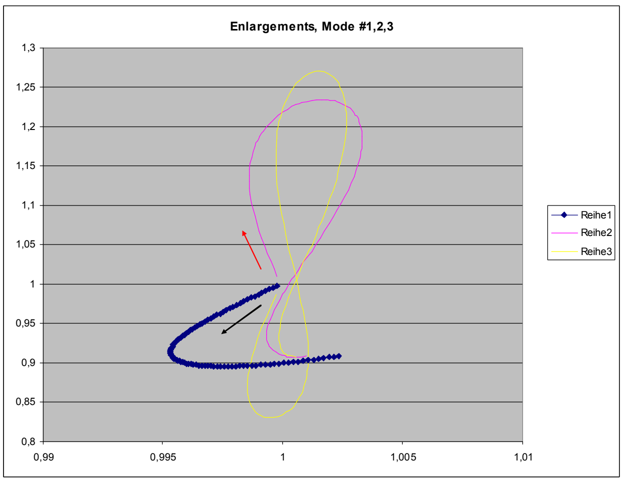
The pitch pot is almost always down; Mode #1 is now not inverse, but still down; ~ 2.1 times the pot. $1/q0^2$ = -6 cents



with a centered perturbation length of 100%, this corresponds to a complete bore size reduction,
q0= 1.1 $q0^2$=1.21 and Xe = 0.21. The magnitudes become stronger by q0 = +10%.
The potential shift of the magnitude pot. runs in the opposite direction to enlargements (falling),
every integer fraction of tube length results in a crossing point of modes with the same potential, with ½, 1/3 and 2/3 RL being the most prominent centered perturbation lengths, but see also e.g. ¼, 1/5, etc.
Mode #1 has no inverse pot, but already at 70% PL Pot q0, max. overpot at 85% (ar. mean) to 100% PL.
0.7 RL = the root of 1/2 with constriction, 0.5 RL = the root of ¼ with enlargement.

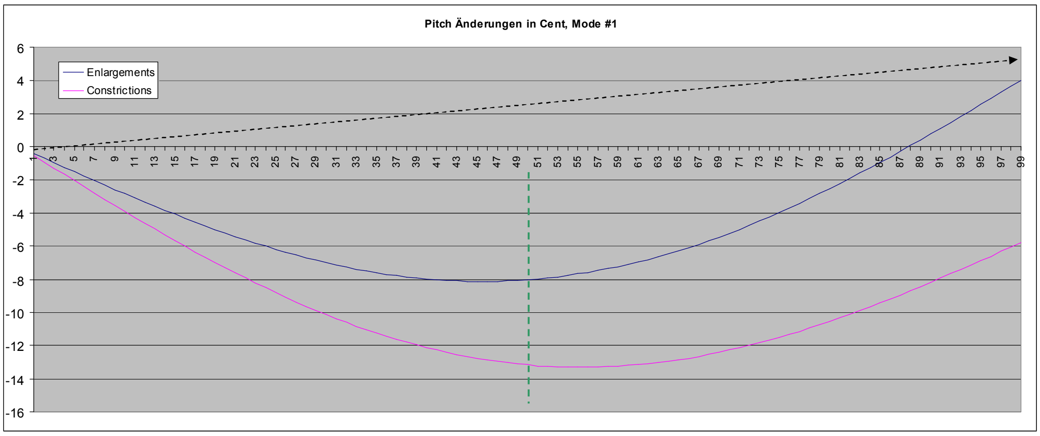


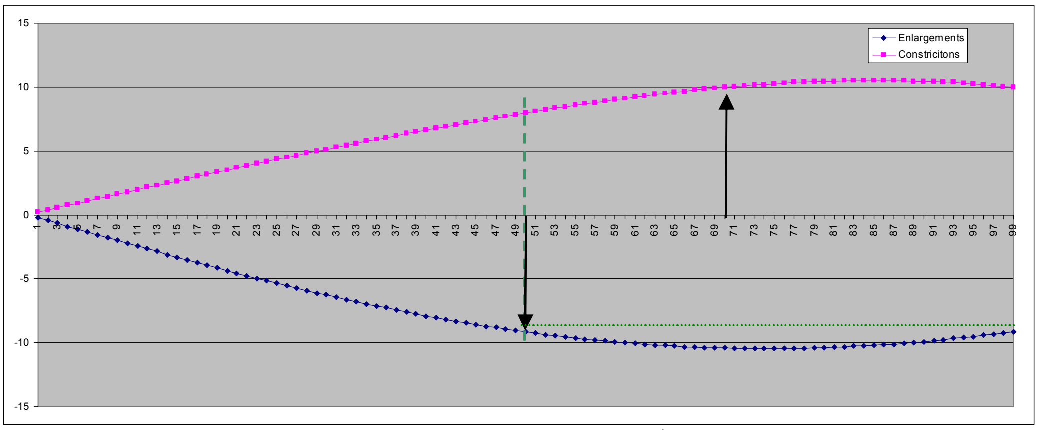
Mode #1, strong lowering of frequency,
with Constriction -13 Cent and 57% PL to RL
with Enlargement -8 Cent and ~45% PL to RL



Mode #1-3 with increasing, centered Perturbations
even Modes (#2) start invers (Magn. up).
higher modes are building Magn. Nodes

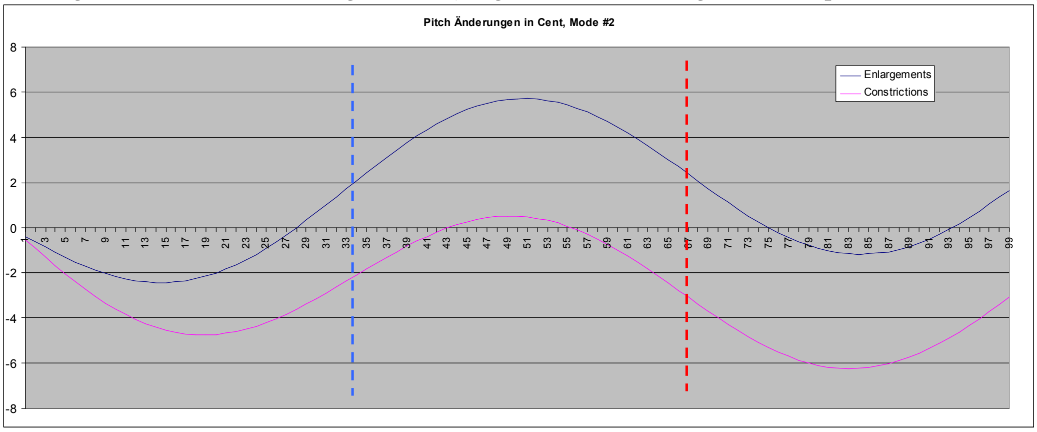
Mode #1, x = Proportion of centered perturbation length to pipe length, y = Change in Cent or % Input Magn. |Z|in

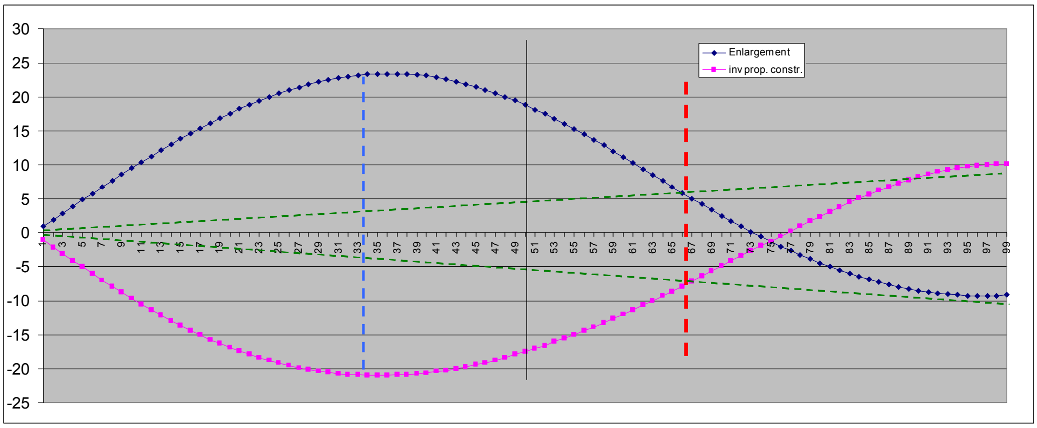




Mode1: Magn. Pot. 1/q0 with Enlargement and PL=50% = √0,25 Magn. Pot = q0 with PL=70% = √0,5

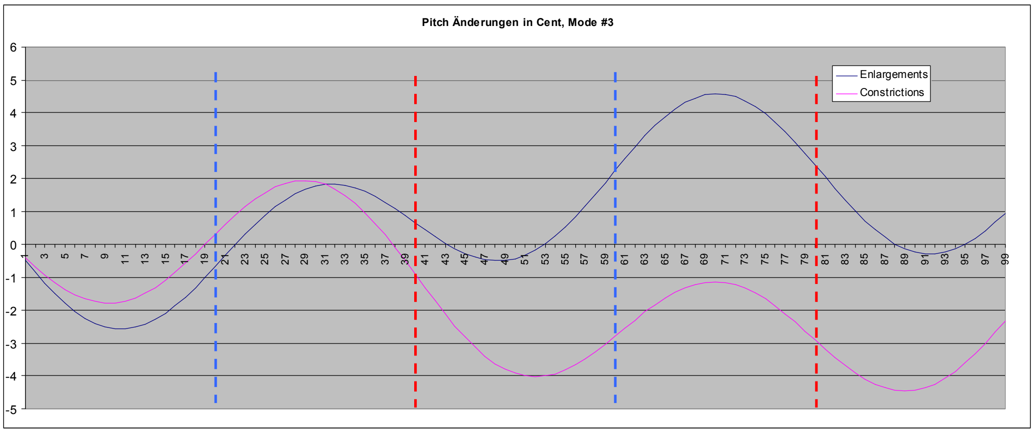
Mode #2, x = Proportion of centered perturbation length to pipe length, y = Change in Cent or % Input Magn. |Z|in
even / gerade Mode # are starting inverse (Magnituden Pot. enlargements = up, constrictions =dn)

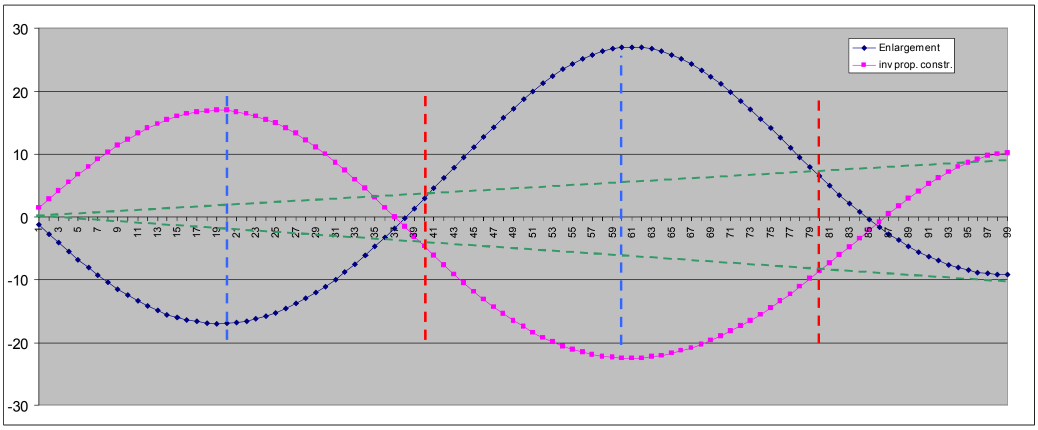




Blue = PL = ¼ WL and also x= Pressure Node Pos., Red = PL= 2/4 WL and also x=Press. Antinode Pos. in the tube
Green: 0 to invers q0-1; This number lines cross at Pressure Antinodes (Position and centered PL = 2 x ¼ WL)

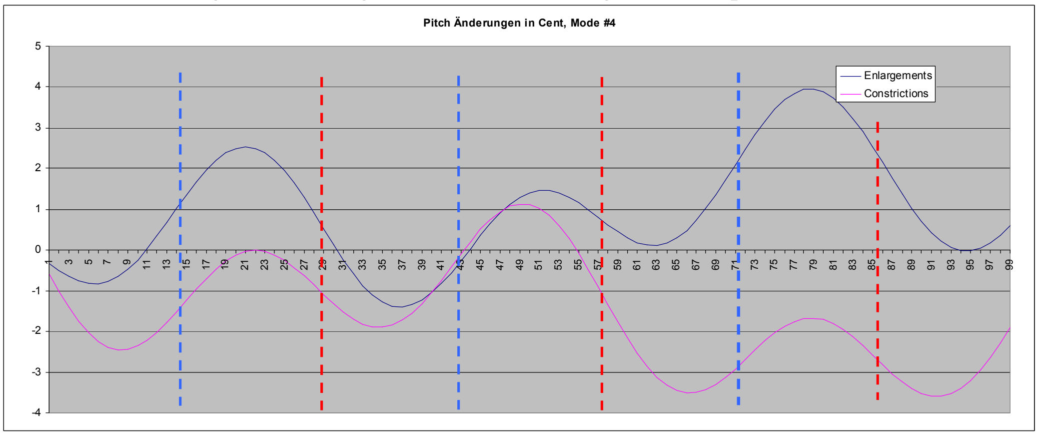
Mode #3, x = Proportion of centered perturbation length to pipe length, y = Change in Cent or % Input Magn. |Z|in

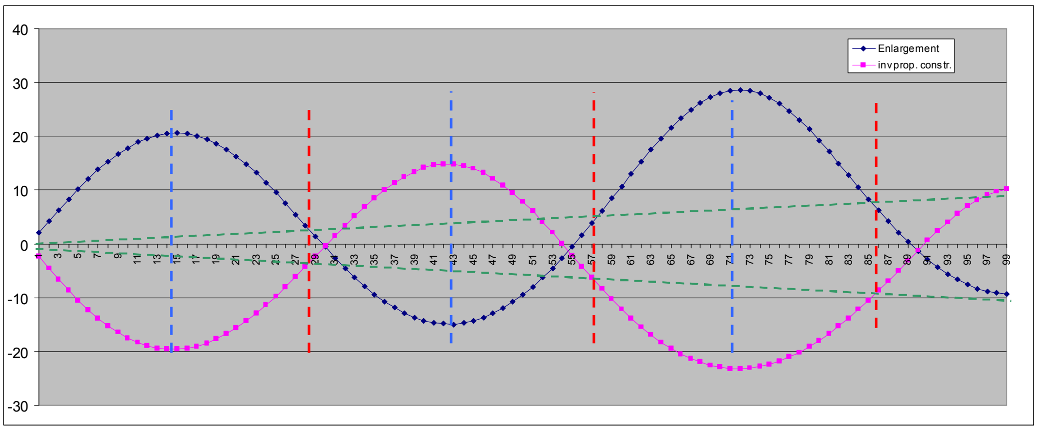




Inverse pot is much stronger and magnitude zero crossings = cancelling therefore earlier and later than DB!

Mode #4, x = Proportion of centered perturbation length to pipe length, y = Change in Cent or % Input Magn. |Z|in even mode # starting inverse (Magnitude Pot. with enlargements = up, constrictions =dn)





Comparison of centered perturbation lengths with the results from the ART simulations:

1. With bore steps, there are large deviations, especially at 50% step position (see chapter Bore steps).

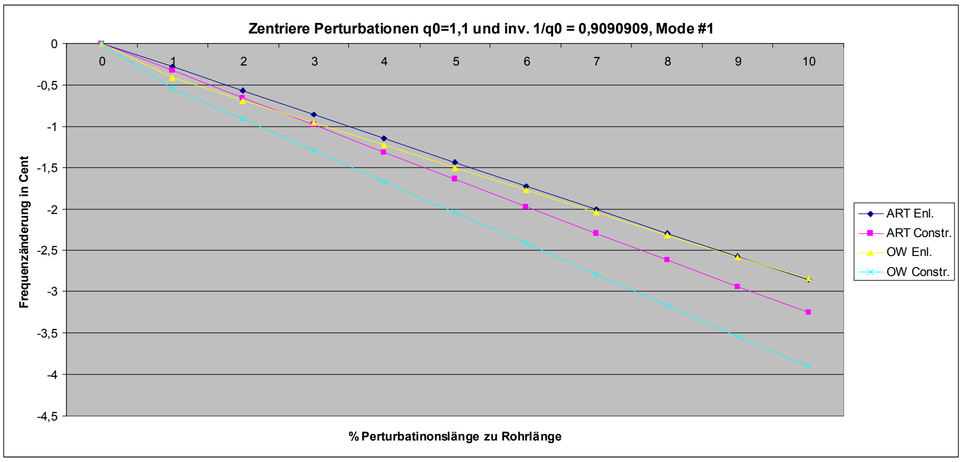
2. Results based on local perturbations, with position center x = 50% RL and PL = 2% RL:
see the previous chapters, at this position was almost the only position between ART and OW in Mode 1 without a particularly large deviation of the models. With OW, constrictions have more potential (pitch + magnitude), but the potential works specifically in the direction of lowering / stronger reduction of the input magnitudes.

3. For centered perturbations with standard perturbation q0=1,1 and perturbation lengths of 1-10% RL, which at higher modes correspond to ~ ¼ WL, I have comparison data that were determined with ART.
Intern: File: (ART CC Constr Enl Spectrum BVxx.xls)

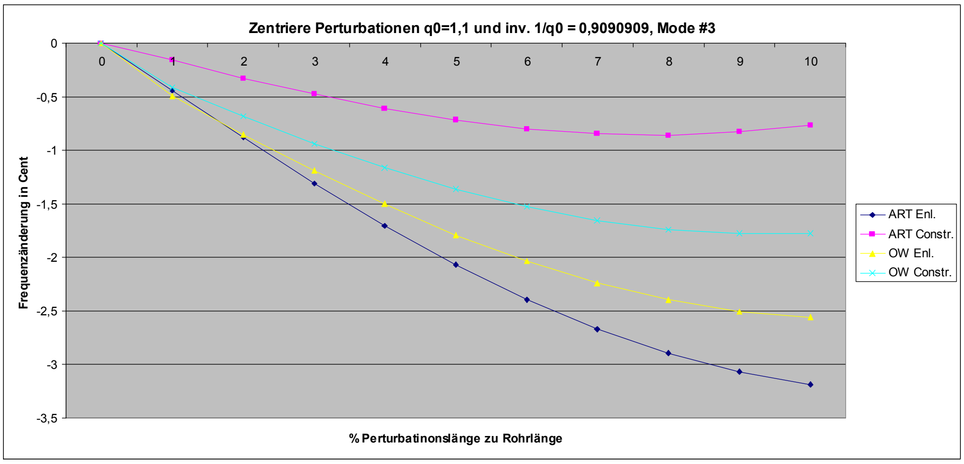
4. In the experiments with ART simulations, I did not use a complete series of measurements and calculated the expected behavior PL > ¼ WL using the formulas that I found. Other tests were with cross-sectional areas doubling / halving, etc.; see Sideletter #3. Here, again, there are big differences.

In principle, the resonance frequency should not be changed by a perturbation at 50% of the pipe length, but the already known pitch offset down results, which means that any perturbation leads to a slightly lower resonance frequency and the actual zero crossings are before and after 50% of the pipe length. If the perturbation length is increased, and thus approaches or exceeds the length of a 1/4 wavelength at higher modes, a pitch potential is already generated (as seen).

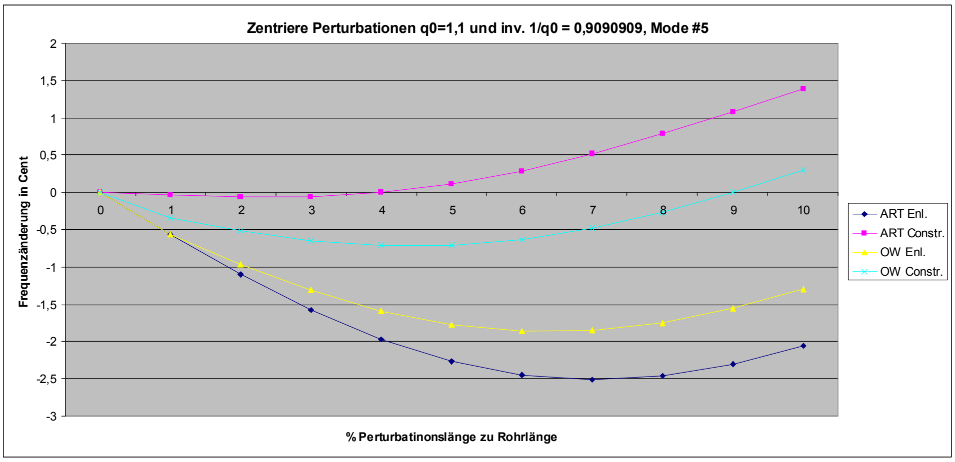
Centered Perturbations, odd # Modes, Pitch:



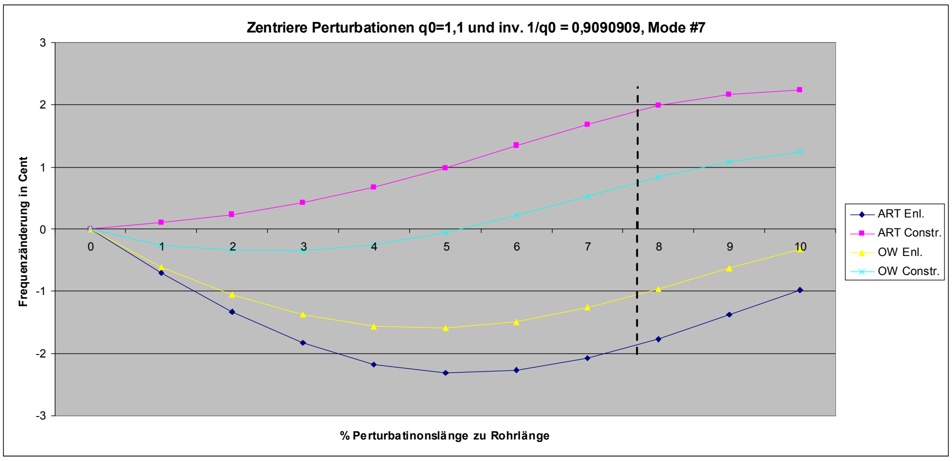
1/4 WL =100 % RL



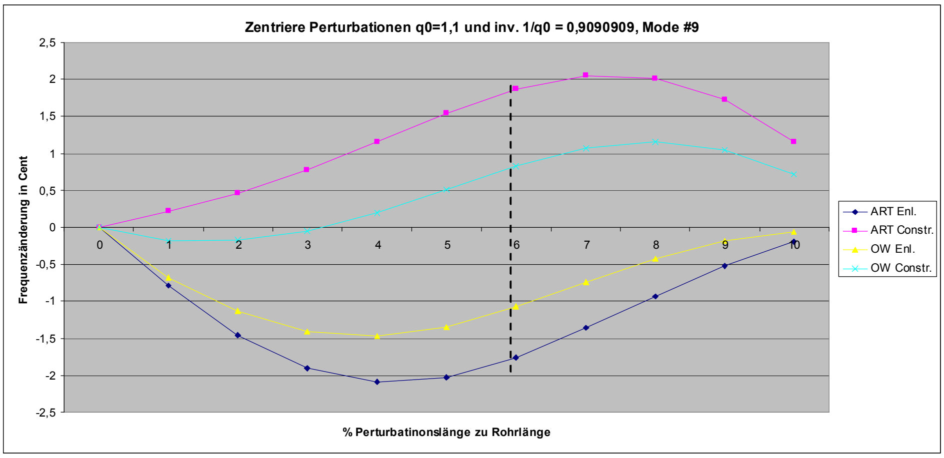
¼ WL = 20% RL



¼ WL = 11,1% RL



1/4 WL ~7,7% RL



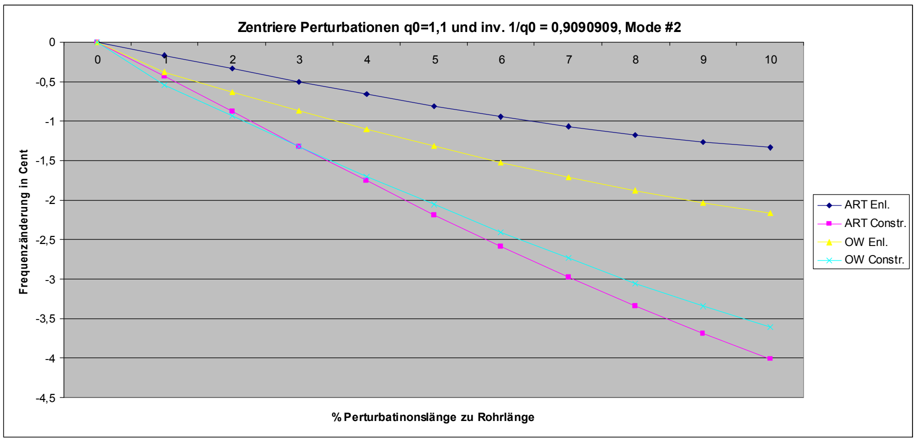
1/4 WL ~5,9% RL

Pitch Changes	with centered Perturbations, odd # Modes:	
Openwind:	Enlargements lowering less (Mode #3 and above)	in contrast to ART
	Constrictions lowering more / raise up is weaker	-"-

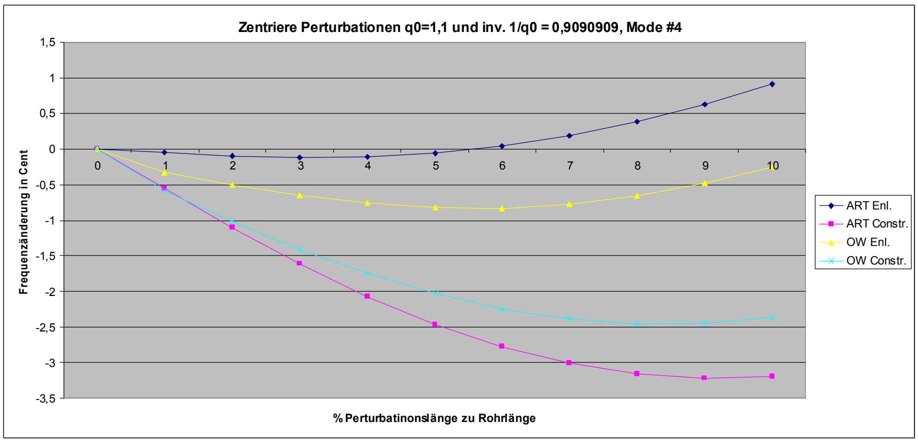
Pitch changes	with centered Perturbations, even # Modes (see next page):	
Openwind:	Enlargements lowering is stronger	in contrast to ART
	Constrictions lowering is weaker	-"-

With Open Wind: less overall potential (mode #1 more), but pitch potential in the direction of frequency lowering
With standard perturbation, PL=2% RL, there is only an increase potential from mode #6 and mode #7 upward, but it remains with a pitch offset "down". In general, this offset is dominated by the cross-section change much more than the length of a perturbation.

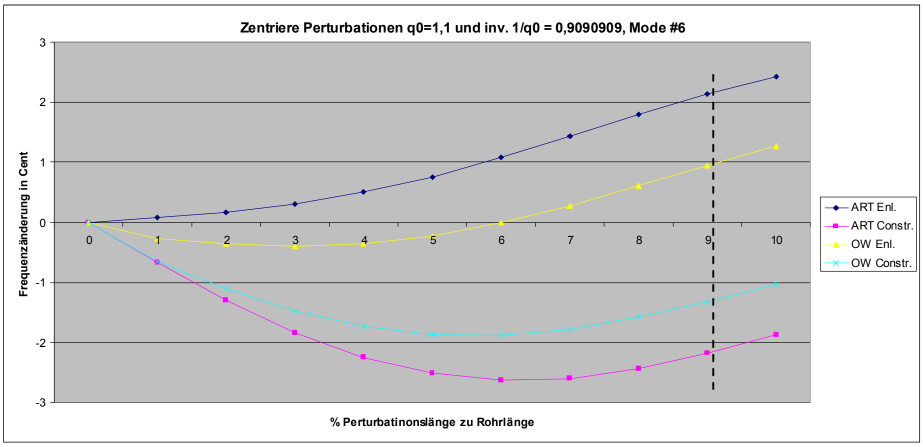
Centered Perturbations, even # Modes, Pitch:



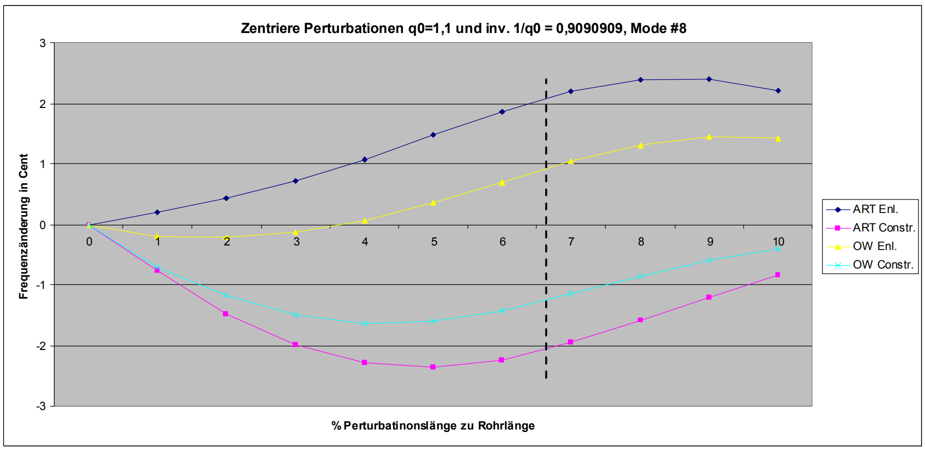
1/4 WL = 33,3% RL



1/4 WL ~ 14,3 % RL

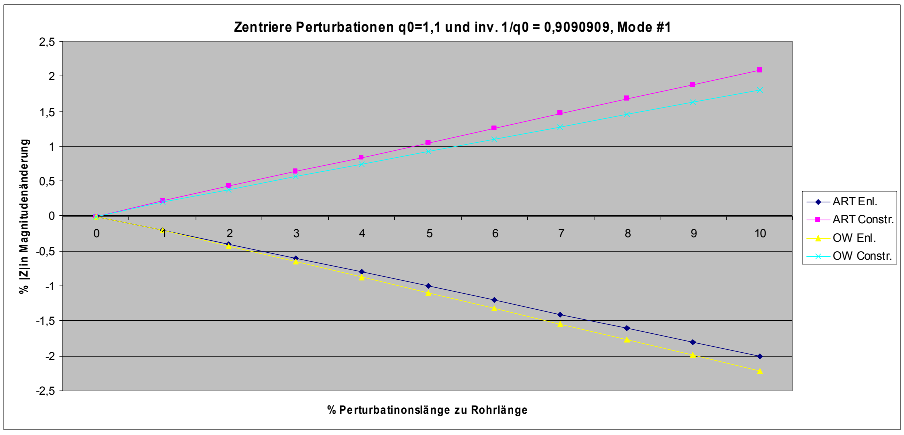


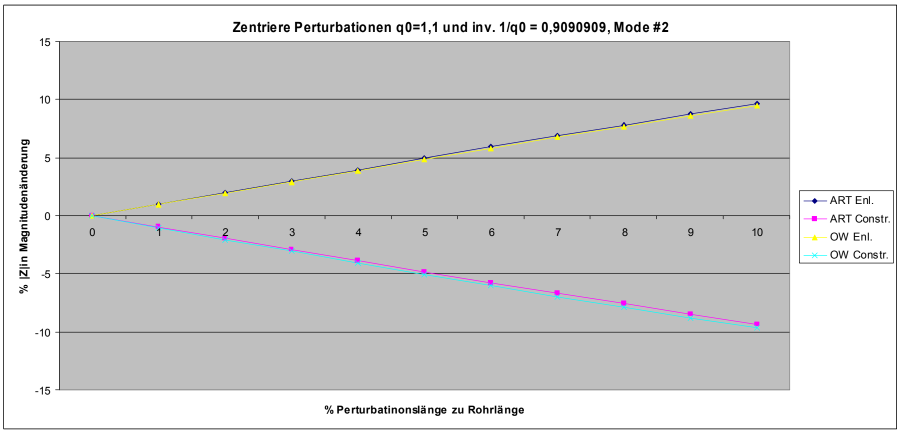
1/4 WL ~ 9% RL

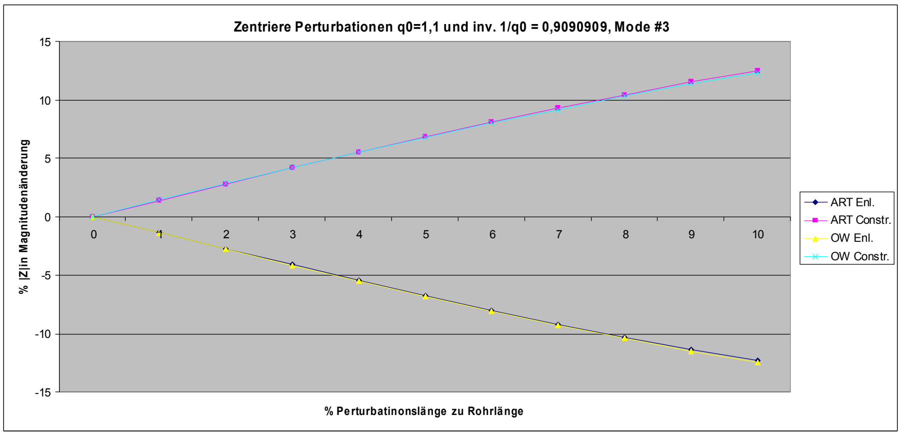


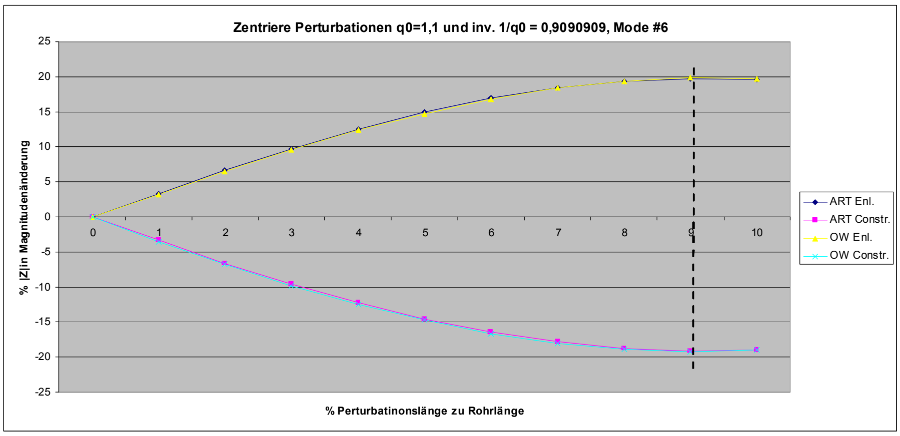
1/4 WL = 6,66% RL

Centered Perturbations, |Z| Input Impedance Magnitudes:









1/4 WL = 9,09% RL

OW: The magnitude pot. is stronger down with q0=1.1, from mode #3 onwards there is no significant difference to ART. The magn. pot. corresponds to approximately Xg potential = +/-19.09% up / down for higher modes q0=1.1 = 10% more or 9.09% less diameter and PL= ¼ WL, and decreases then with higher PL.

Openwind: Centered Perturbations, Change of cross section – q0 factor and inverse 1/q0:

Pitchpotential, Pitch Nodes and Pitch Offest

In the closed-open cylinder, centered perturbations at the position 50% of the pipe length can be referred to as a "pitch node" or zero crossing. The greater the cross-sectional change, the more down-shift there is, both with expansions and with constrictions. It was also found that both perturbations generally have a greater potential for lowering the Peak frequency. The potential for increasing the global frequency is factor of $1/q0^2$ lower, provided that constrictions are inversely proportional to expansions.

The effective change in the global wavelength is inversely proportional to this, which means that the potential for reducing the global wavelength (higher frequency) is $1/q0^2$ lower.

Cent values =log(2;frequency factor)^1200 are logarithmic difference values and equal differences (X) as + and - cent values mean inversely proportional potential up / down.

A local pipe expansion centered on a pressure antinode lowers the global resonance frequency of the mode, an inverse expansion = narrowing raises the frequency, but the potential is $1/q0^2$ less.

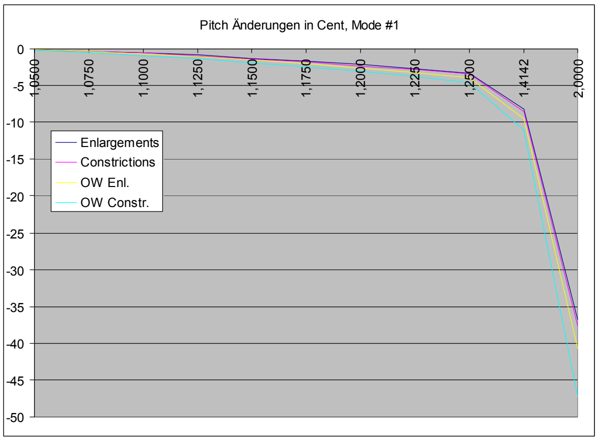
A local pipe expansion centered on a pressure node increases the global resonance frequency of the mode, but by a factor of $1/q0^2$ less than an inverse expansion = constriction lowers it. The total possible change potential is therefore $q0^2$ stronger down than up. Therefore, there is a zero crossing between pressure antinodes and pressure nodes before and after 1/8 wavelength, a common intersection point "shared" = pitch node based on enlargements and constrictions (here at 50% pipe length) results in a global depression = pitch offset down.

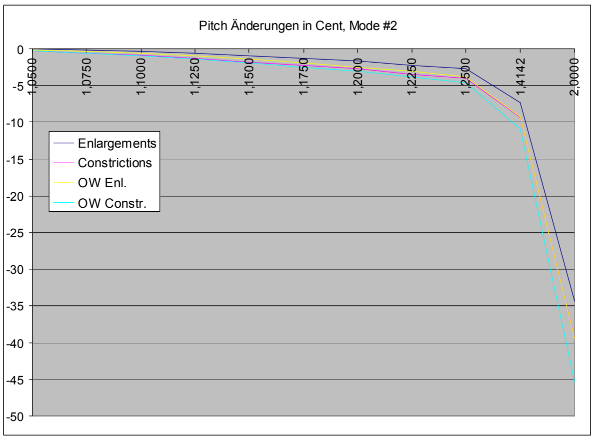
Even mode numbers have a pressure node 1/8 wavelength before 50% RL, enlargement pot up is $1/q0^2$;
Position 50% is here on a rising pressure antinode flank, after that the pressure antinode with enlargement pot dn $=q0^2$.
The pitch pot at 50% is falling and closer to the enlargement pot = offset down, the actual zero crossing before 50%.

With constrictions at pressure nodes the pot is $q0^2$ down, at pressure antinodes $1/q0^2$ up, the pitch pot at 50% is still down, and rising, the actual zero crossing later.

Odd mode numbers have a pressure antinode 1/8 wavelength before 50% RL and the pitch pot with enlargements is stronger down ($q0^2$) than up at pressure nodes and 50% RL is on a falling pressure antinode flank. The pitch pot down is still down with enlargements, zero crossing later. With constrictions the pitch pot at the pressure antinode is $1/q0^2$ weaker up, at pressure nodes $q0^2$, at 50% already dn, the zero crossing earlier.

In the following comparisons, the perturbation centered at 50% RL with a length of 2% of the pipe length was changed in the cross section. Differences between OpenWind and ART are again compared. In the previous comparisons, OpenWind with constrictions already shows more pitch and also magnitude potential down, or less pot up, contrary to the ART simulations, and the differences found are stronger in the lower modes.

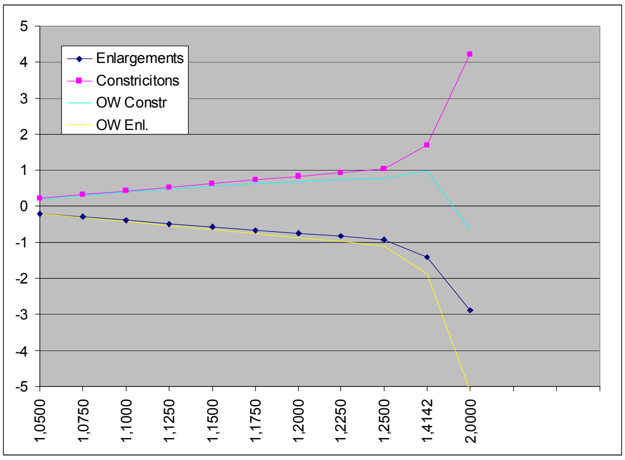


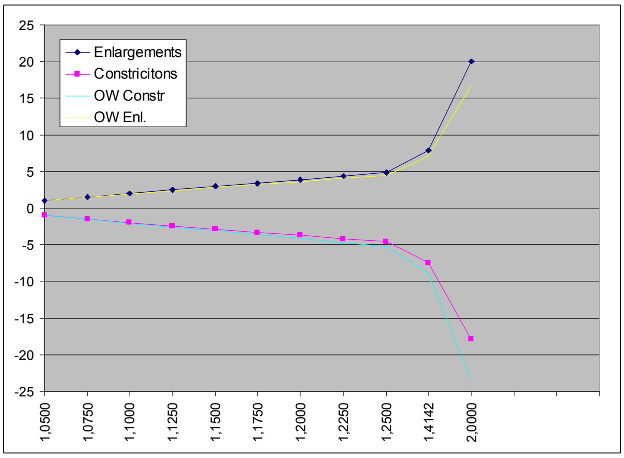


x = q0 cross-sectional factor enlargements, where constrictions are inversely proportional = 1/q0.
q0=1,4142 = Area doubling or halving, q0=2.0 = four times the area or ¼ cross-sectional area
OW: with very high cross-sectional change more pitch pot (offset) down, especially with constrictions compared to ART.

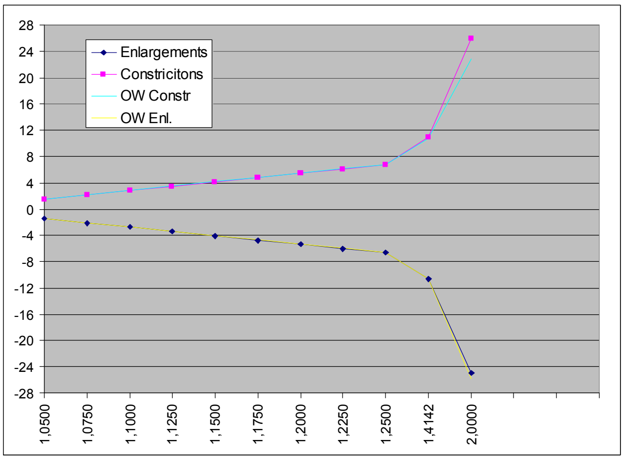
|Z|in Magn. Potential Change in %, centered Perturbations, PL = 2% RL (tube length)

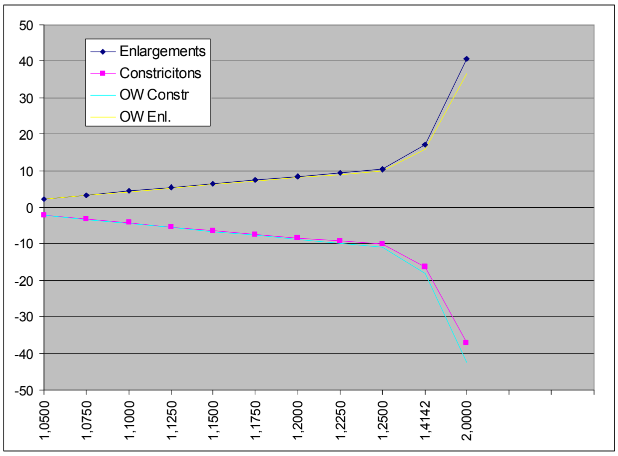
On falling pressure flanks = all odd modes at 50% pipe length result in (viewed from the closed end)	Enlargements Magn. Pot. dn, Constrictions Magn. Pot. up
On rising pressure flanks = all even modes at 50% pipe length result in = inverse behavior	Enlargements Magn. Pot. up, Constrictions Magn. Pot. dn





Mode #1 x=q0 Factor Mode #2





Mode #3 x=q0 Mode #4

Note the different behavior of Mode #1 with q0=2, which means that the inverse potential down becomes so strong that the zero crossing of constriction would occur before 50% instead of at position ~ 66% RL, but enlargements continue to reduce impedance peaks.

Apart from Mode #1, the trend remains that OW with constrictions develops more potential downwards, the differences are greatest in deep modes. The mean potential +/- XG hardly deviates from the XG value at low q0 factors upwards, at potential downwards a larger correction compared to the ART values must be made in order to get mathematically close to the simulation values.

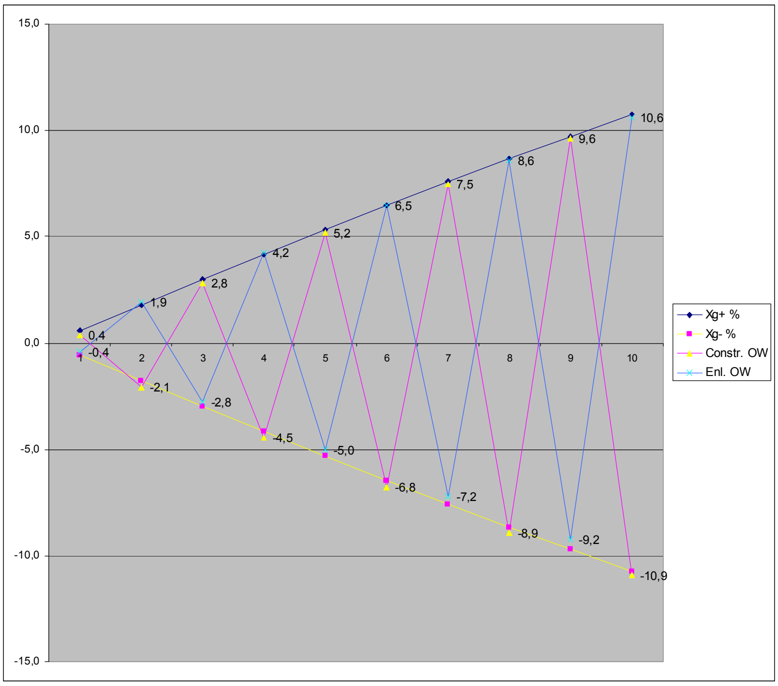
There should therefore be a magnitude offset down with OW, especially if the cross-section changes are large, which means that magnitude zero crossings are offset due to strong local constrictions based on the over-disproportionate Magn. Pot down, since there is still residual potential (at shared nodes).

	After Pot down: ..... later,	at 50%RL	after Pot up earlier; (odd)
odd modes and constriction:	rising at XM1, later	Pot up=not inverse	falling at XM2, earlier.
even modes and constriction:	falling at XM1, earlier	Pot dn=inverse	rising at XM2, later

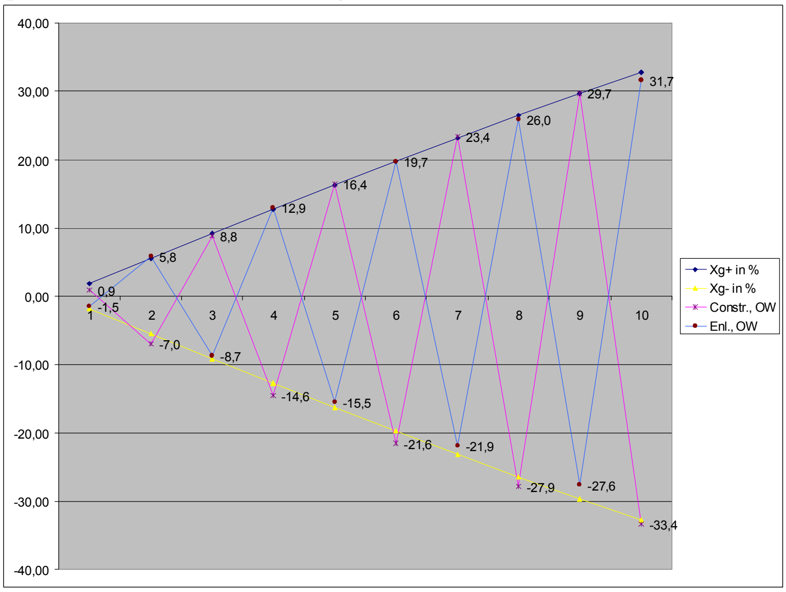
"Shared" nodes would be in the inverse range, so a magnitude Pot. Offset dn similar to Pitch Pot.
With ART, such an offset was not determined even with extreme perturbations and that has surprised me so far.

Magnitude Potential Xg – centered at 50% tube lenght, Correction factors:

Put simply, the zero crossings depend on the potential, which is somewhat stronger with OW and constrictions and also experiences a drift after magnitude reduction (losses). The magnitude potential with centered perturbation therefore has a different “weight” in open wind than it does with ART. Magn. Pot. up is almost Xg, and apparently no correction is necessary; Magn. Pot. down is stronger with constr. - weaker with enlargements (see also OW last quarter length); therefore an inversely proportional correction factor is necessary in addition to Xg.
The potential of odd modes on falling pressure antinode flanks is not inverse here, =dn with Enl.; Even inverse = up.



OW - Magnitude Pot. Change in % centered at 50 % Tube lenght, Pipe Dia 10mm,
local Perturbations, PL=20mm, q0=1,1, and inv. prop. 1/q0 = 0,90909
q0² = 1,21 Xe=0,21 Xg=0,1919 Xc=0,17355



= equivalent change like a “inserted” bolt with Diameter 7,25mm in a tube with Dia 11mm
OW - Magnitude Pot Change in % at 50 % tube lenght, tube Diameter = 10mm,
lokale Perturbationen, L=20mm, q0=1,333 and inv. prop. 1/q0 =0,75
q0² = 1,7777 Xe=0,7777 Xg=0,5833 bzw. 58,33% Xc=0,4375
Xg Pot is here 3 * stronger than the „Std.“ Perturbation 0,5833/0,1909

A correction factor + for Magn. Pot down with constrictions is required for Xg Pot., even modes = inv. Pot.
and a smaller correction factor - for Magn. Pot down with enlargements is required, odd modes = not inv. Pot.
For higher modes, it must be taken into account that the determined Pot. values are somewhat too low (resolution error).

Magnitude Potential of local Perturbations, Comparision ART und Open Wind:

with Diameter change +10% and invers proportional = -9,0909% Diameter
q0=1,1 = q0²= *1,2100 (Factor Area Change) 1/q0=0,90909 = 1/q0² = *0,82645 (Area)

Xe = Diff. Cross sectional Area Enlargement		= 0,2100		= q0²-1 =Xc*q0², Xg*q0
Xhe= harmonic Mean	from Xe and Xg	= 0,2000		= (q0-1)*2
Xq = quadratic Mean	from Xc and Xe	= 0,1926	= square root of	(Xc² + Xe²)/2
Xa = arithmetic Mean 1	from Xc and Xe	= 0,1917	=	(Xc + Xe)/2
Xg = geometric Mean	from Xc and Xe	= 0,1909	= sqare root of	(Xc * Xe) =Xc*q0, Xe/q0
Xh = harmonic Mean	from Xc and Xe	= 0,1900	= 2 /	(1/Xc + 1/Xe)
Xhc=harmonic Mean	from Xg and Xc	= 0,1818		= (1/q0) *2
Xc = Diff. Cross sectional Area Constriction		= 0,17355		= 1-(1/q0²) =Xe/q0², Xg/q0

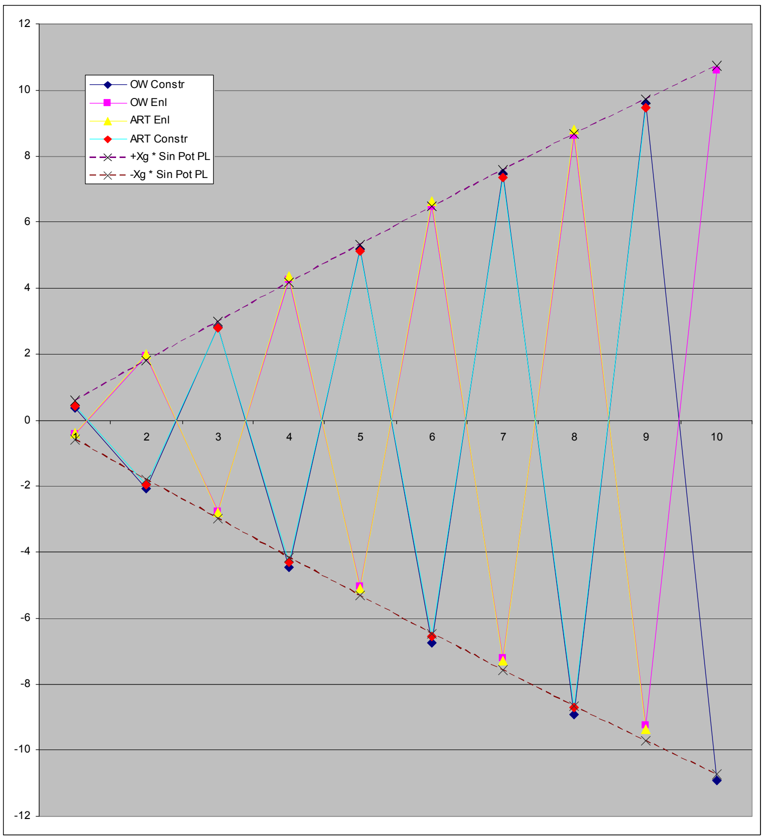
ART- Magn. Pot. envelope curves – found approximations:

PL Pot = PL Portion ¼ WL PL / RL Portion PL = Portion Perturbation lenght to tubelenght
x = Perturbation Center Pos= Factor (Abstand Perturbationszentrum vom closed Ende/ Rohrlänge)
Position Potential Pos. Pot. = 1-x

Enlargements, ART Corr = Xhe:
DZin(x) = 0- (2 Xg * Sin (PL Pot)) - (Xhe * PL) * (1-x) Enl. not inverse (dn) =less Pot than Xg dn
DZin(x) = 0+ (2 Xg * Sin (PL Pot)) + (Xhe * PL) * (1-x) Enl. **inverse (up)**. =more Pot than Xg up
ati 50% RL = -/+ (Xg * Sin (PL Pot)) -/+ (Xhe **/2** *PL)

Constrictions, ART Corr = Xc:
DZin(x) = 0- [(2 Xg * Sin (PL Pot)) + (Xc * PL) * (1-x)] Constr. inverse (dn). =more Pot than Xg dn
DZin(x) = 0+[(2 Xg * Sin (PL Pot)) - (Xc * PL) * (1-x)] Constr. n. invers (up) =less Pot than Xg up
bei 50% RL = -/+[(Xg * Sin (PL Pot))] +/-(Xc**/2** * PL)

Perturbation at 50% RL, Magnitude Potential |Z|in, Magnitude change in % = X *100, with q0=1,1



OW vs. ART; more Corr value down necessary, but in return no correction up necessary.

Openwind - found approximations (the correction dn ist almost twice that of ART):

We find, Pot UP = with Enlargements inverse requires no Corr., Corr. = -0
Pot UP = with Constrictions not inverse requires no Corr . Corr. = +0

*result in constrast to ART a „Over-Potential“ with Constrictions, about ~ 1*Xc *PL Pot up and dn,*
*a „Minder-Potential“ with Enlargements, about ~ 1*Xc *PL Pot up and dn.*

Enlargements, OW Corr = -Xc:
DZin(x) = 0- [(2 Xg * Sin (PL Pot)) - (2Xc * PL) * (1-x)] Enl. not inverse (dn)
DZin(x) = 0+ [(2 Xg * Sin (PL Pot)) - 0 * (1-x)] Enl. **inverse** **(up)**.

at 50% RL: = 0+ [(Xg * Sin (PL Pot)) - 0] inverse up (even#)
at 50% RL: = 0- [(Xg * Sin (PL Pot)) - (Xc * PL)] n. inverse **dn** (odd#) *(Mode #1 somewath to much corr.)*

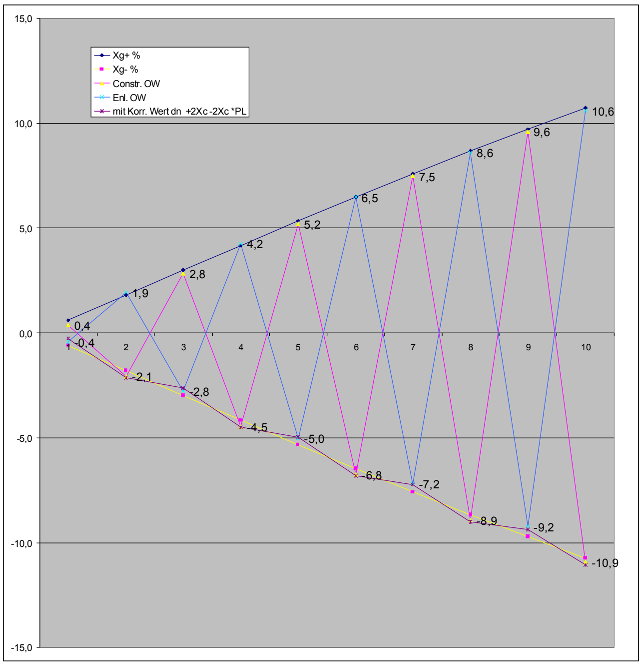
Constrictions, OW Corr = +Xc, respectively +Xe:
DZin(x) = 0- [(2 Xg * Sin (PL Pot)) + (2Xc * PL) * (1-x)] Constr. inverse (dn) ***
DZin(x) = 0+ [(2 Xg * Sin (PL Pot)) + 0 * (1-x)] Constr. n. inverse (up)

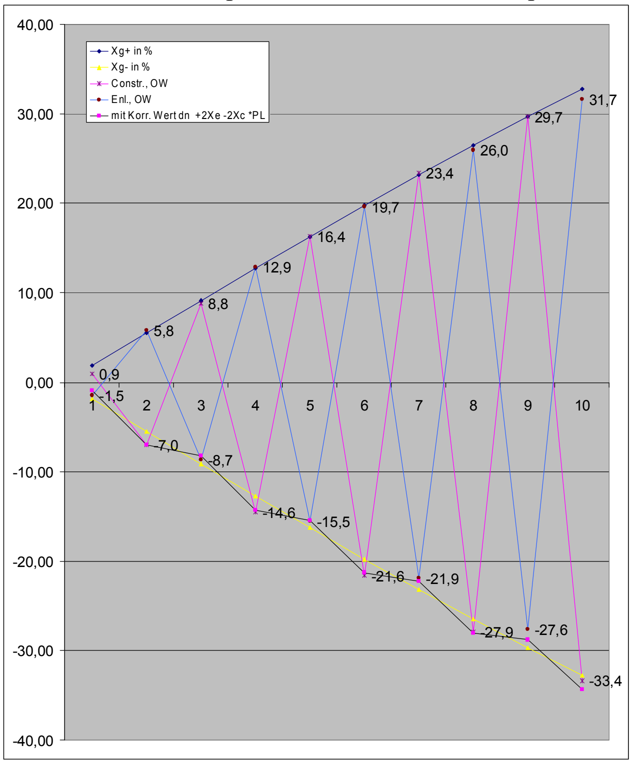
at 50% RL: = 0- [(Xg * Sin (PL Pot)) + (1Xc * PL)] inverse **dn** (even #) ***
at 50% RL: = 0+ [(Xg * Sin (PL Pot)) +0] n. inverse up (odd#) *(Mode #1 somewath to much corr.)*

*** where the necessary correction value Constr. dn at 1/q0 ~ 0.75 is already Xe instead of Xc!

Open Wind, Magnitude Potential |Z|in, Magnitude change in % = X *100

Std. Perturbation, Cylinder closed open, L 1m, Dia 10mm equiv. sleeve to “bolt 725” 1/q0=0,75





Open Wind, PL 2% RL, q0=1,1 Magn. Pot dn XG -/+ Corr. Value PL 2% RL, q0=1,333
Correction value dn: Constr: + 2*Xc Correction value dn Constr: + 2*<u>**Xe**</u>
Correction value dn: Enl. - 2*Xc Correction value dn Enl. - 2*Xc

This means with strong perturbations the necessary correction for Constr. (the Pot. * PL) changes inversely prop. to q0²

Simulation of constrictions with bolts or balls, equivalent sleeves

In former physical impedance measurements on a Bb trumpet, a bolt with a diameter of 7 mm and an 8 mm ball were used in the cylindrical part (diameter 11.0 mm). This was to find the magnitude zero crossings (based on constrictions). = XM-IN1 before and XM-IN2 after XM-PN, where XM-PN corresponds to 50% of the pipe length in the closed-open cylinder position. IN means impedance node or zero crossing, PN stands for pitch node or pitch zero crossing, so these are points with no potential for changes due to the perturbation.

The bolt should cause a magnitude offset down, which would not be present with a smallest or infinitesimal cross-sectional change, and the zero crossing position found with the bolt = a strong constriction would therefore be:

odd Modes and Constriction: at XM1 raising, **later** * Pot up=not inverse at XM2 falling, earlier
even Modes und Constriction: at XM1 falling, **earlier** Pot dn=inverse at XM2 raising, later.
as the "origin" position with smallest perturbation and (barely) offset down. Press.AntiNode Pressure Node

In addition, in the OW simulation, such "origin" magnitude nodes on the closed-open cylinder coincide with pressure antinodes. With odd # modes, for example this corresponds to XM-IN1, and with even # modes to XM-IN2.

Due to a strong perturbation, the results of the zero crossings would therefore be offset from the pressure nodes (see above), or the pressure nodes and the origin zero crossing position sought would be in the opposite direction; here, the pitch pot should be at maximum. At pressure nodes (even modes XM IN-1), the pitch pot should be max. down. At pressure antinodes on the other hand, due to the strong pitch pot shift down, not so strong pitch pot up. (Odd, XM-IN1)

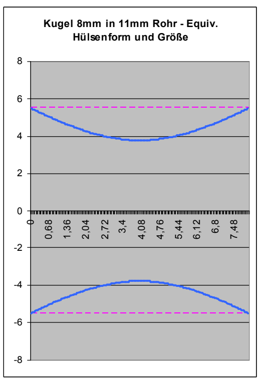
In the case of pressure nodes, the "origin" magnitude zero crossings in the OW simulation occur offset to the closed end of the pressure node. The distance from the following magnitude node on the pressure antinode is greater than ¼ WL. This would be the case with even modes for XM-IN1 and with odd modes for XM-IN2 - here the distance to the preceding pressure antinode would be less than ¼ WL. If you look at the diagram above, you will notice that due to strong constrictions, the magnitude zero crossings found here are in front of the pressure nodes, but the "shared" magn. nodes sought should also be slightly in front of the pressure nodes.

* The physical tests on the trumpet have shown that odd modes at XM-IN1 = at pressure antinodes, specifically mode #7, result in more consistent zero crossings with different perturbation strengths, strong constr. deviate less than is the case with even modes (close to pressure nodes), specifically mode #8. If the above statements are correct, then shared magnitude nodes, which I now refer to as the actual XM-IN1 position with hardly any offset dn - in odd modes must be slightly in front of the passage position determined with bolts and also their pressure antinodes, but the following OW evaluation shows that this is minor at pressure antinodes and only from mode #8 onwards.

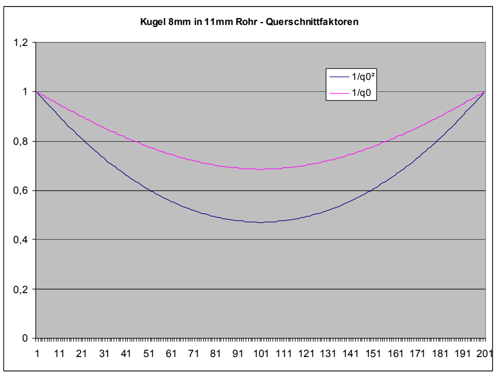
A bolt with a diameter of 7.25mm (length 20mm) in an 11mm tube corresponds to an equivalent sleeve with inner dia 8.272mm in an 11mm tube, the 1/q0 factor is 0.752; I round to 0.75 and an equivalent expansion would be q0=1.333.

Converted to a 10mm tube, this corresponds to a constriction of 1/q0 = 0.75, i.e. a remaining inner diameter of 7.5mm at the constriction. An equivalent expansion in the 10mm tube would be 1/0.75 = 1.33 * 10mm= Dia 13.33mm.

The ball with a diameter of 8.0mm (length 8mm :); corresponds to an equivalent sleeve with an inner diameter of 7.55mm in the 11mm tube, the 1/q0 factor in the center of the ball is 1/q0=0.686 and q0=1.46
In the 10mm tube this corresponds to a ball with a diameter of 7.27mm, the equivalent sleeve would be a diameter of 6.86mm (only in the center). *(I did not run a simulation of the ball with OW, but with the simpler bolts 7mm and 5mm).*



Ball: - equiv. Sleeve in 11mm Tube



Equiv. Cross-Section-Factors with Ball: $1/q0^2$= 0,686 und $q0^2$ = 2,12

The bolt 725 in the 11mm tube results in an almost halving of the cross-sectional area of $1/q0^2$ =0.565, the ball would exceed the value 0.5*area and reaches a value of $1/q0^2$ = 0.47 (but only) in the center

The arithmetic mean value is 8.8mm diameter, which corresponds to 1/q0 = 0.8, or q0=1.25 and $q0^2$=1.56. The ball acts somewhat like an "immediate" constriction or bulge, but the ball is only 40% of standard PL, or 0.8% RL. Which in turn means that the overall change potential should be lower than with the bolt.

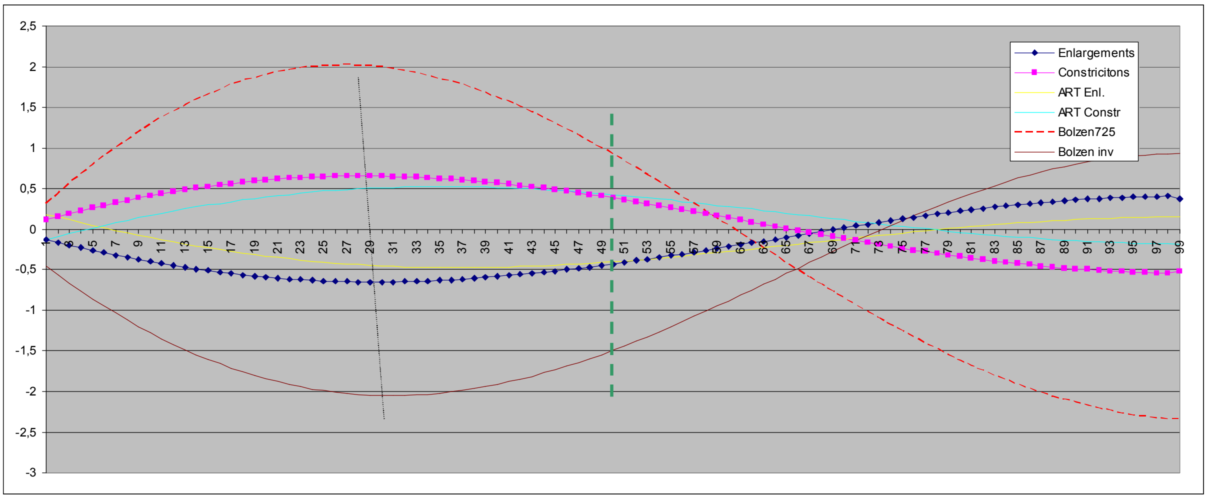
One should now be able to understand the effects, particularly on the bolt, based on the equivalent sleeves and consider this sleeve thickness = -25% diameter or inverse expansion +33% in the previous comparisons. The constrictions are at (around 2%) PL and at inverse q0 1.33 = 1/q0=0.75. This should therefore result in an additional lowering of at least 5 cents in all modes compared to the standard perturbation with q0=1.1 and PL 2% RL, and magnitude changes should be around 2.5 * stronger.

So far, cross-section changes have only been considered centered at 50% of the pipe length, where magnitude changes have great potential in the closes-open tube. In order to consider the effects of the OW simulation on the magnitude zero crossings, other pipe positions must therefore be perturbed. I have therefore chosen a region of 25-35% of the pipe length for this.

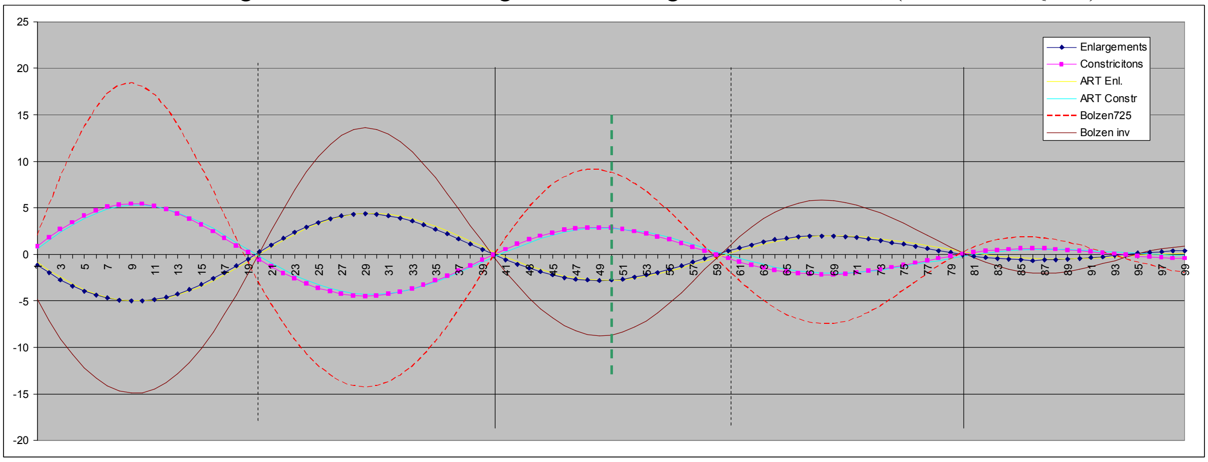
Simulation OW, Magnitude Potential (and Offset) with "Bolzen 725" / equ. sleeve = 1/q0=0,75, PL=2%RL

The remaining shown data are perturbations with 1/q0=0,909 bzw. q0=1,1; Simulation OpenWind + ART; PL=2% RL

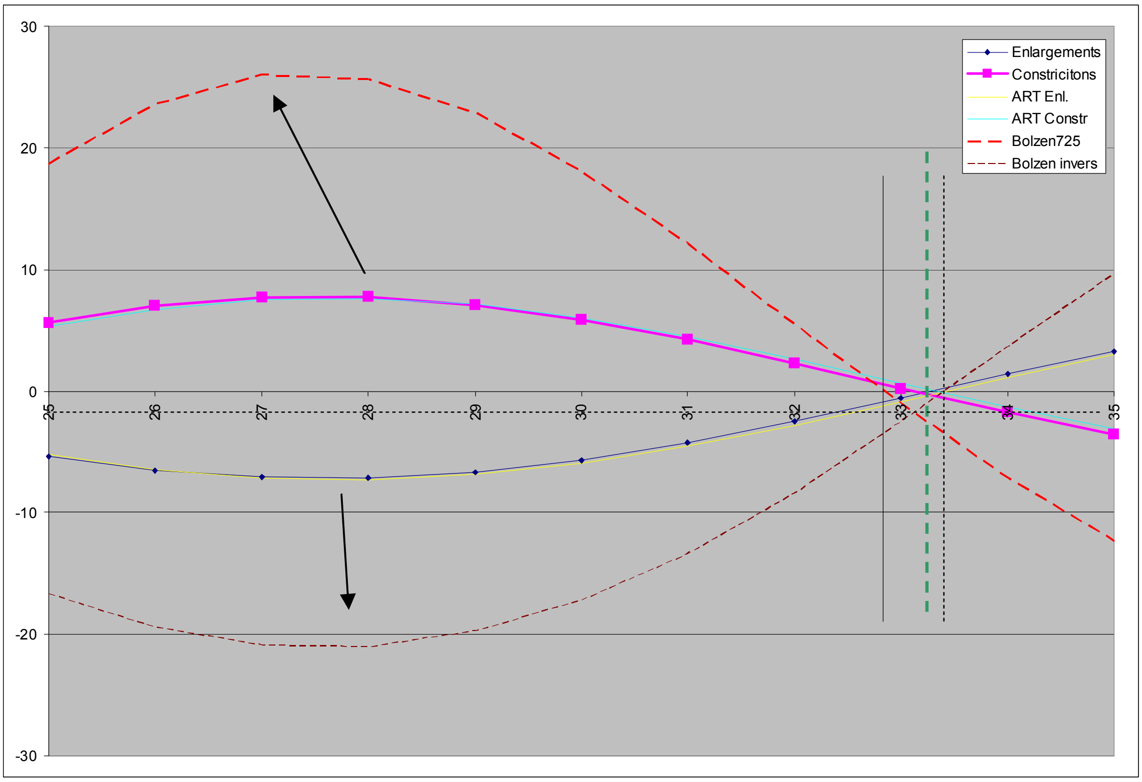
Odd Modes: Pressure Antinodes at 1/4WL * even #, also XM-IN1, Pressure Nodes at 1/4WL*odd #, also XM-IN2



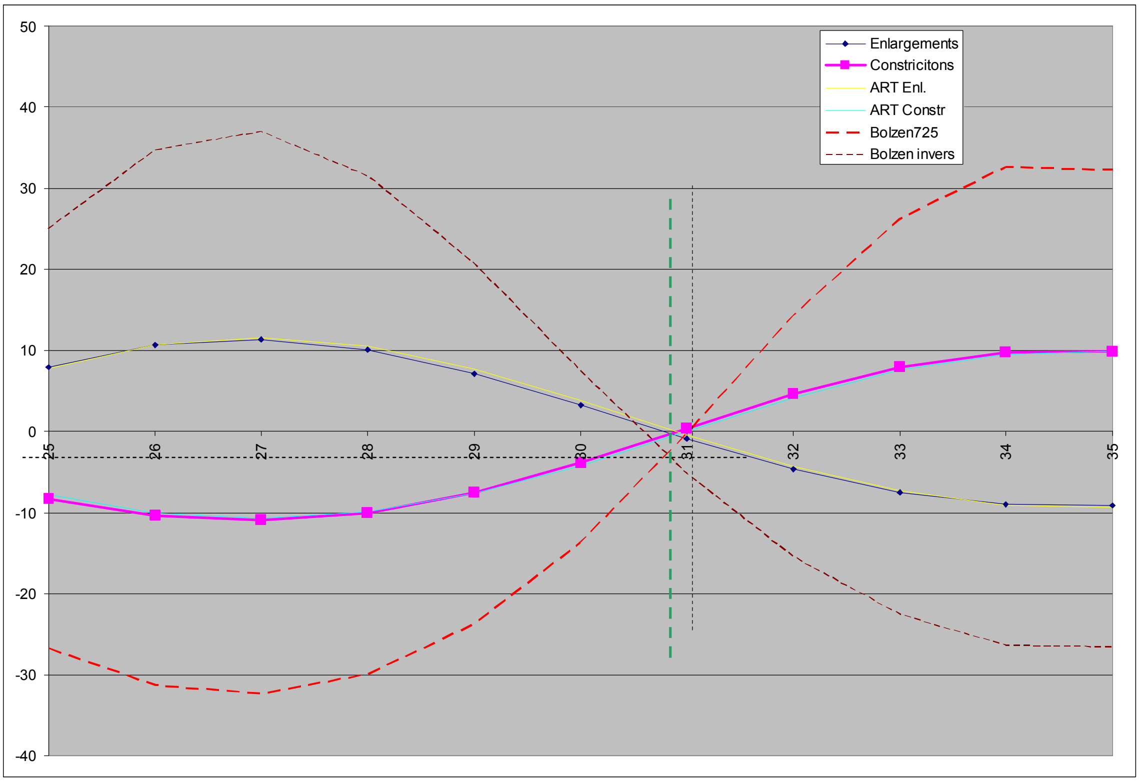
XM-IN1=0%, IN2=67% RL *You may notice the complete different results with mode#1 = last quaterlenght!*
Mode #1: has in the region of 25-35% tube lenght its max. Magn. Pot., not inverse, (last ¼ WL, QWR).



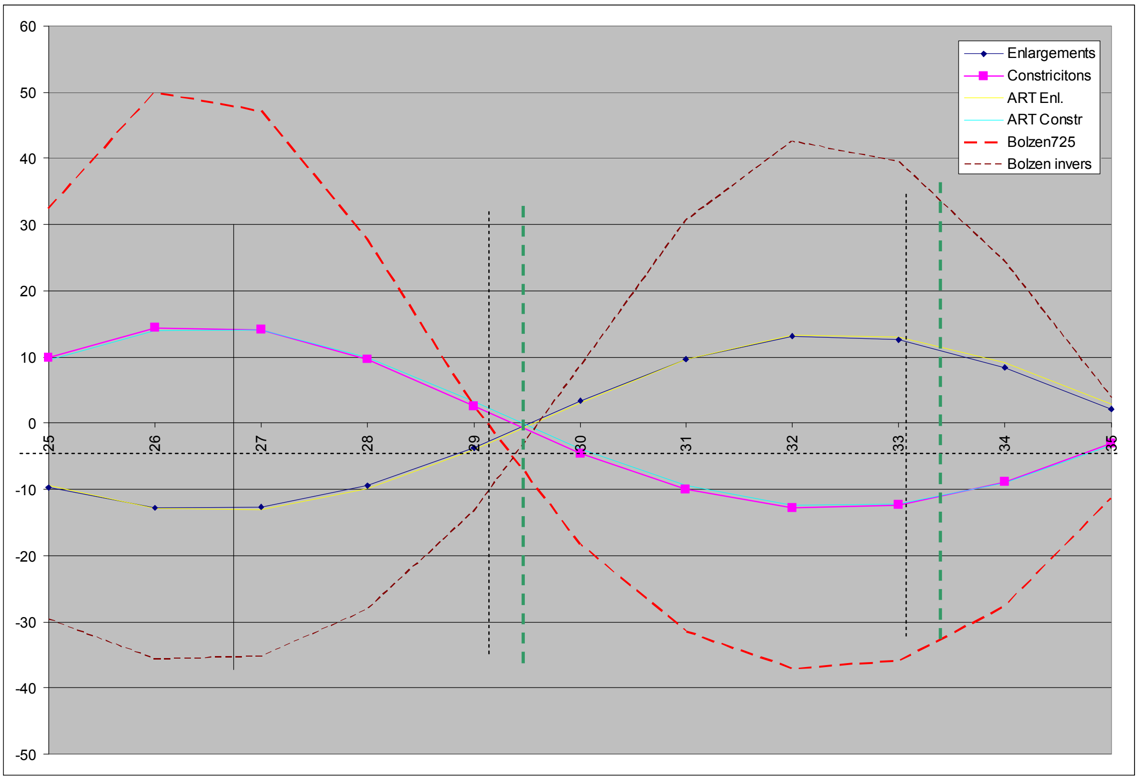
1/4WL*2=40% RL =XM IN1, Pressure Antinode
Odd Mode #3: has inverse Magnitude Pot. before XM-IN1, Constrictions stronger dn.
Crossing at XM-IN1 should occur later with the bolt. (at higher modes it is not later!)
2. The Pot. difference ist here very small, so here rather not later.
shared Magnitude Node at XM-IN2 is shorthly before the Pressure node (earlier)



1/4 WL*3= at Position = 33,33 % RL, Pressure Node
Odd Mode #5: Magnitude Node, zero crossing with the bolt occours earlier (behavior same as at XM-IN2).

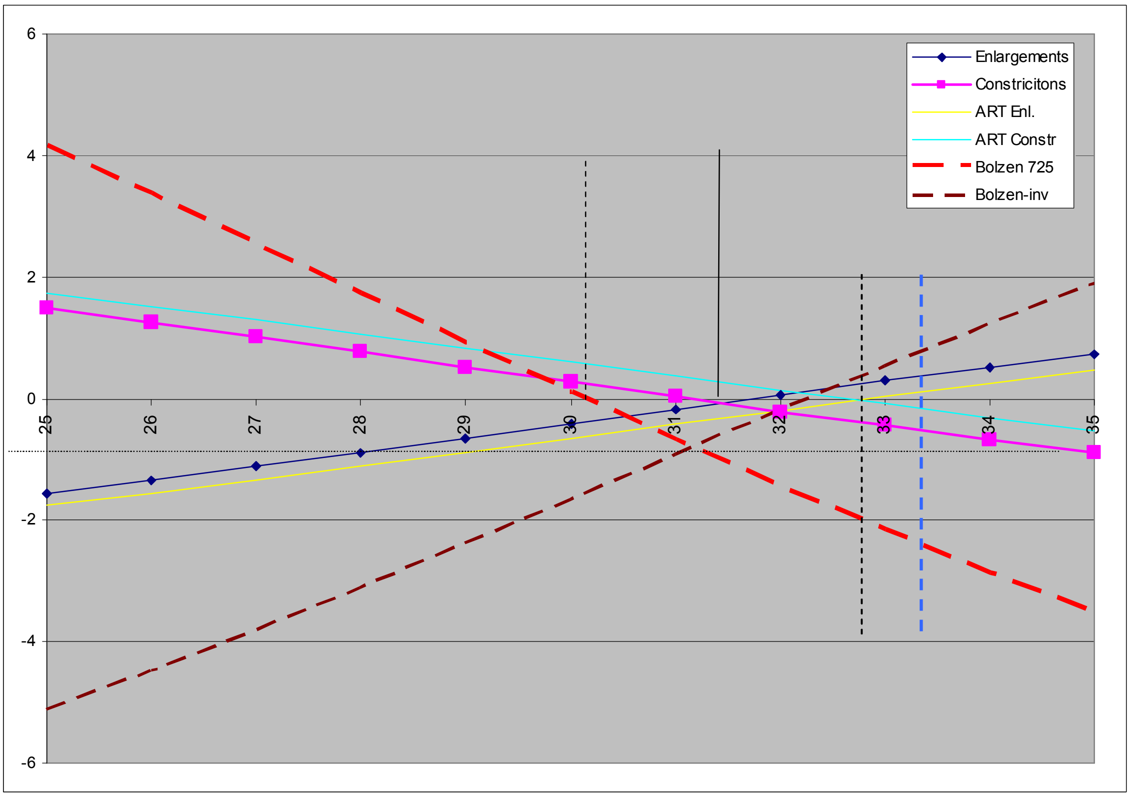


1/4WL*4 = at Position = 30,7 % RL, Pressure Antinode
Odd Mode #7: Magnitude Node, zero crossing with bolt not later (behavior as is at XM-In1).

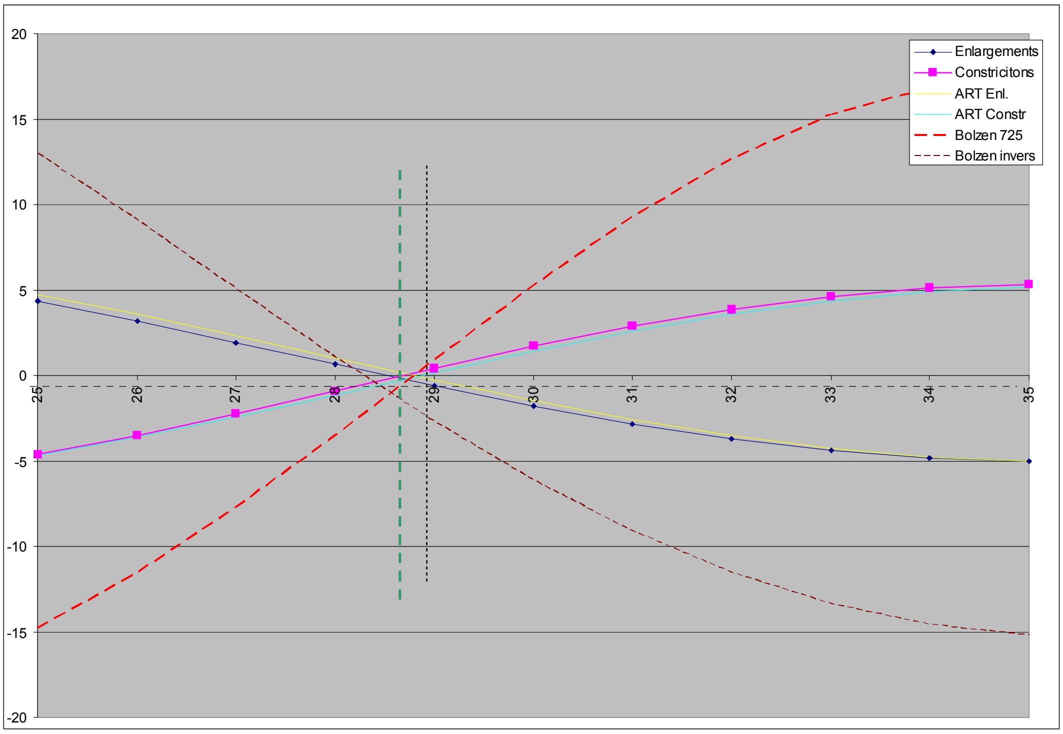


1/4WL*5= at Position = 29,4% tube lenght, Pressure Node
Odd Mode #9: Magnitude Node, zero crossing with bolt earlier (behavior as is at XM-IN2).

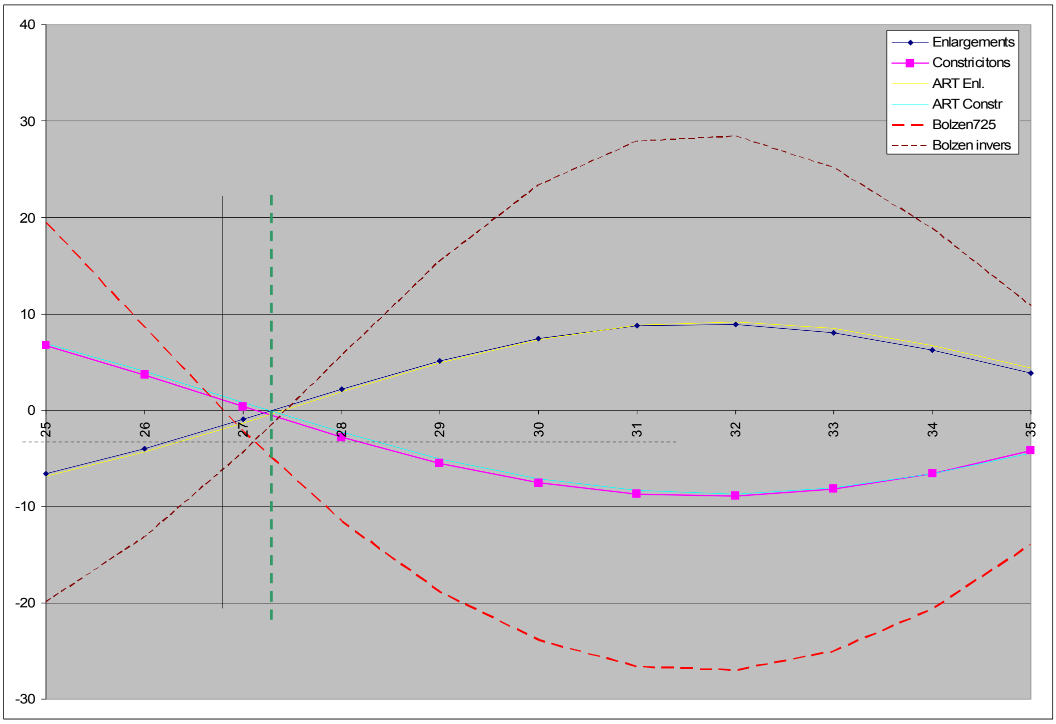
Even Modes: Pressure Antinodes at 1/4WL * even #, also XM-IN2, Pressure Nodes at 1/4WL*odd #, also XM-IN1



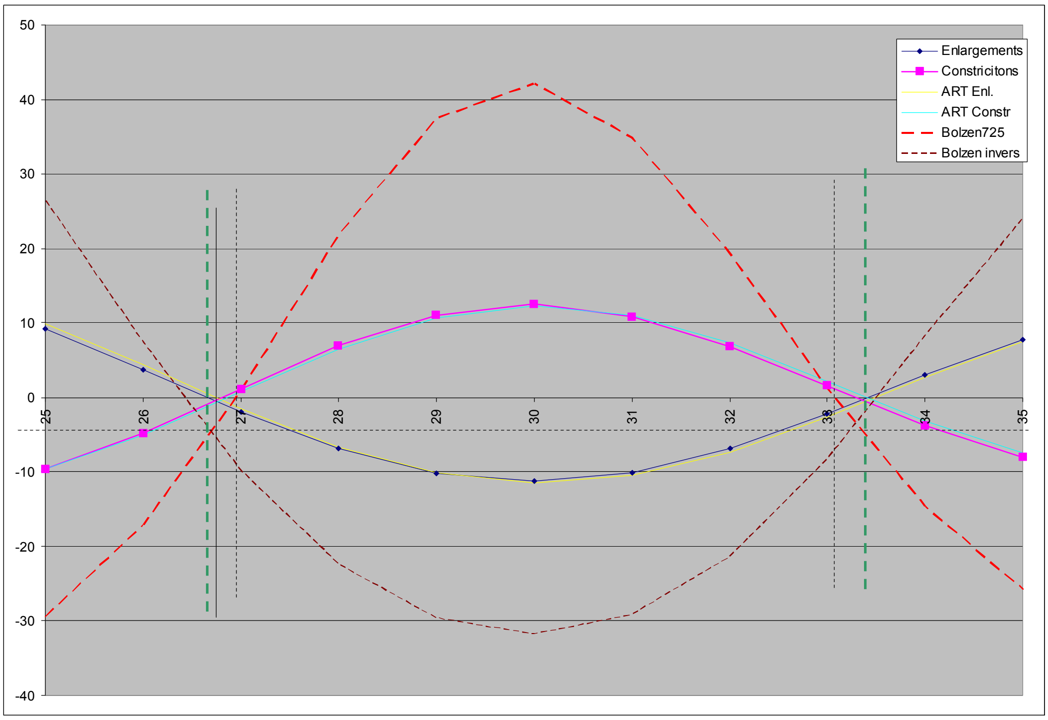
1/4WL*1= at Position = 33,3% tube lenght, Pressure Node
Even Mode #2: Magnitude Node, with bolt zero crossing earlier (= XM-IN1). ~ -10% ¼ WL



1/4WL*2= at Position =28,6% tube lenght, Pressure Antinode
Even Mode #4: Magnitude Node, zero crossing with bolt not later (behavior as is at XM-IN2).

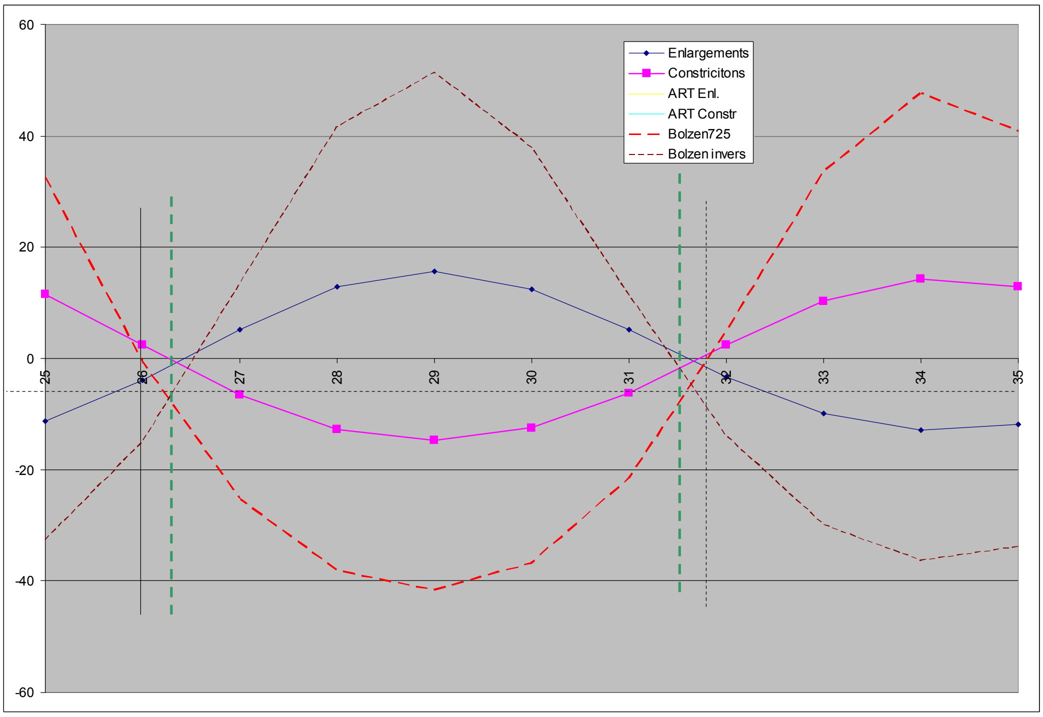


1/4WL*3= at Position = 27,3% tube lenght, Pressure Node
Even Mode #6: Magnitude Node, zero crossing with bolt earlier (behavor as is at XM-IN1). around -10% von ¼ WL.



1/4WL*4= at Position = 26,7% tube lenght, Pressure Antinode 1/4WL*5= at Position = 33,3%, Pressure Node

Even Mode #8: Pressure Antinode: Magnitude Node, zero crossing with bolt here somewhat later
Even Mode #8: Pressure Node: Magnitude Node, zero crossing with bolt earlier (behavior as is at XM-IN1).



1/4WL*5=Position at 26,3% RL, Pressure Node 1/4WL*6= Position at 31,5% RL, Pressure Antinode

Even Mode #10: Pressure Node: Magnitude Node, zero crossing with bolt earlier
Even Mode #10: Pressure Antinoderuck: Magnituden Node, zero crossing with bolt here almost not later.

One can therefore generally say, with the Open Wind model: With strong constriction the
Magnitude zero crossing is always before Pressure Nodes (even # XM-IN1; odd # XM-IN2);
at Pressure Antinodes (nicht later); higher modes but still.
(odd # at XM-IN1, even # at XM-IN2).

The found impedance magnitude zero crossings positions are:

	1/q0=0,75	1/q0=0,909	ART (alle 1/q0)	Pressure Node	¼ WL =	
Mode #1	-				100	cm / %
Mode #2	30,0	31,3	32,8	33,33	33,3	2 / 3,33cm
Mode #3		59,0	60,0	60,0	20,0	- / 1,0 cm
Mode #4	(is at Pressure Antinode, no deviation)				14,285	
Mode #5	32,8	33,3	33,3	33,33	11,111	0,5
Mode #6	26,8	27,2	27,27	27,27	9,0909	0,4
Mode #7	(is at Pressure Antinode, no deviation)				7,6923	
Mode #8	33,1	33,3	33,33	33,33	6,6666	0,2
Mode #9	29,1	29,4	29,4	29,41	5,8823	0,3
Mode #10	26,0	26,3		26,315	5,2631	0,3

Mode 8 and 10 on pressure antinodes: deviation max. +0.1cm; From ~ Mode 5 there is also no discernible deviation at pressure nodes with standard perturbation, with an equivalent sleeve to bolt 725 the zero crossings found are around 5% of a ¼ wavelength before the suspected pressure nodes, and these would be * odd # at 1/4WL.

With the bolt tests and very strong perturbations I am actually only interested in higher modes in order to determine the position of shared XM-IN1, and that on a brass instrument and not in a cylinder. Conclusion, if you can apply this to an instrument with a mouthpiece and bell: Zero crossing position of mode 7 (rising) is not changed by strong perturbations and is located (in the cylinder) exactly on a pressure antinode – if we believe in Openwind. Zero crossing position of mode 8 is determined with bolt 725 around 2mm too early and is located in the cylinder just before a pressure node.

Here I must be mention, that the Magnitude Node Positions and the whole Input Impedance potential at all are not those found by experimental measurements. This is processed and discussed in Sideletter #5 of this work, where the strong differences found are examined. However, at least the Pitch Change Potential ist much better in line with measurements

Pitch-Pot / Frequency Change Potential:

Cent is a logarithmic difference: frequency factor 0.5 results in -1200 cents. Frequency factor 2.0 results in +1200 cents.
In this case, octave intervals. The same +/- cent values mean inverse prop. ratios or frequency factors.
+/- 100 cents is +/- a semitone, so inverse prop. frequency ratios are necessary for this interval.
The inverse necessary factor (down) for equal cent differences is smaller.
It follows that the same change factors up / down result in a larger cent value down.
A higher frequency change factor is therefore necessary for a frequency increase than for a reduction.

A local Constriction centered at a Pressure Node loweres the global resonant frequency of that mode
Centered at a Pressure Antinode the global resonant frequency is raised – but weaker by a factor of ~ $q0^2$.

So, the effects of constrictions can only be compared with expansions if the constrictions are inversely proportional (smaller). Then the only result is a pitch potential up equal to $Xe/q0^2$ = Xc and pitch potential down = Xe.
X=change in area as difference, Xe = $q0^2$-1; Xc = $Xe/q0^2$, Xg = geometric mean = Xe/q0

Pitch Pot. up down with equv. sleeve: (Example) 1/q0= 0,90909 =$q0^2$=1,210 Xe=0,210 Xc=0,1736 Xg=0,1909
as well as (Bolzen 725, Example): 1/q0 = 0,7500 = $q0^2$=1,777 Xe=0,777 Xc=0,4375 Xg=0,5833

If q0 Factors are "small", it was determined using HAL#2 formula and calc of cross sectional changes, that the pitch raising pot is factor $q0^2$ smaller, than the lowering pot, being Xe, if the perturbation length equals ¼ wavelength and is centered on pressure nodes or pressure antinodes.

In case of $q0^2$ = 1,210 (Std. Perturbation) pitch lowering pot should be factor 1,210 stronger in contrast to raising pot,
In case of $q0^2$ =1,777 (Bolzen 725) factor 1,777 stronger –"-

The OW simulation results in an even stronger pitch potential down for constrictions around pressure nodes, even with standard perturbation compared to the Hal#2 calculation. However, the potential is comparable for enlargements.

ART results also differ, but here the pitch potential is lower for enlargements at pressure nodes. The deviations follow a pattern that is worked out below.

Pitch pot down with Hal #2 and pure cross-sectional aera change pot. are in between the 2 simulation models.

Simulations of the closed-open cylinder L=1000mm und Dia 10mm and Perturbation length =20mm deliver the following results (arithm. Mean of Modes #1 - #9; Hal Values calculates based on Mode #2):

ART Simulations with assumed Loss-Faktor =1,1; Openwind with Losses = true;
Hal#2 =lossless (no losses are taken into account), Standard Perturbation with q0=1,1 and 1/q0= 0,90909

Perturbation, Cross-Section Area Change **q0²= 1,21**			OpenWind:	OW: **ART:** **HAL#2:**
Enlargements,	Pot up	1,003491 Frequ. Factor	0,003491 Freq. Change d+	Cent +6,0 +6,0 +6,0
Enlargements,	Pot dn	0,995782	0,004218 Freq. Change d–	Cent -7,3 -7,0 -7,29
Pot. Ratio		0,004218 /0,003491 = **1,208** **(1,174)**	*7,3 Cent / 6,0 Cent*	*= 1,213 =1,179 =1,215*
	Hal #2	= 1,210		
Constrictions,	Pot up	1,003562 Frequ. Factor	0,003562 Freq. Change d+	Cent +6,2 +5,9 +6,0
Constrictions,	Pot dn	0,995533	0,004467 Freq. Change d–	Cent -7,7 -7,1 -7,26
Pot. Ratio		0,004467 /0,003562 = **1,254** **(1,207)**	*7,7 Cent / 6,2 Cent*	*= 1,259 =1,212 =1,215*
	Hal #2	= 1,210		

The correct change potential can only be determined from the frequency factors!
A factor formed from cent values is incorrect due to the logarithmic values.

Hal #2 gives a general Pitch Pot down, which is a Factor q0² =1,2100 stronger, then pot up
The Potential up is Xe/q0² =Xc= 0,17355 so Pot dn is = *1,21 = 0,21 = Xe = Xc*q0²
The Factor dn is 1+(**Xe*1**) = 1,2100 as well as at Pressure Antinodes and also at Pressure Nodes.

ART gives with Enlargements (at Pressure Antinodes) a pitch pot down, only Factor 1,17355 stronger than pot up.
The Potential up is Xe/q0² =Xc= 0,17355 so Pot dn is = *1,17355 = 0,2036 -0,0064 against Xe dn (less)
The Factor dn is 1+(**Xe/q0²**) = 1,17355. or = 1+(Xc).

OW gives with Constrictions (at Pressure Nodes) a pitch pot down, which is Factor 1,254 stronger than pot up.
The Potential up is Xe/q0² =Xc= 0,17355 so Pot dn is = *1,254 = 0,2176 +0,0076 against Xe dn (more)
The Factor dn is 1+(**Xe*q0²**) = 1+(0,21*1,21) = 1 + 0,254 = 1,254.

At all the simulations so deliver the following Pitch Potential with local perturbations, because of Xc=Xe/q0²:

Openwind,Hal#2	with Enlargements at Pressure Antinodes Xc*[1+Xe]=Xe dn, around Pressure Nodes:	Xc	up
	OW: ~ with q0² >1,333 = >33% more Area	*Xc * (0,95)*	*up*
ART	with Enlargements at Pressure Antinodes Xc*[1+Xc] (less) dn, at Pressure Nodes:	Xc	up
ART, Hal #2,	with Constrictions at Pressure Antinodes Xc up, around pressure Nodes Xc*q0²	=Xe	dn
Openwind	with Constrictions at Pressure Antinodes ~Xc up, around Pressure Nodes (more)	Xc*1+(Xe*q0²)	dn
	OW: ~ witht 1/q0² <0,75 = >25% less Area	*Xc* (q0²*1,1)*	*dn.*

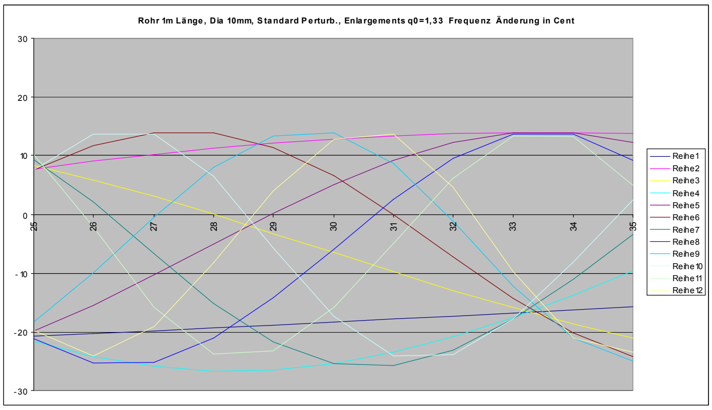
We find with ART Simulation therefore 3 „Sizes" of Pitch Potential based on Cross Section Area Changes:

local Enlargement at Pressure Antinodes	**Xc*[1+Xc] dn (*less pot*)**	around Pressure Nodes Xc up,	(Xc= Xe/q0²)
local Constriction at Pressure Antinodes	Xc up	around Pressure Nodes **Xe dn**	

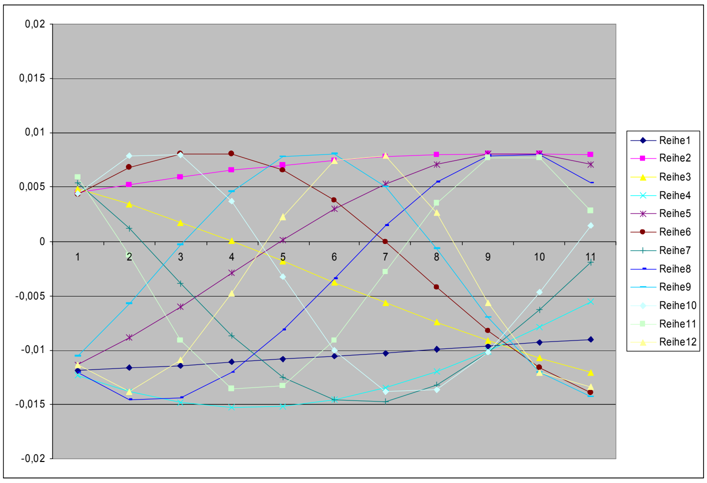
We find with Openwind Simulation also 3 „Sizes" of Pitch Potential based on Cross Section Area Changes, however, these must be approximated differently based on the magnitude of cross-sectional changes:

local Enlargement at Pressure Antinode	Xe dn	around Pressure Nodes	Xc up, (Xe= Xc*q0²)
	but if q0 > 1,15<1,4142 then:	around Pressure Nodes	Xc * 0,95 up
local Constriction at Pressure Antinodes	~Xc up	around Pressure Nodes	Xc*1+(Xe*q0²) **dn *more pot*)**
	but if q0 > 1,15 <1,4142 then:	around Pressure Nodes	*Xc* (q0²*1,1)* **dn**

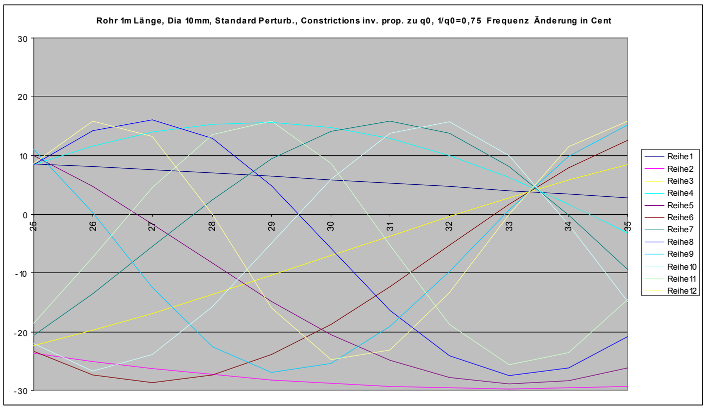
Below are the Open Wind results and data used for these approximations, x=Pos 25-35% of tube lenght:



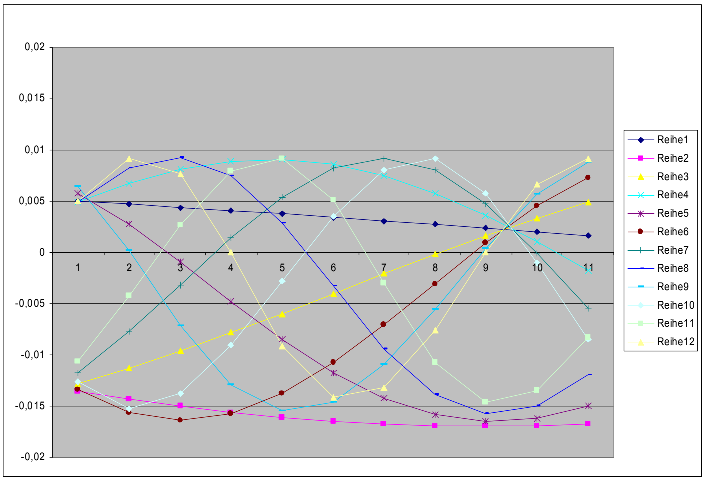
Freq. Diff. in Cent, Open Wind q0=1,333



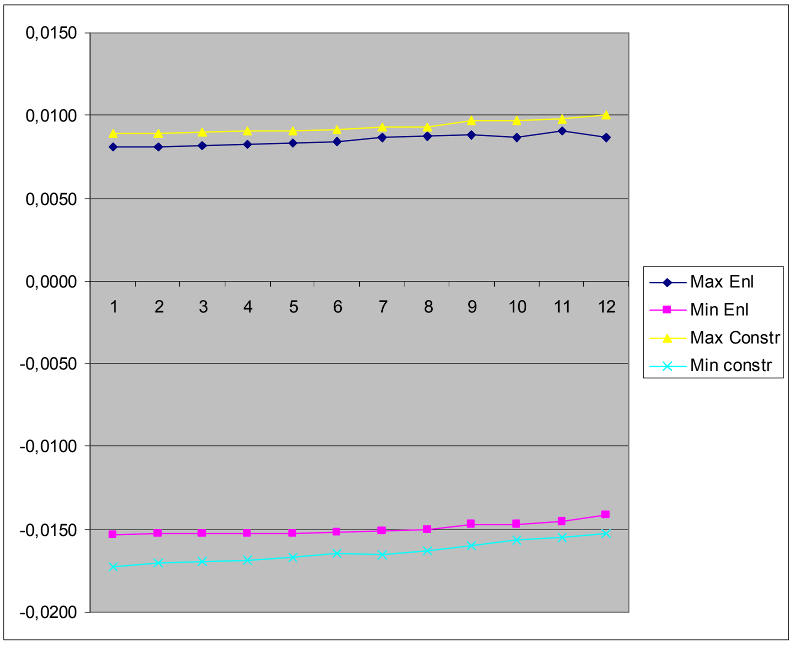
Freq. Change Diff. in %, Open Wind, q0=1,333



Freq. Diff. in Cent, Open Wind, 1/q0 = 0,75



Freq. Change Diff. in %, Open Wind, 1/q0=0,75



Freq. Diff. in %, Openwind, q0=1,333

Open Wind – Cross Section Area changes q0² = 1,777:
the Ratio is nearly: 8 parts up against 16 parts dn from 24 parts total = +1 : - 2 von 3
24/2= 12; 8-12= -4 + / - 12 x (= the theor. Area Ratio q0²=2, with change factors 2: 0,5)
3/2= 1,5; 1-1,5 = +0,5 / - 1,5 x -„- but the pitch change ratio found is ~1,955

Pitch Pot. up /down with equiv. sleeve 1/q0= 0,90909 =q0²=1,210Xe=0,210 Xc=0,1736 Xg=0,1909
and (Bolzen 725): 1/q0 = 0,7500 =q0²=1,777 Xe=0,777 Xc=0,4375 Xg=0,5833

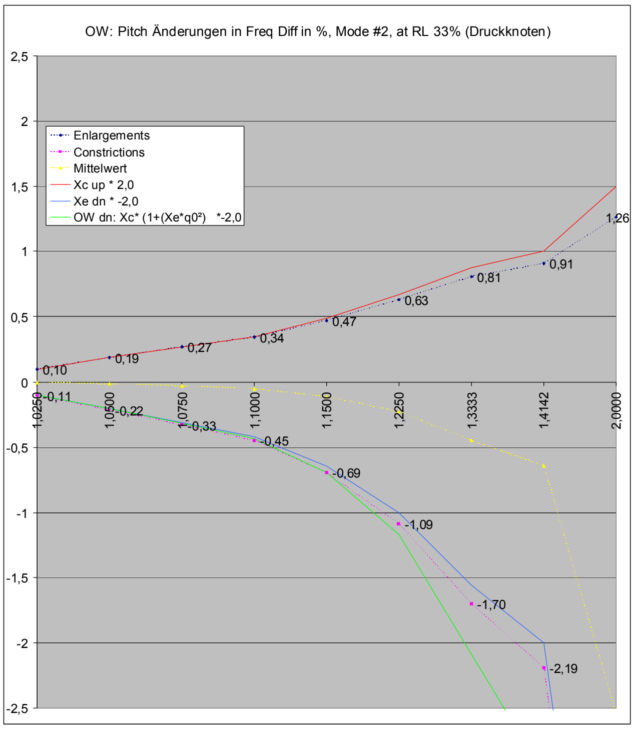
HAL #2, Pitch Pot down, Constriction

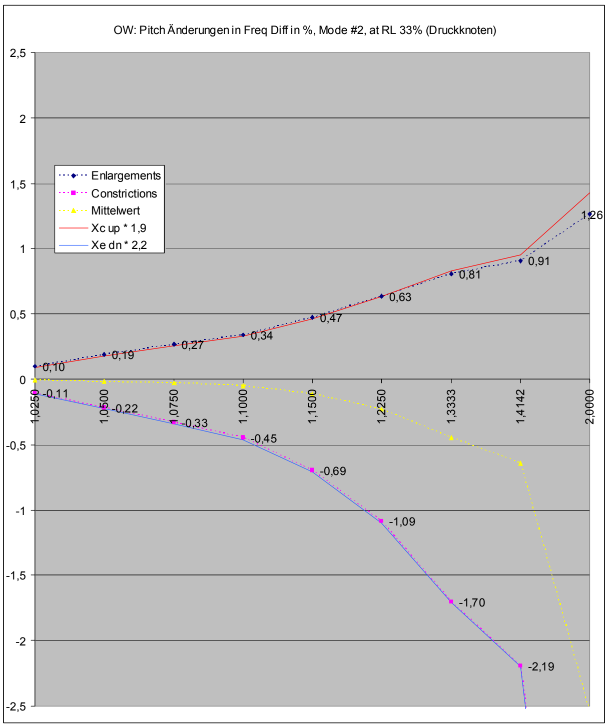
With Hal#2 calc: Double or half the area, giving q0²=2,0 would be almost -34 zu +17 Cent = definitely not invers! This would be nearly 2 times more pitch pot down. We should see, that this effect is in the openwind simulation already reached with a q0² of "only" ~1,777 - which is almost identical with the sqare root of pi!

Small q0	Large q0
With Pitch Pot up, Constriction Xc 0,1736 up	Xc 0,4375 up Hal#2: +15 Cent *1/q0²
	OW Diff found: up 0,009 = 0,9% = +15 Cent.
with Pitch Pot up, Enl. ~detto	~ Xc * 0,95 up
	OW Diff found: up 0,008 = 0,8% = +14 Cent.
*With Hal#2 Pitch Pot dn = Xc *q0² =0,21 =Xe dn*	*= 0,7777 Xe dn Hal#2: -27 Cent *q0²*
Factor stronger dn = q0²	**OW Diff found: dn 0,0152 = 1,527% = -26,4 Cent.**

Open Wind, Pitch Pot down, Constriction (Approximation)

Small q0	Large q0
q0 < 1,15 bzw. ~ 1/q0² **> 0,75**	q0 >1,15 bzw. ~ 1/q0² **< 0,75**
Std. Perturbation, q0=1,1:	equiv. Bolzen 725, q0=1,333:
1+(Xe*q0²) dn * Xc ***(more pot. then q0²=1,21)***	(1+Xe) * 1,1 dn *Xc
	q0² * 1,1 dn *Xc
1-(0,21*1,21) =1,254 * 0,1735 = 0,2176 dn	1,7777 * 1,1 dn =1,9554 * 0,4375 = 0,8555 dn
	OW Diff found: dn 0,017 = 1,7% = -29,7 Cent
	0,8555dn/0,4375up = 1,955 Xdn OW stronger then Xc up
effective Factor dn ~ = q0² *** 1,03636**	effective Factor dn ~ = Factor q0²***1,1**





Approximation Xc up and Xe dn to OW results; Xc up *1,9 and Xe dn *-2,2 equals ~OW upt to q0=1,333

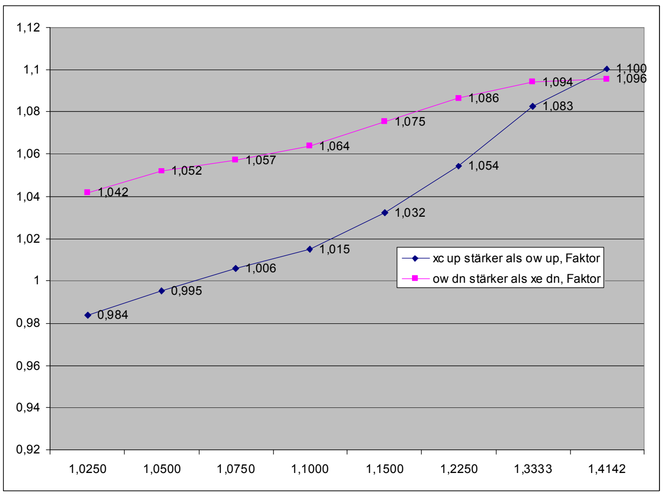
$q0^2=2$: Xc up=1 Part, Xe dn=2 Parts of TL 3 =+33,3:-66,6% $q0^2=2$, OW: 0,91 up to 2,19 dn of TL 3,1 = +29,3% : -70,6%

=Verteilung gegenüber Flächenänderung: = - 4% up Enl.; +4% dn Constr. w.respect to Xc up and Xe dn.

with q0=1,1 $q0^2$ Pot = 1,210 is OW Pot 1,32 stronger down than up (Xc)
with q0=1,333 $q0^2$ Pot = 1,777 is OW Pot 2,10 stronger down than up, but up is 5% less; ~ 2,0
with q0=1,4142 $q0^2$ Pot = 2,0 is OW Pot 2,40 stronger down than up, but up is 10% less; ~2,2

Since 2,0 is a linear scaling factor, the neccesary factors are /2: dn 1,1 constr; and 0,95 enl.

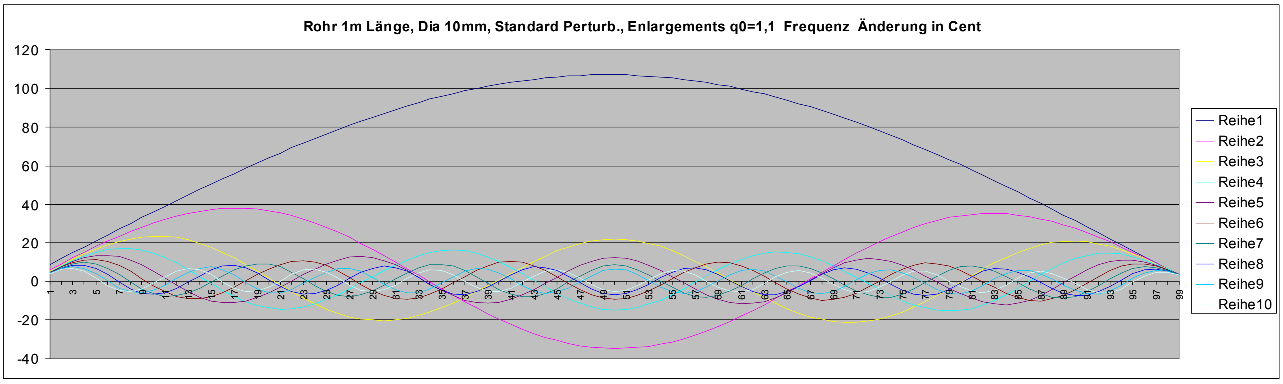
with ~ q0 < 1,15 $q0^2$ Pot = 1,3225 OW Pot up = Xc Pot up =1/$q0^2$ Pot = 0,756 Xc ~< 25 % less area
OW Pot dn = Xc * (1+(Xe*$q0^2$))
with ~q0 > 1,15 OW Pot up = Xc Pot up * 0,95 (found with Enlargements)
Xc Pot up * ~1 Constrictions, always somewhat stronger.
OW Pot dn = Xc * ($q0^2$*1,1) Pot dn.

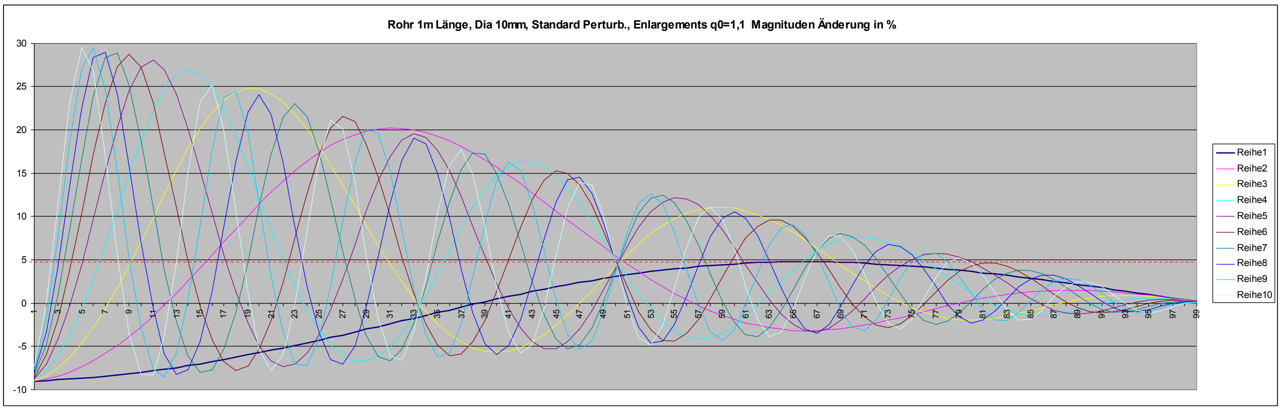


x=q0, no linear progression

Cross Sectional Area Factors, respectively Hal #2:
with q0=1,100: xc up 1,5% stronger; xe dn 6,4% weaker than OW results
with q0=1,333: xc up 8,3% stronger, xe dn 9,4% - „ –
with q0=1,4142: xc up 10% stronger, xe dn 10 % weaker thans OW results
The resulting pot shifts more and more downwards as the q0 factor increases.

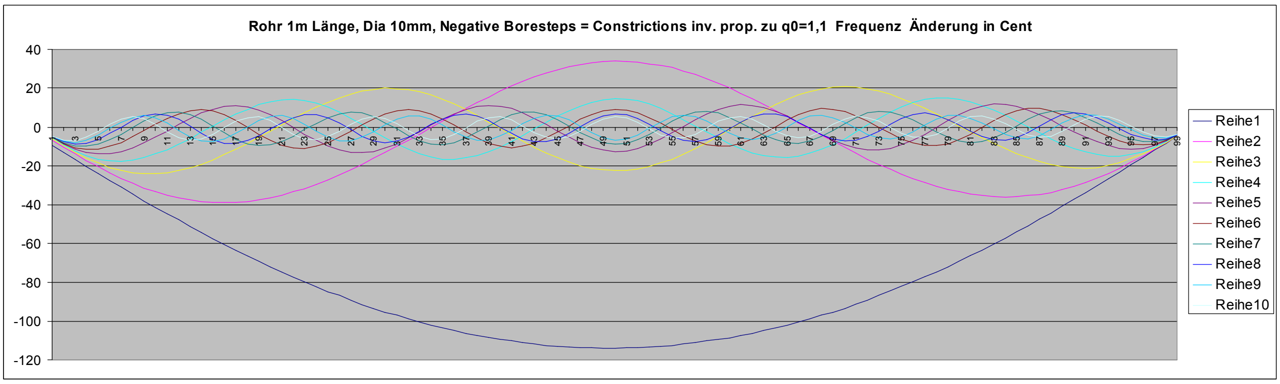
Positive Boresteps, OpenWind:

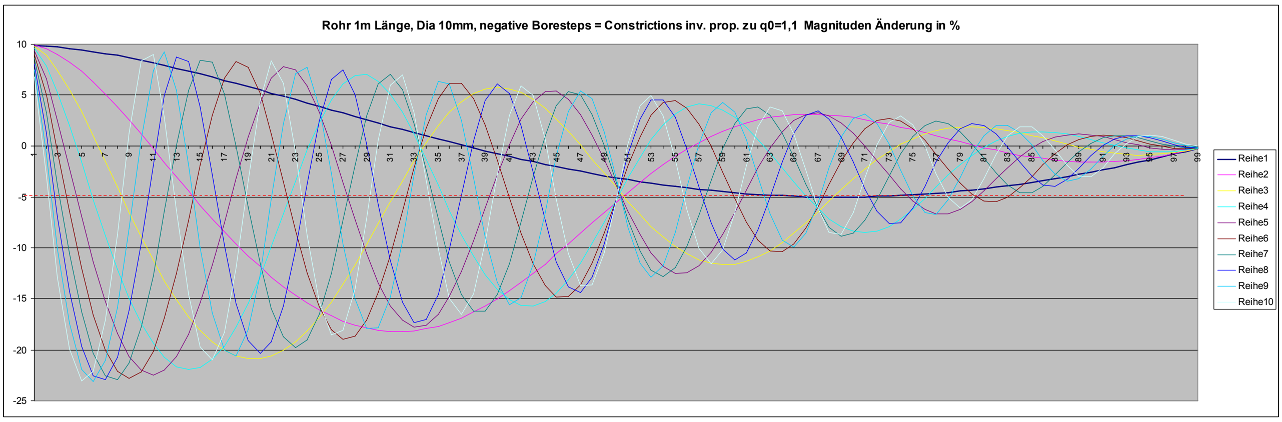




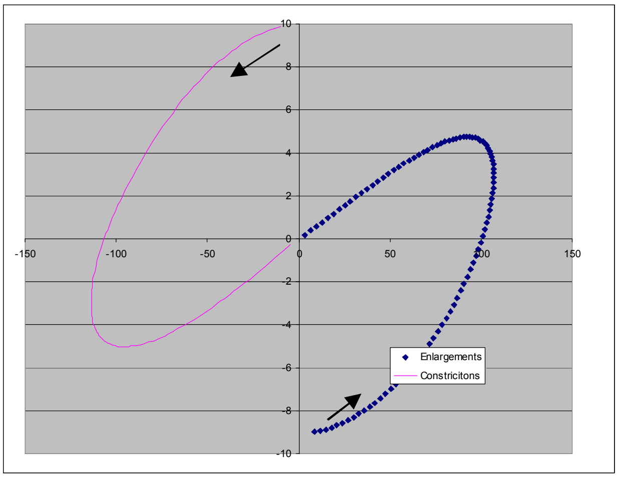
y0/x0 = Reference = Dia 9,090909 mm, x1-x99 =positive Steps to Dia 10mm, x100= no Step.
More total volume runs in this direction: <<<---, start x=1 = non-inverse pot.

Negative Boresteps, OpenWind:

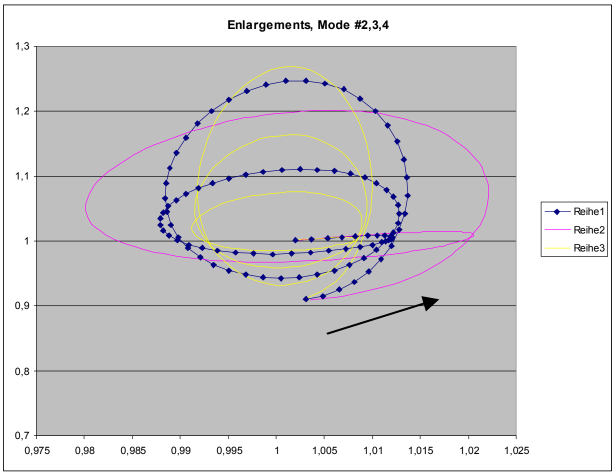




y0/x0 = Reference = Dia 10 mm, x1-x99 = negative steps to Dia 9,090909 mm, x100= no Step.
Less total volume runs in this direction: <<<---, start x=1 = non-inverse pot.



OW, Mode #1 x=Cent Change, y= % Magn. Change
blue: positive steps, pink = negative steps



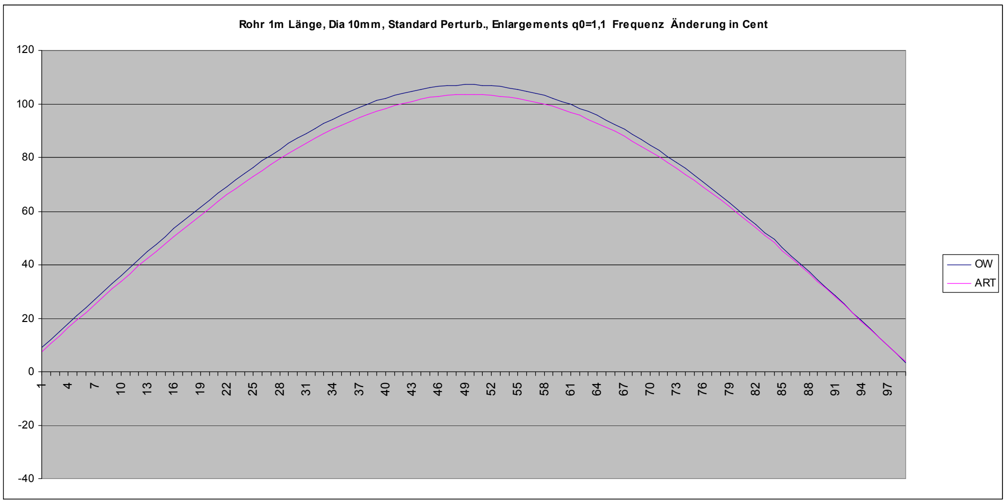
OW, x=Frequ. factor: pink= Mode #2, blue #3, yellow #4.
positive steps shown

Mode #1 shows about ½ inverse Magn. Potential,
Steps at 50% tube lenght each have inverse Magn. Pot:
Mode #1 about ~ 1/3 q0,

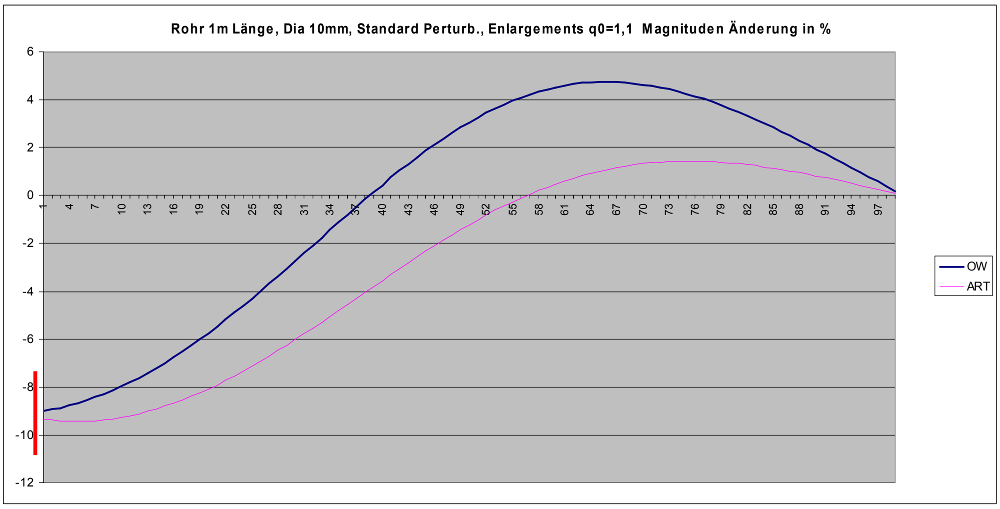
higher Modes develop very strong inv. Magn. Pot.

higher Modes ~ ½ q0

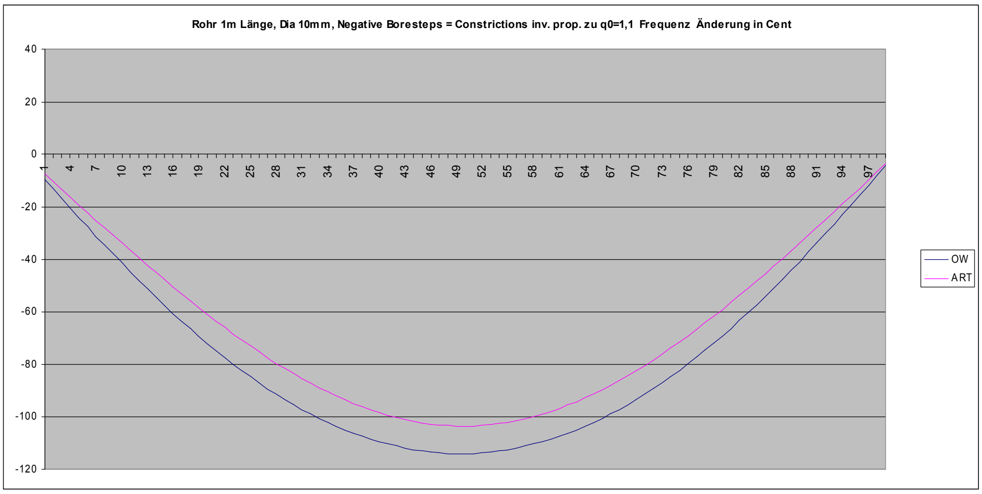
There are very large differences between the OW and the ART simulation, compared below, with comments.
-> Neg. Boresteps have stronger potential in OW, but specifically significantly more Magn. Pot. down



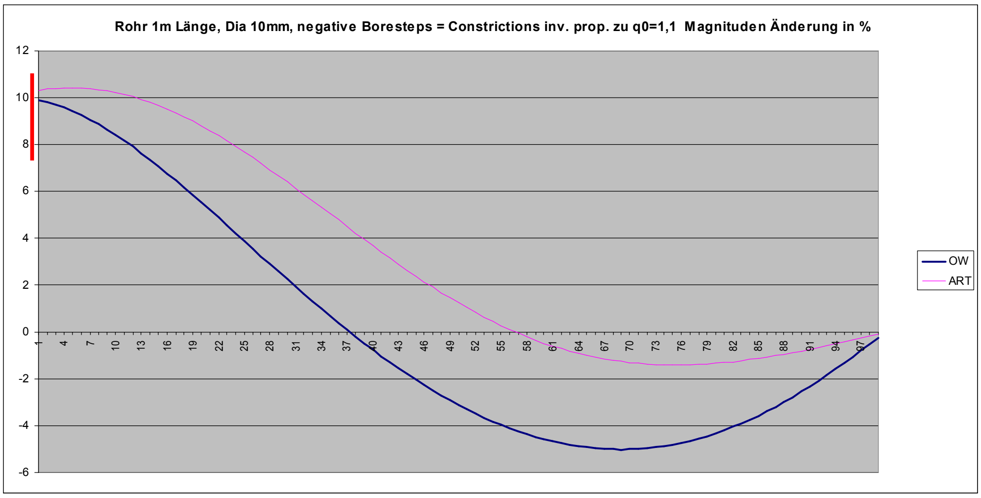
Mode #1: Pitch Pot stronger than ART result, max. pot at exactly 50% position in the tube; here ~ +6,5% Freq. change



Mode #1; with positive Step 50%: around 1/3 inverse Pot., at 66% approx. ½ inv. Pot.
Der Magnituden Nulldurchgang ergibt sich bei 37,5% Step Position.
Mode #1 (and Mode #2) show the strogest deviations.

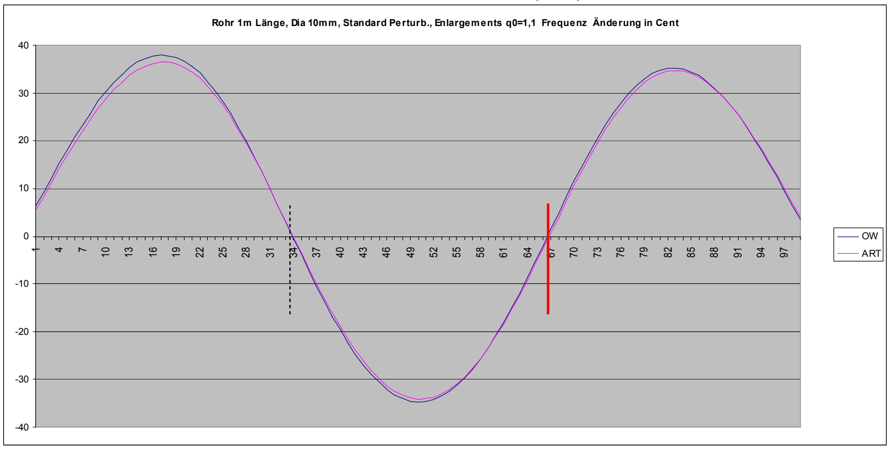


Mode #1 with a neg. step Pitch Pot. is down (inverse) with OW even stronger, max at Pos. 50%RL, ~ -6,5% Frequ.

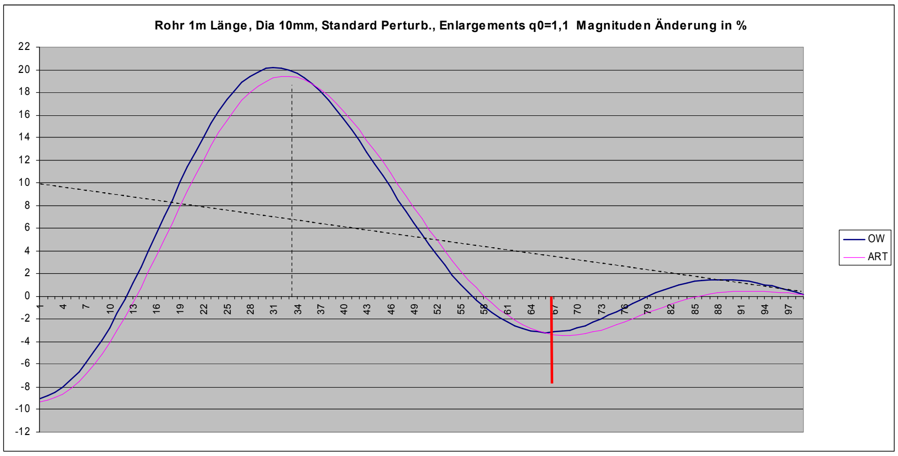


Mode #1, neg. Boresteps, the Magn. Pot is nearly invers to pos. Boresteps. 0,5 * max. Pot q0.
Magn. Node identically at position 37,5% RL, max. inverse Pot at position 70% RL

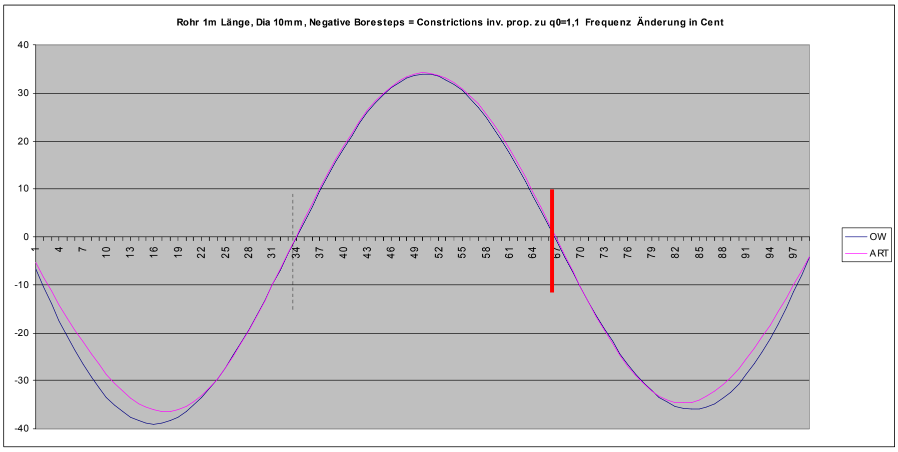
Mode #2: Pitch Pot: ~ 1/3 of Mode #1, inv. Magn. Pot. at 1st DK: ~2x q0, 50% RL ~0,5 q0, at last DB: ~1/3 q0
dotted line: Position Pressure Node Druckknoten (DK), red line: Position Pressure Antinode Druckbauch (DB)



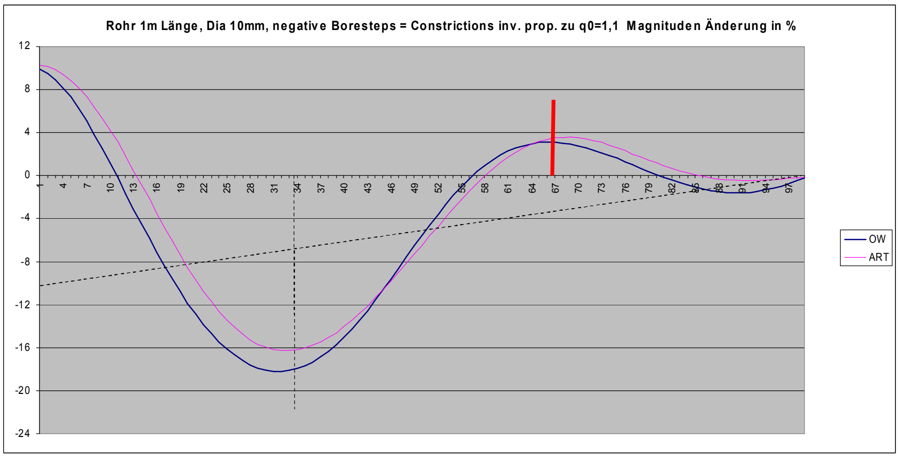
2. Pitch Node exactly at DB



max. Magn. Pot before DK and DB

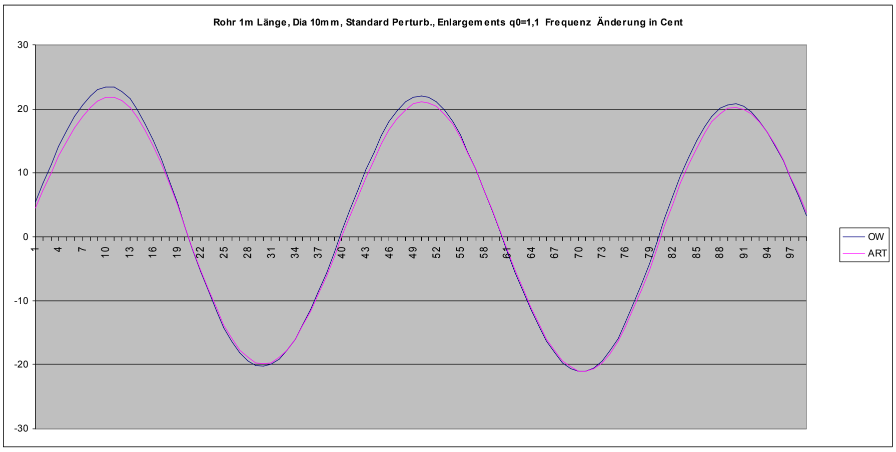


2. Pitch Node exactly at DB

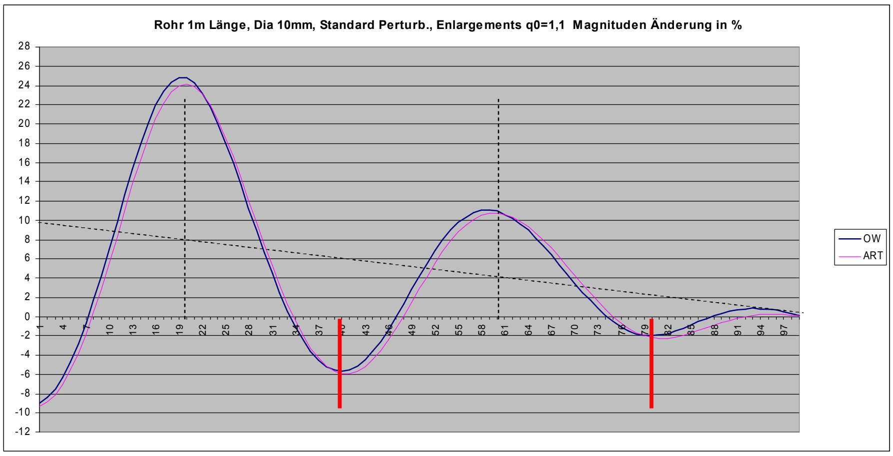


max. Magn. Pot before DK, DB

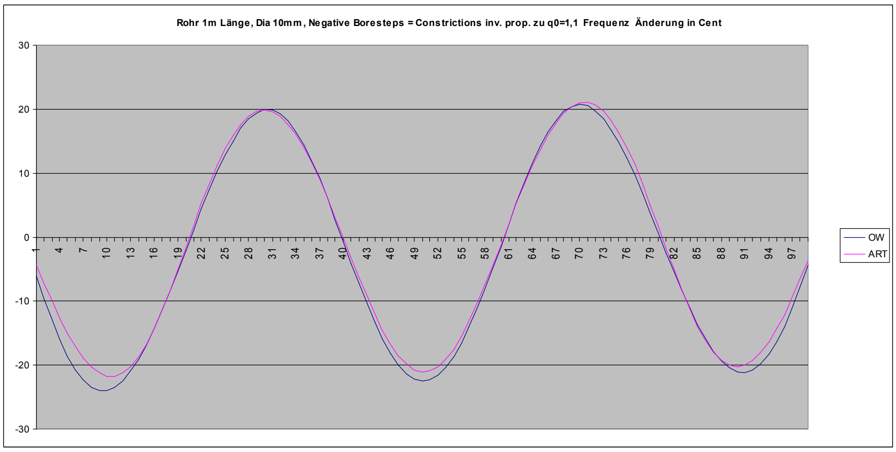
Mode #3: Pitch Pot: ~ 1/5 of Mode #1, inv. Magn. Pot. 1st DK: ~2,5x q0, 50% RL ~0,5 q0, last DB: ~1/5 q0
dotted line: Position Pressure Node / Druckknoten (DK), red line: Position Pressure Antinode / Druckbauch (DB)



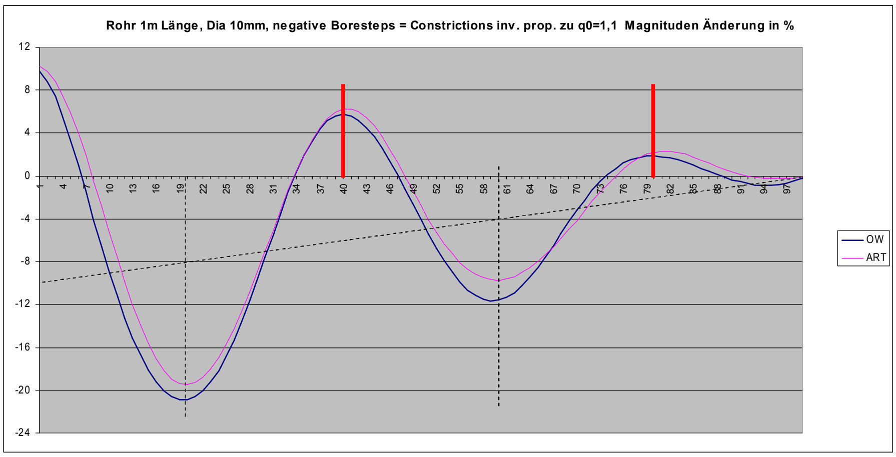
Pitch Node exactly at DK, DB



max. Magn. Pot at DK, at DB



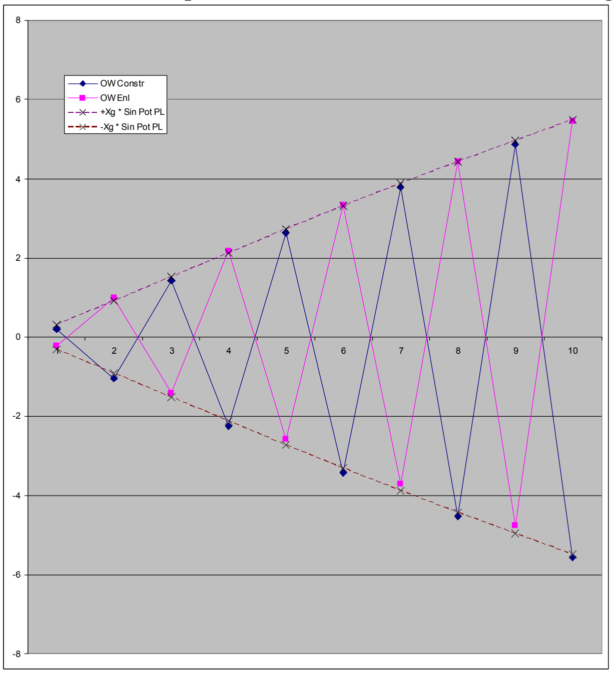
Pitch Node exactly at DK, DB



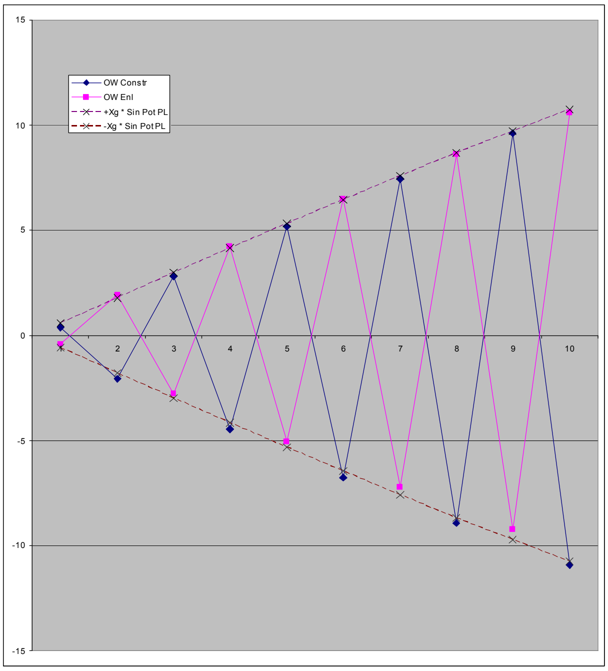
max. Magn. Pot before DK, DB

Input Magnitude Potential, Envelope curves, Open Wind

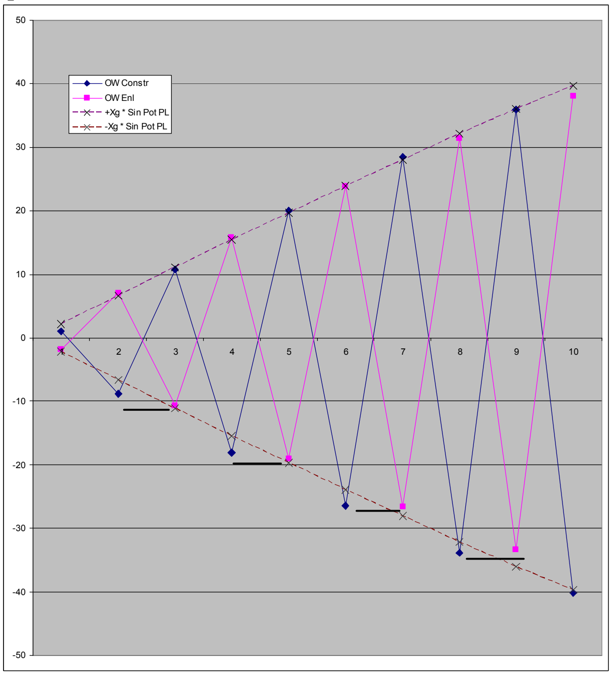
1. Situation with perturbations, centered at 50% tube length / supporting points for envelope design

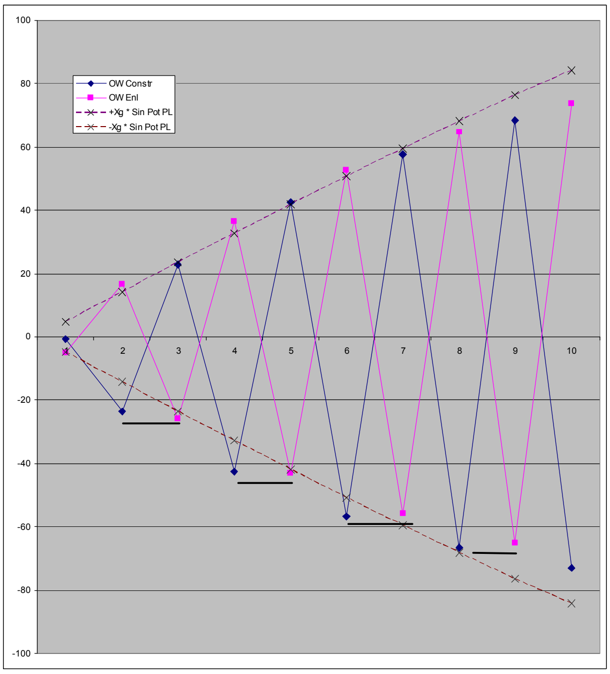


q0=1,05



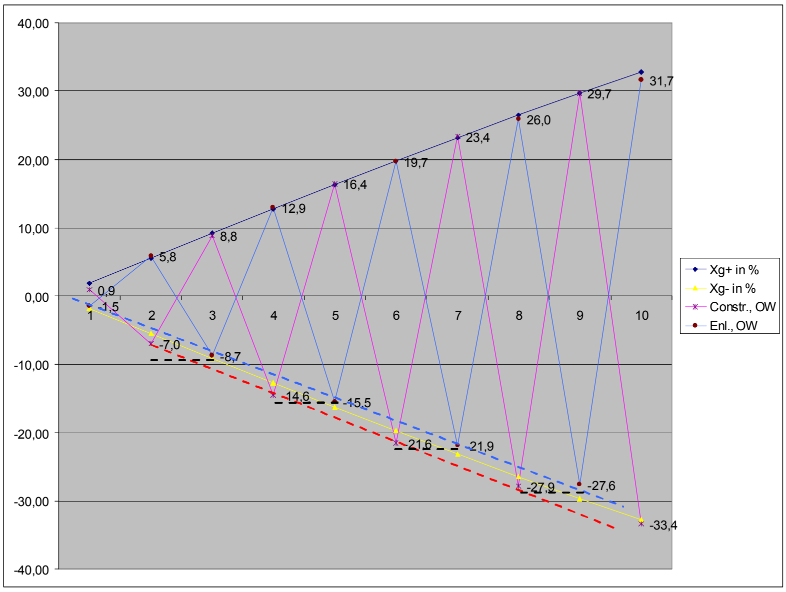
q0=1,1





q0= 1,4142 =double / half Area change q0=2,0 = double / half Diameter = 4times Aerea change

q0=2: Beginning with Mode #4, Constrictions down are stronger than Enl. down pot of the next higher mode; and pot up with constr. gets also shifted downward



Magn. Change Pot.% with local perturbations at 50% RL, PL=2% RL, Diameter Change q0=1,333 and inv. prop. 0,75

Looking at this introductory graphic and the following calculations, it becomes clear, that

since at Pert. Pos. x=0.5 pipe length the entire envelope Zin magnitude change potential X = 1/2
and at Pos. x=0 it is equal to 1/1, all possible envelope values can thus be determined approximately linearly.
(I neclect here for simlicity, that there is a small "end pot", found on the open end; this is discussed in Sideletter #5.)
And I have to remind, that measured values and envelope curves are very different compared to the simulated results!

Odd # Modes: Missing and searched inv. Envelope curve potential dn at 50 % pipelenght is in first proximity
(inv. Pot at 50% 1 Mode # higher - inv. Pot at 50% 1 Mode # lower) / 2 = arithm. mean of both inv. potentials!

Even #Modes: Missing and searched non inv. Envelope curve potential dn is calculated in the same way:
(n. inv. Pot at 50%, 1 Mode # higher – n. inv. Pot at 50%, 1 Mode # lower) /2 = arithm. mean of both n. inv. pots.

Pot. up inverse and also not inverse is, as we find already almost the arithmetic mean for open wind results,
and the envelope potential up is therefore also calculated in the same way as Pot dn.

There are a total of 8 cases, cases 1 - 4 can be determined at position 50% of the pipe length, 5-8 by calculation.
all odd # modes have non-inverse potential at Pert. position 50% (they are on the falling pressure antinode flank)

1. Odd Modes and	Enlargements	Pot dn = 0- [Xg - (PL*Xc)]	(less Pot. than -Xg) *high odd most.*
2.	Constrictions	Pot up = 0+[Xg Pot]	
3. Even Modes (inverse)	Enlargements	Pot up = 0+[Xg Pot]	
4.	Constrictions	Pot dn = 0- [Xg + (PL*Xc->e)]	(more Pot. than -Xg), *Mode #2 most.*

The complete formula for any perturbation position is, Open Wind:
1. Enl. non inverse (dn) falling DB flank, DZin(x) = 0- [(2 Xg * Sin (PL Pot)) - (PL*2Xc) * (1-x)] odd less
2.Constr. non inverse (up) falling DB flank, DZin(x) = 0+[(2 Xg * Sin (PL Pot)) + (0) * (1-x)] odd less

3. Enl. inverse (up) raising DB flank, DZin(x) = 0+[(2 Xg * Sin (PL Pot)) - (0) * (1-x)] even more
4. Constr. invers (dn) raising DB flank, DZin(x) = 0- [(2 Xg * Sin (PL Pot)) + (PL*2Xe) * (1-x)] even more

However, half of all values are missing as envelope values at 50% tube lenght:
5. all even Modes, Enlargement dn = non inverse falling. DB flank = less Pot, (but elsewhere) less dn
6. all even Modes, Constriction up = non inverse -"- less up*

7. all odd Modes, Enlargement up = inverse, raising DB flank = more Pot, (but elsewhere) more up*
8. all odd Modes, Constriction dn = inverse -"- most dn
* Open Wind: Case 6 and 7 can be approximately ignored; these are Pot up = Xg +/- ~ more / less 0

Taking a look at the perturbation spirals, one notices that with the same number of 1/8 wavelengths from the open end to the perturbation center, the same Zin magnitude change potential is always achieved!

5. Missing Envelope value with example even Mode #4, with Enl. dn non INVERS results from:
Even Mode #4 will have the same value as non INVERSE Mode 3 at 50% = **at 5/8 WL** from (before) the open end, so with 7/4WL = 14/8WL – 5/8WL = 9/8 WL from 14/8 TL = at 64,2% tube length, value - 8,7% dn.

even Mode #4 will have the same value as non inverse mode 5 at 50% = at **9/8 WL** from (before) the open end, so with 7/4WL = 14/8WL- 9/8WL =5/8 WL von 14/8 TL = at 35,7 % tube lenght a value of -15,5% dn.
dy=15,5-8,7 = 6,8% dx = 4/8WL Mode 4 = 64,2-35,7 = 28,5 (cm or % RL) dy/dx = 0,2386 slope
dx /2 = 50% tube lenght = distance x to 50% = 14,25 * 0,2386 = 3,4% more oder less = -12,1% at 50% RL.
Even, Enlargements: The non inverse Pot dn is here 6,6% weaker down than up.
Constr. at 50% -14,6%, non inverse Env. dn at 50% -12,1% = non inv. Env. dn 20,6 % weaker than inverse.

6. Missing Envelope value with example even Mode #4, with Constr. UP non INVERSE results from
even Mode #4 will have the same value as non INVERSE Mode 3 at 50% = at **5/8 WL**, from (before) the open end, so with 7/4 = 14/8 – 5/8 = 9/8 WL von 14/8 TL = at 64,2% tube lenght, a value of 8,8% dn.

To summarize: Values resulting at 50% RL:

non inverse, at falling DB flank,		1. Enlargement lowers -[**Xg** –Korr]		2. Constr. raises ~ **Xg** +0	
Open Wind Magn. Pot found at:			per 1/8 WL		per 1/8 WL
5/8 WL	(Mode 3 at 50% RL),	- 8,7 % Xg-Corr =0,1%	-1,74%	+ 8,8 %	1,76%
9/8 WL	(Mode 5 at 50% RL,	-15,5% Xg-Corr =0,9%	-1,722%	+16,4%	**1,82%**
13/8 WL	(Mode 7 at 50% RL)	-21,9% Xg-Corr =1,5%	-1,685%	+23,4%	**1,8%**
inverse, at raising DB flank,		3. Constriction lowers –[**Xg** +Korr]		4. Enl. raises ~ Xg +0	
Open Wind Magn. Pot found at:			per 1/8 WL		per 1/8 WL
3/8 WL	(Mode 2 at 50% RL),	- 7 % Xg + Corr=1,2%	-2,33%	+ 5,8%	1,93%
7/8 WL	(Mode 4 at 50% RL)	-14,6% Xg + Corr=1,7%	-2,08%	+12,9%	**1,84%**
11/8 WL	(Mode 6 at 50% RL)	-21,6% Xg + Corr=1,9%	-1,96%	+19,7%	**1,79%**

Due to the sine PL pot, the found potential increases in deep modes.

Case #, Envelope values at 50% tube lenght:
5. Even, Enl.: The n. inv. envelope Pot dn is here 6,6% weaker dn than up, *-20,6 % weaker than Constr.*
6. Even, Constr.: The n. inv. envelope Pot up is here 6,8% weaker up than dn, *-2,3 % weaker than Enl. (~Xg)*
7. Odd, Enl.: The inverse envelope Pot up is here 7,5% stronger up than dn, *6,25% stronger than Constr. (~Xg)*
8. Odd, Constr. The inverse envelope Pot dn is here 22,7% stronger dn than up, *+24% stronger than Enl. Pot dn.*

1. (Mode 3) -8,7% n. inv. with Enl. down
8. (Mode 3) -10,8% Env. inv. Constr. down + 24 % inv. more Pot. dn. but (7.) only +6,25% inv. Pot up

3. (Mode 4) **-**14,6% inv. with Constr down, +20,6 % inv. more Pot dn., but (6.) ~ Xg Pot up (-2,3%)
5. (Mode 4) -18,1% Env. n. inv. Enl down + 24 % inv. more Pot dn.

1. (Mode 5) -15,5% n. inv. with Enl. down
8. (Mode 5) -18,1% Env. inv. Constr. down + 24 % inv. more Pot. dn.

And so on, one problem occuring is, that X values of higher modes have to be guessed at 50% tubelenght, because of raster / resolution x-Axis, the sin(PL Pot) reduces the pot, which would be larger at lower modes, Openwind shows a not to neclectable "end pot", a small offset, which is not the case with ART results,and so on,
this remains an first approximation!

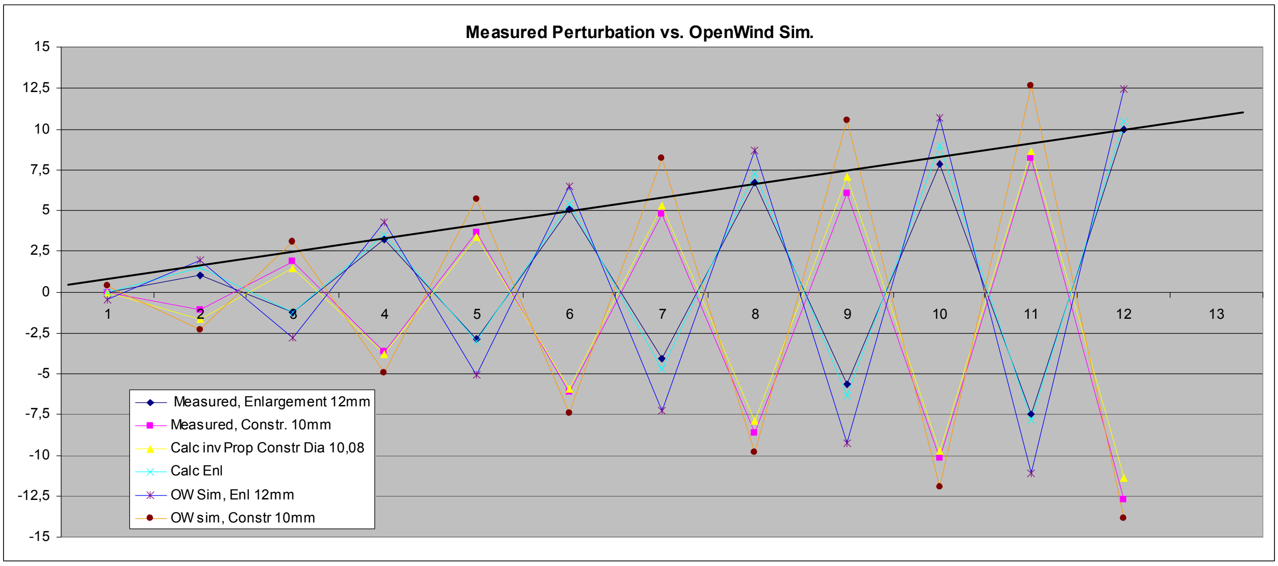
I will stopp here with this topic, it is considered in sideletter #3 (ART results) and especially in sideletter #5, where the differences found by measurements are compared with open wind results.

It should be pointed out, that there are very strong deviations found between ART and OpenWind, especcialy at the first fundamental mode, although it is repeatedly suggested that the physics of a cylindrical pipe are clearly understood.

The question arises whether anyone has ever compared the theoretical values obtained with measurements, or whether they were just copied and blindly assumed that they will be correct!

A few concluding words on this part 1 of sideletter #4

In March 2024, I carried out measurements to compare the simulations with Openwind using a cylinder with a length of 1000mm and a diameter of 11mm. The detailed results can be found in the next part, Sideletter #5, but here in advance are some of the differences between simulation and measurements presented, and as you can easily see, there are very large differences. And you must therefore be aware that the simulation results from ART, and therefore also from Openwind, regarding input magnitude changes do not match the measurements and practice I carried out.



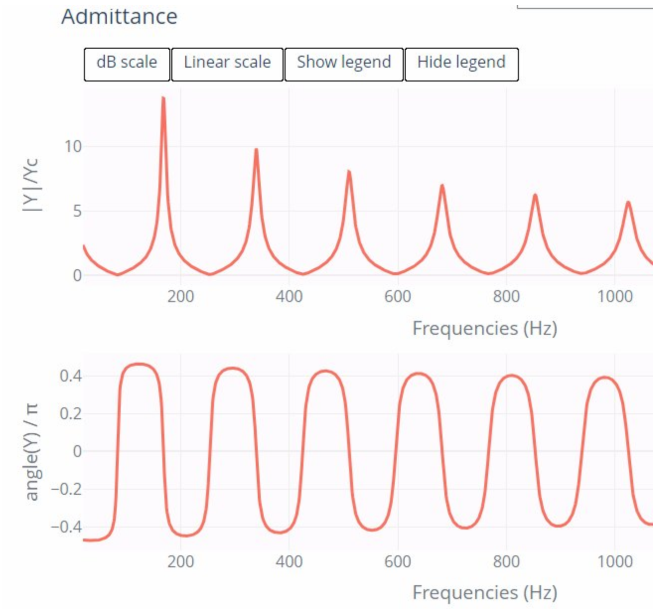
y: Input Magnituden |Z|in, Change in % , x: Mode Number
Perturbations are centered at 50% tube lenght, Constrictions or Expansion, each with 22mm lenght

„Calc" are preliminary values that I found based on approximations to the measurement results due to the cross-sectional change (q0).

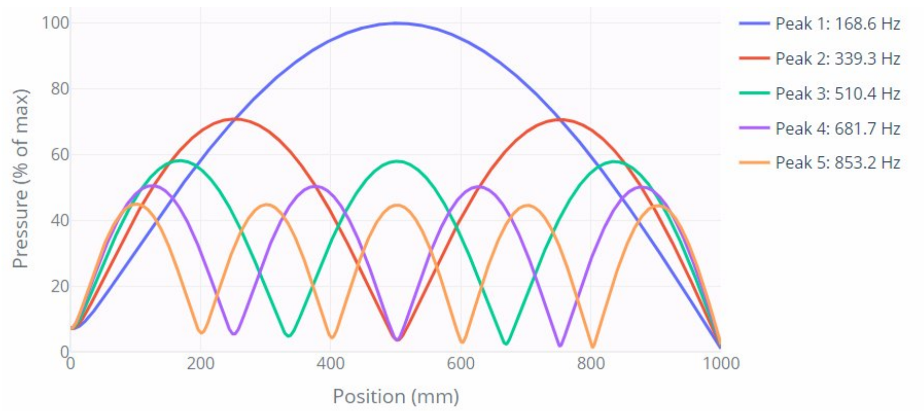
Sideletter #4, Open Wind, Part 2:

Open Wind – Additional Features – Pressure and Flow Distribution in Tubes

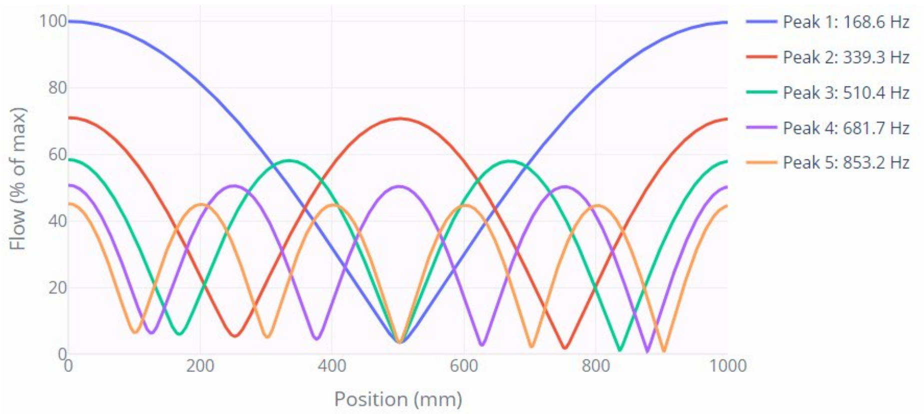
OpenWind Online Simulations:
open-open Cylinder, L=1000mm, Dia =11,0 mm, 23 °C
(left side is the open “blowing” end, having a different radiation impedance)



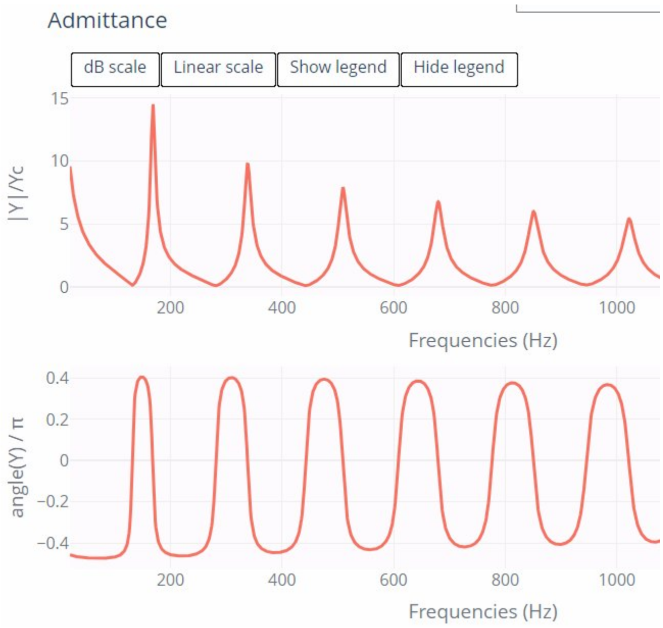
Admittance (Modulus) + phase angle
(= 1/Impedance)



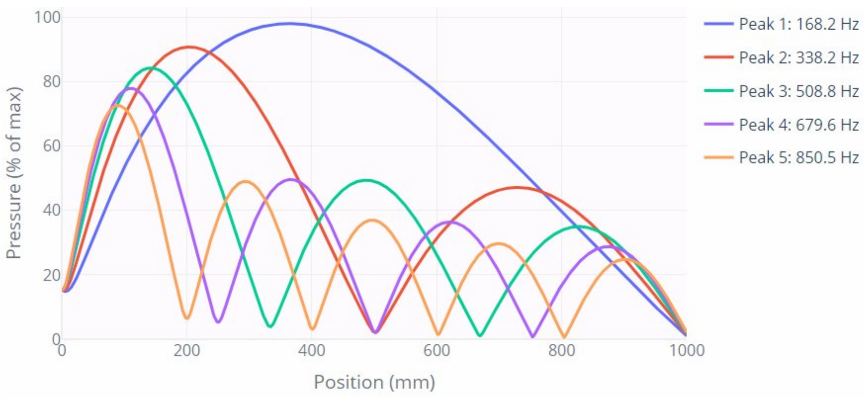
left side = blowing end



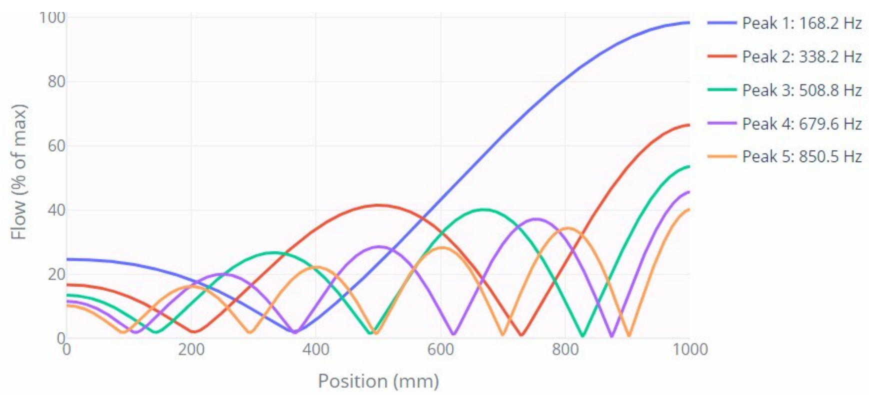
OpenWind Online Simulations:
open-open Cone = Frustum, L=1000mm, Dia 5-20mm, 1/B= 4,0 23 °C
(left side is the "blowing" end, having a different radiation impedance)



Admittance (Modulus) + phase angle
(= 1/Impedance)

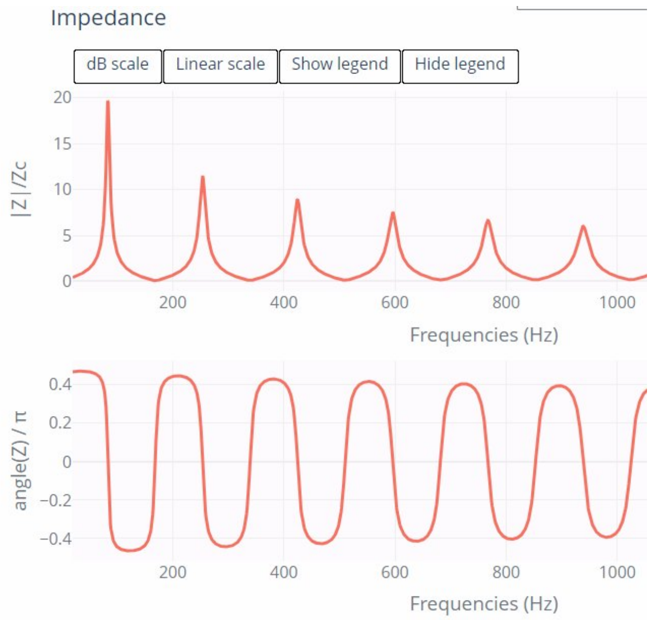


calculated Pressure Distribution

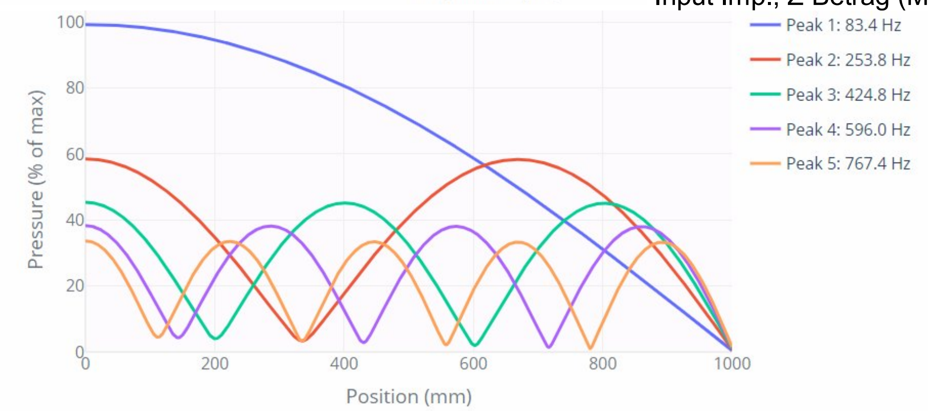


calculated Flow Distribution

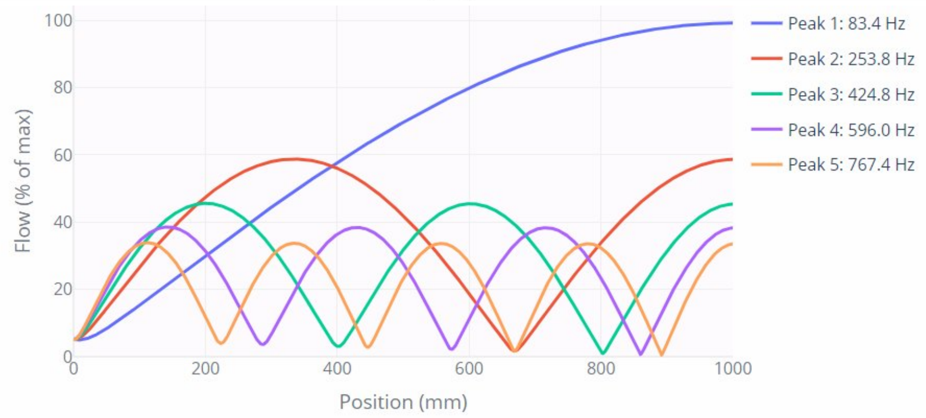
OpenWind Online Simulations:
closed-open Zylinder, L=1000mm, Dia =11,0 mm, 23 °C
(left side is the “blowing”, closed end – no radiation assumed)



Input Imp., Z Betrag (Modulus) and phase angle

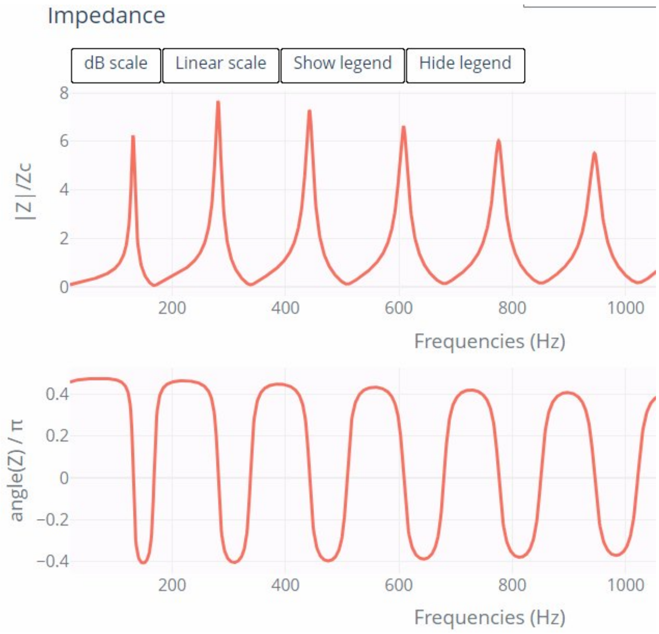


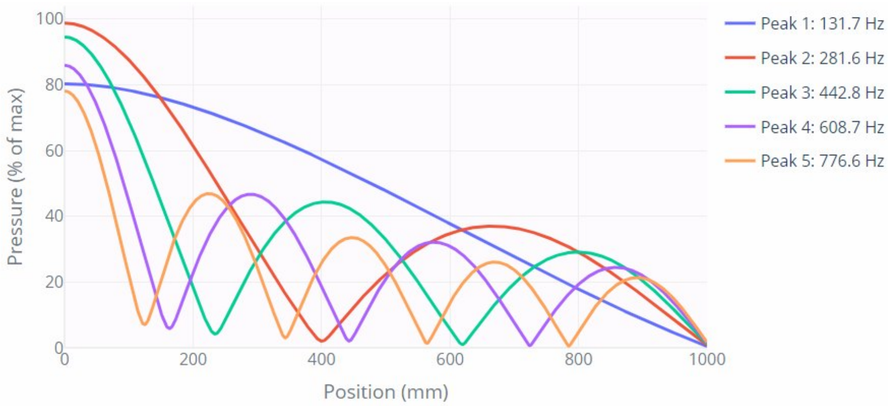
Pressure Distribution



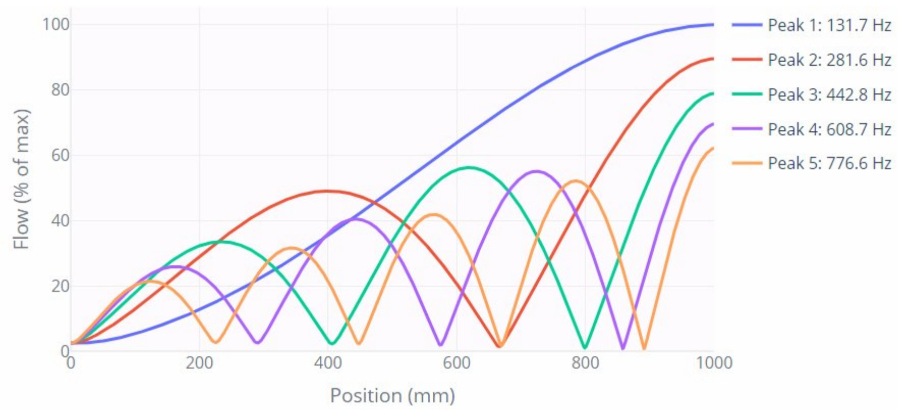
Flow Distribution

OpenWind Online Simulations:
closed-open Cone = Frustum, L=1000mm, Dia 5-20mm, 1/B= 4,0 23 °C
(left side is the “blowing”, closed end – no radiation assumed)



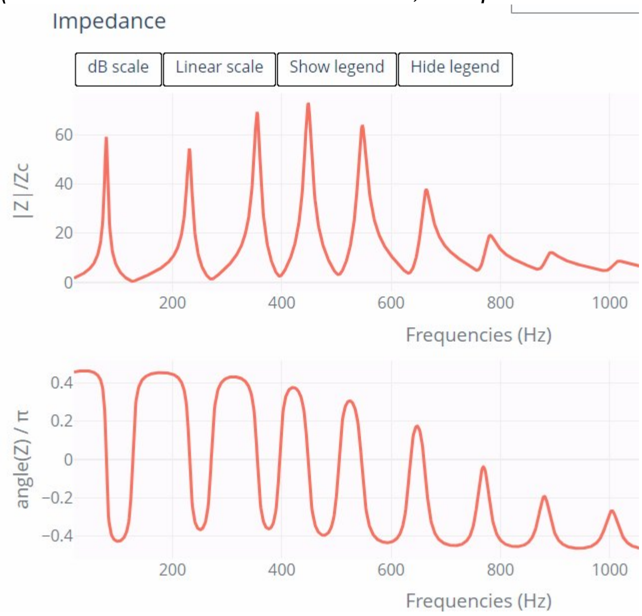


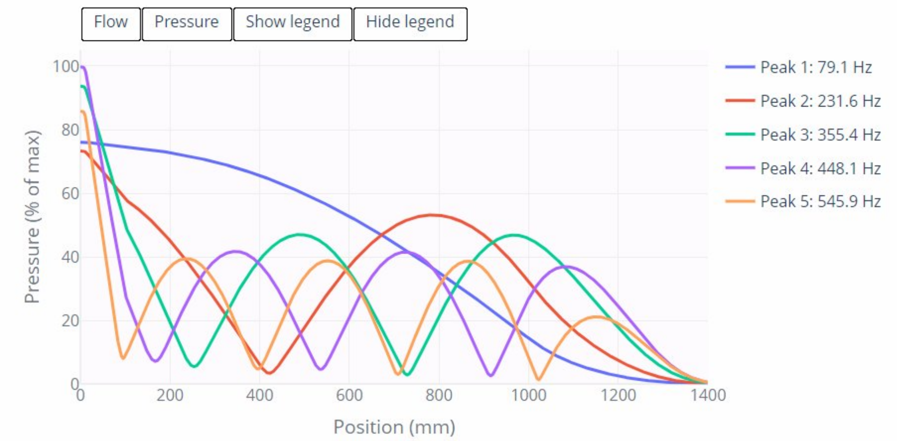
Pressure Distribution



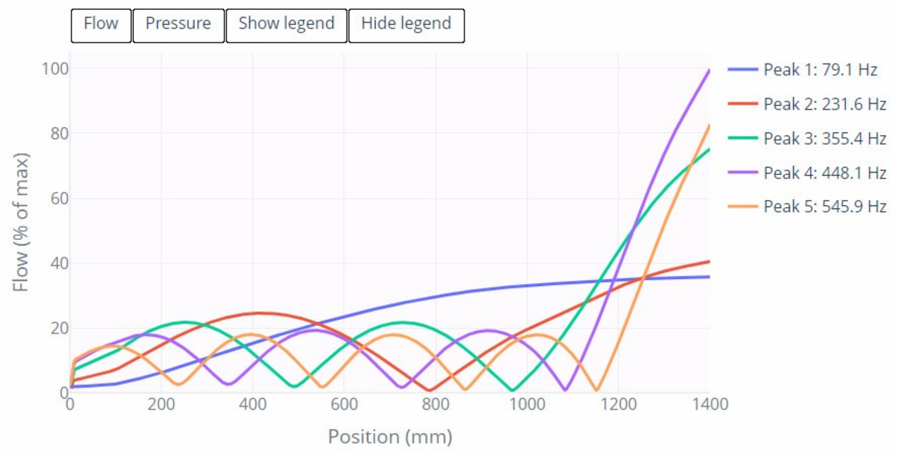
Flow Distribution

OpenWind Online Simulations:
A very poorly and simplified trumpet like instrument,
Implied: Cup Mouthpiece, Leadpipe, Main cyl. tubing, Bell Stem + Bell Skirt; L=1400mm (Mainbore=10mm)
(Resonance Peak #4 is here tallest, trumpeters would absolute not like this instrument and mouthpiece!)





Pressure Distribution



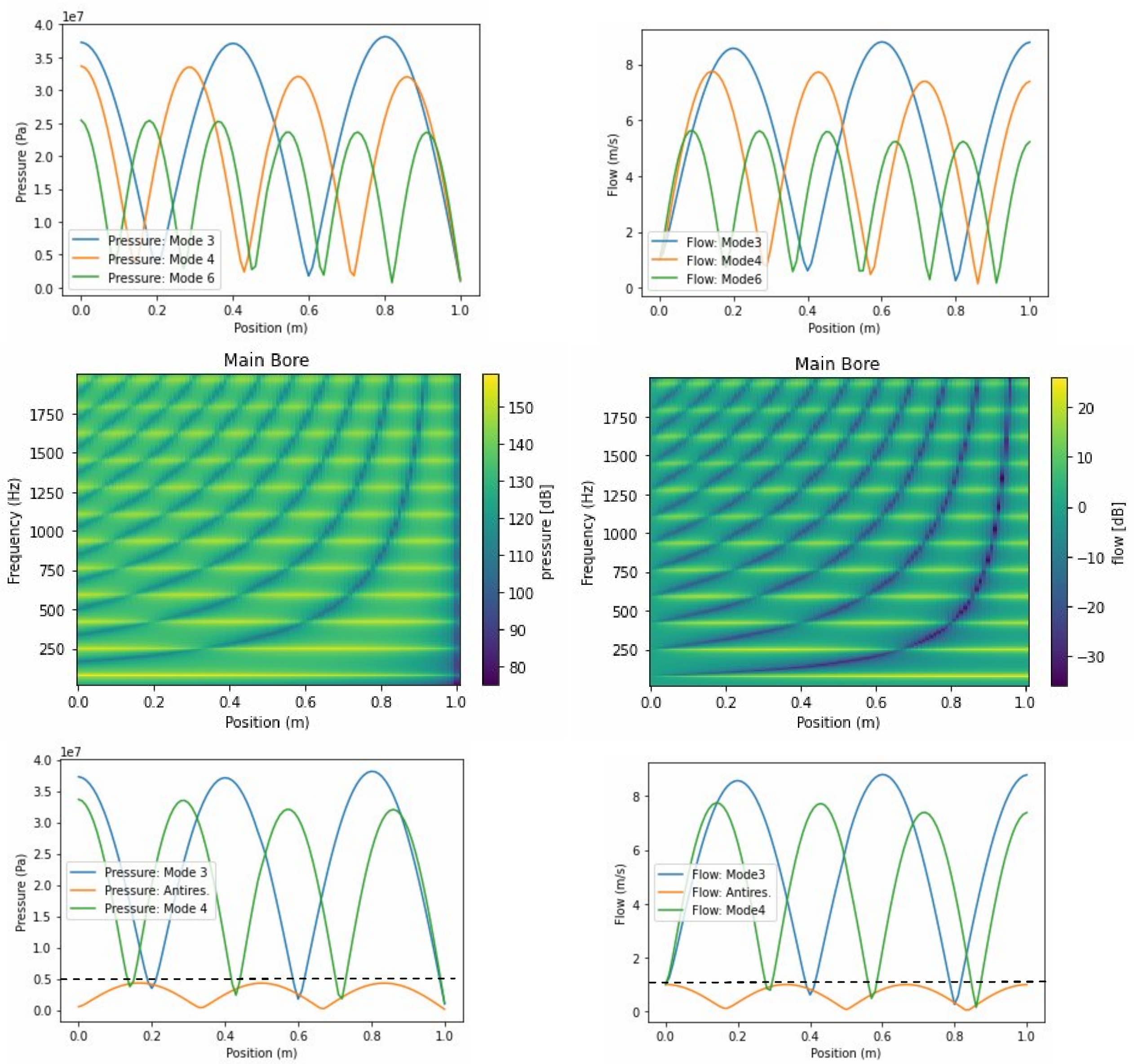
Flow Distribution

Openwind - Druck- und Flussverteilung

This presents low level implementation giving access to the acoustic fields
in the entire instrument.
It presents also how to interpolate data to a specific grid.
Based on OpenWind Example #9

```
import numpy as np
import matplotlib.pyplot as plt

from openwind import (ImpedanceComputation, InstrumentGeometry, Player,
                      InstrumentPhysics, FrequentialSolver)

fs = np.arange(20, 2000, 0.3333) # frequencies of interest: 20Hz to 2kHz by steps of 1Hz

# %% Low level implementation

# Load and process the instrument geometrical file
instr_geom = InstrumentGeometry('instrument.txt')
# Create a player using the default value : unitary flow for impedance computation
player = Player()
# Choose the physics of the instrument from its geometry. Default models are chosen when they are not specified.
# Here losses = True means that Zwikker-Koster model is solved.
instr_physics = InstrumentPhysics(instr_geom, temperature=23, player = player, losses=True)

# Perform the discretisation of the pipes and put all parts together ready to be solved.
freq_model = FrequentialSolver(instr_physics, fs)

# %% Visualization

# Solve the linear system underlying the impedance computation.
# interp_grid allows to interpolate the data on a uniform grid with a given spacing, 0.001 = 1mm Steps
freq_model.solve(interp=True, interp_grid=0.001)

# You can observe at the flow and pressure for all interpolated points at one
# given frequency, e.g. 424Hz and 595Hz:
plt.figure()
freq_model.plot_flow_at_freq(424, label='Flow: Mode3')
freq_model.plot_flow_at_freq(595, label='Flow: Mode4')

plt.figure()
freq_model.plot_pressure_at_freq(424, label='Pressure: Mode 3')
freq_model.plot_pressure_at_freq(595, label='Pressure: Mode 4')

# You can also display these ac. fields for all frequencies.
freq_model.plot_var3D(var='pressure')
plt.title('Main Bore')
freq_model.plot_var3D(var='flow')
plt.title('Main Bore')

plt.show()

# %% With plotly

# if you have plotly installed on you computer you can display this plot in 3D
freq_model.plot_var3D(var='pressure', with_plotly=True)
```

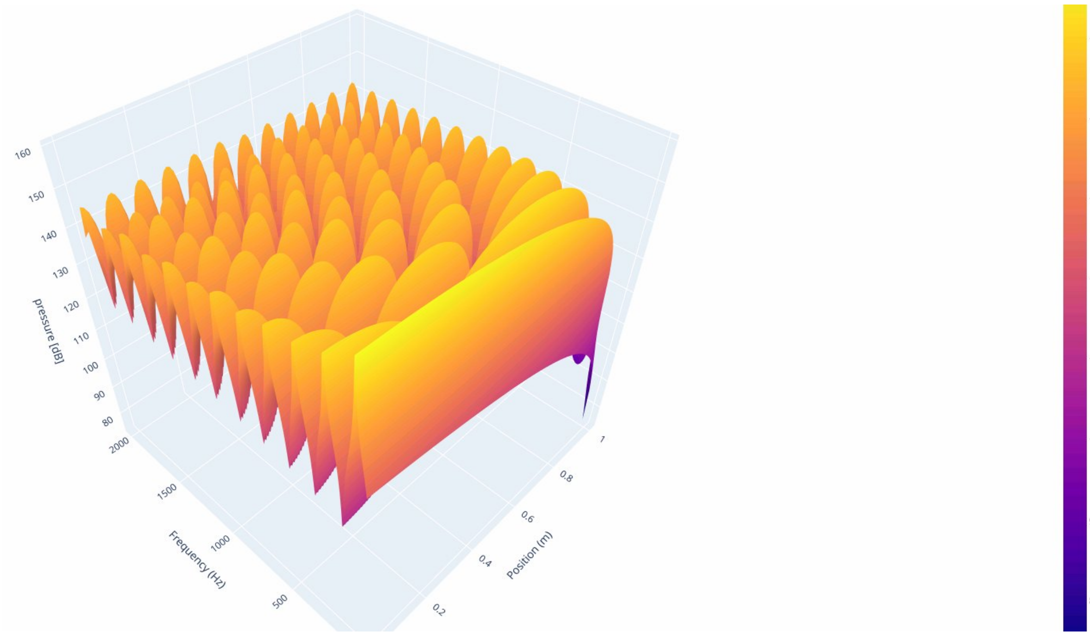
Cylinder closed-open, 1000mm, Dia 11mm,
Mode 3, 4 und 6 are selected, and the calculated resonating frequency is used.
Pressure (Pa) * 1e7 = 7 digits more = *10.000.000 equals ~ resulting Input Impedance in Mohm, because the unity Flow m/s ~ 1,0 invers prop. = sec/m ~ 1,0!



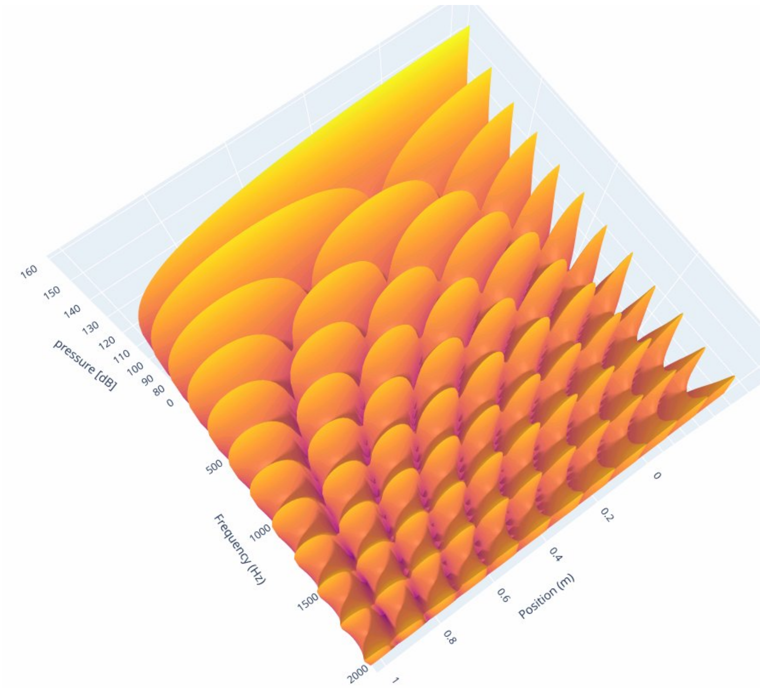
Left: Closed End, Mode 3 = 424 Hz, shared Min.= Antires. = 507Hz, Mode 4 = 595 Hz, Mode 6 = 935Hz

Very interesting: Pressure and Flow Values found at the „antiresonant“ Frequencies!
Characteristic Flow Impedance with 11 mm Durchmesser ~ 4,3 Mohm und Pressure = 0,43 *1 E^7 Pa

Cylinder closed-open, 1000mm, Dia 11mm,
Pressure Distribution, Resonance Frequ. Mode #1-#12
Open Wind, FEM Simulation



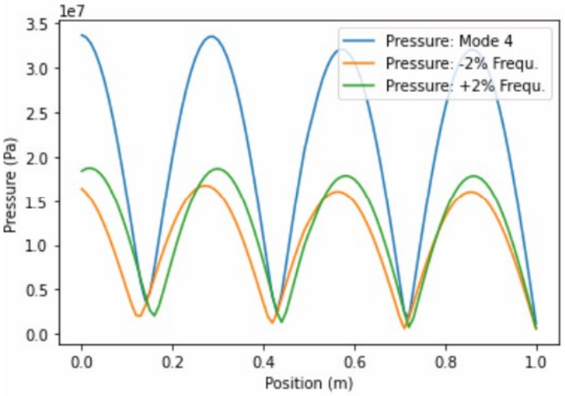
Pressure Distribution, left side is the closed End

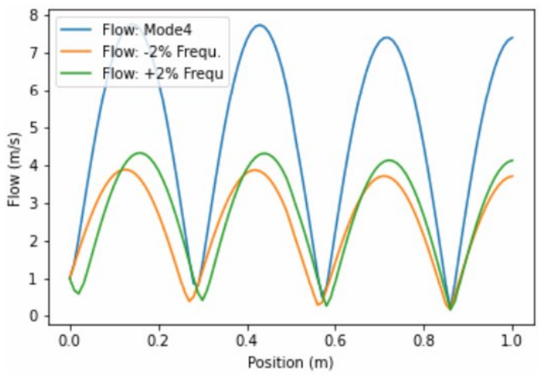


Pressure Distribution, left side is the open End

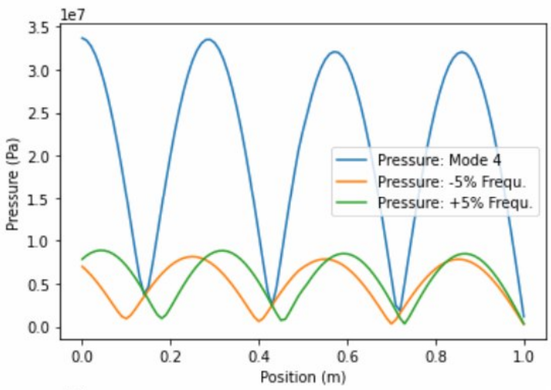
Pressure and Flow Distribution at resonant Frequency,
and the behaviour at Frequencies somewhat below or above the resonant Frequency:

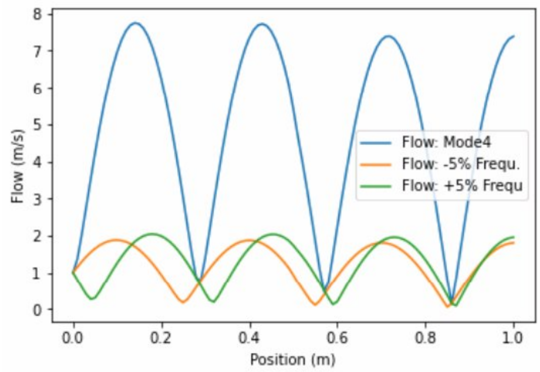
Cylinder closed-open, 1000mm, Dia 11mm, ¼ WL Mode #4 = 0,142m

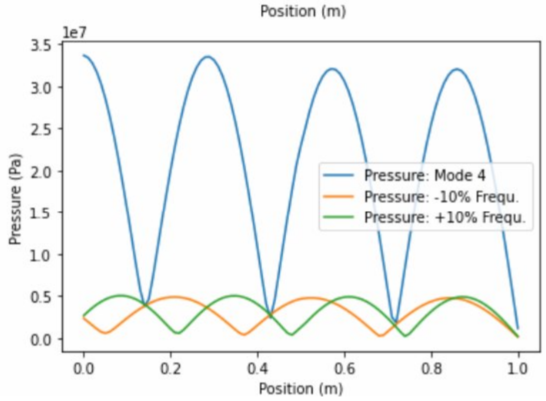


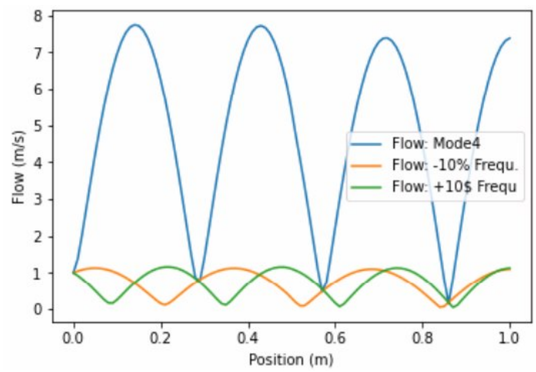


Pressure Amplitude is almost ~ 2 times less *Flow is also about ~ 2 times less*

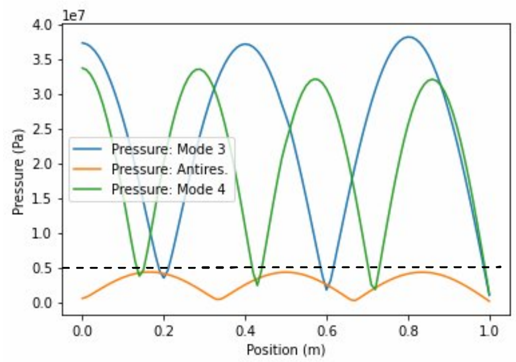


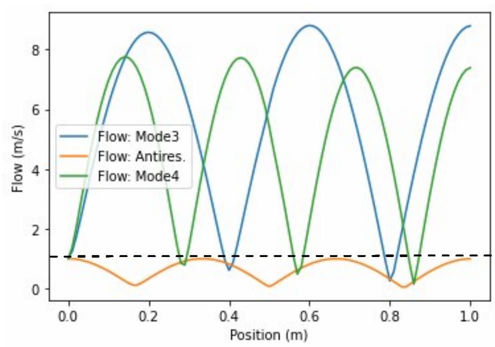






Pressure Amplitude is ~ 7 times less Flow is also ~ 7 times less.

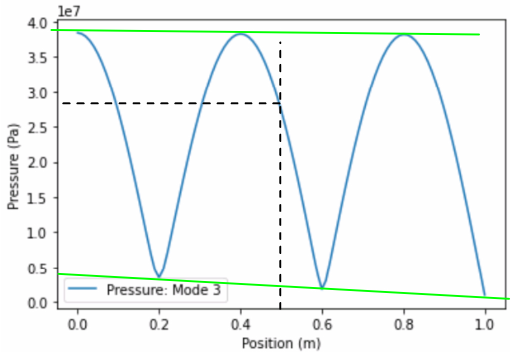


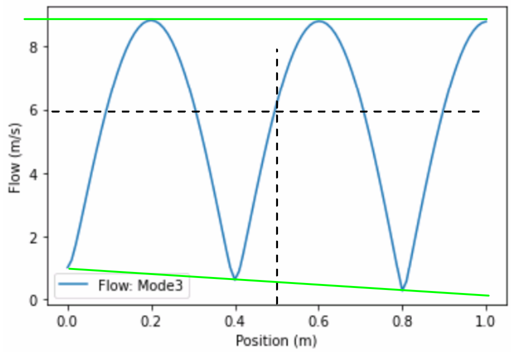


Antiresonant Frequency below Mode #4; Pressure Node Positions show change of wavelenght < ----
Flow Nodes also show the change of wavelength, best tracked as positions from the open end of the tube.

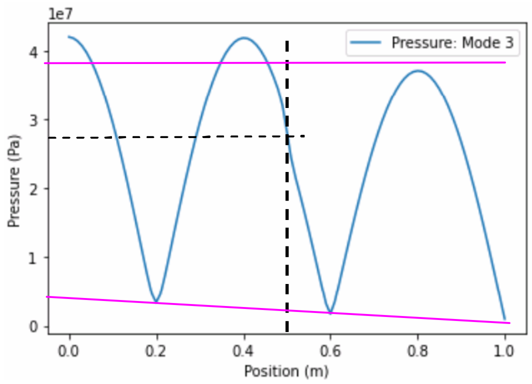
Open Wind - Pressure and Flow Distribution inside the tube, changes caused by local perturbation of the bore, here centered at 50% tube lenght

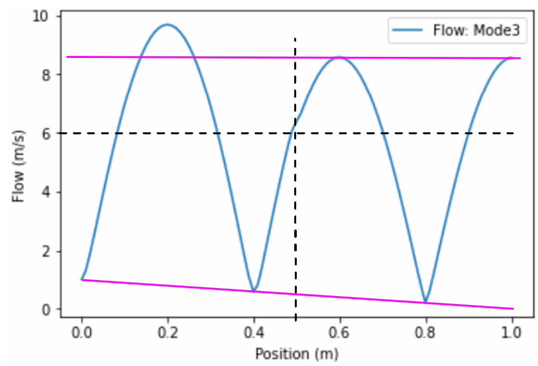
Result (Reference) with no Perturbation, Cylinder closed-open, L 1000mm, Dia 11mm, 23 °C
Resonant Frequ. Mode #3 = 424,4 Hz, ¼ WL = 0,2m:





Perturbation = strong Constriction 1/q0= 0,75 and PL =2,2% centered at 50% Tube lenght
gives a slightly lower Resonance = 422 Hz:





Mode #3 acts with a local perturbation centered at 0,5 tube length not inverse proportional, meaning the input impedance magnitude is raised with constriction of the bore. Pressure and Flow are raised to higher levels before the perturbated position at the closed side of the tube but remain mostly unchanged after the perturbated position an the open side of the tube.

The resulting Input Impedance Modulus |Z|in changes from 38,6 MOhm to ~ 42 Mohm.
The pressure Amplitude from ~3,8 Pascal *10.000.000 = 38 Mpascal * ~ 1m/sek =1 sek/1m = 42 MPascal.

Here is Unity Flow mit 1,0 als „blowing source“ selected, the pressure at the closed end (in MegaPascal) equals therefore the input impedance vector length with phase 0 rad.

Please note: FFT-Measurements do not show so strong differences, they are much smaller, an so the change off pressure fluctuations at the closed end will be less than the simulated results.

How ever, it’s not a very useful tool to examine the exact differences found by perturbating the bore.
Thanks to chat gpt it is simple to export the acoustic field data of pressure and flow distribution.
So I created an extension of the python script, which is able to export the simulated Data into Excel.

This is not limited to simple geometries, it reads the same geometry.txt file, as used for the impedance data “harvesting” script, which is actually script06.py.

Here is the script extension, which grabs the data from plot writes it into pressure_data.txt and flow_data.txt files. Those files can be easily imported to excel, the grid was set to 0.001 = 1mm Resolution of Positions x.

```
#chatgpt python code for  export of plot Data to pressure_data.txt and flow_data.txt
import csv

# Define the frequencies of interest - must be filled with peak data obtained by simulation  ## manual input required
# Data is from script6 = harvesting impedance data
frequencies = [422.506, 592.407, 763.792]

# Initialize empty dictionaries to hold the data for pressure and flow
pressure_data_dict = {}
flow_data_dict = {}

# Collect data for pressure
for freq in frequencies:
    plt.figure()
    freq_model.plot_pressure_at_freq(freq, label=f'Pressure: Mode at {freq} Hz')

    # Extract data from the plot
    ax = plt.gca()
    lines = ax.get_lines()
    for line in lines:
        x_data = line.get_xdata()
        y_data = line.get_ydata()

        # Populate the dictionary with x and y data and replace . with , for excel import.
        for x, y in zip(x_data, y_data):
            x_str = str(x).replace('.', ',')
            y_str = str(y).replace('.', ',')
            if x_str not in pressure_data_dict:
                pressure_data_dict[x_str] = [y_str]
            else:
                pressure_data_dict[x_str].append(y_str)

    plt.close()

# Collect data for flow
for freq in frequencies:
    plt.figure()
    freq_model.plot_flow_at_freq(freq, label=f'Flow: Mode at {freq} Hz')

    # Extract data from the plot
    ax = plt.gca()
    lines = ax.get_lines()
    for line in lines:
        x_data = line.get_xdata()
        y_data = line.get_ydata()

        # Populate the dictionary with x and y data
        for x, y in zip(x_data, y_data):
            x_str = str(x).replace('.', ',')
            y_str = str(y).replace('.', ',')
            if x_str not in flow_data_dict:
                flow_data_dict[x_str] = [y_str]
            else:
                flow_data_dict[x_str].append(y_str)

    plt.close()

# Write the pressure data to a TXT file with tab delimiter
pressure_txt_filename = 'pressure_data.txt'
with open(pressure_txt_filename, 'w', newline='') as txtfile:
    csvwriter = csv.writer(txtfile, delimiter='\t')

    # Write the header row with frequencies as column labels
    header = ['x'] + [str(freq).replace('.', ',') for freq in frequencies]
    csvwriter.writerow(header)

    # Write the data rows
    for x, y_values in pressure_data_dict.items():
        row = [x] + y_values
        csvwriter.writerow(row)
```

```
# Write the flow data to a TXT file with tab delimiter
flow_txt_filename = 'flow_data.txt'
with open(flow_txt_filename, 'w', newline='') as txtfile:
    csvwriter = csv.writer(txtfile, delimiter='\t')

    # Write the header row with frequencies as column labels
    header = ['x'] + [str(freq).replace('.', ',') for freq in frequencies]
    csvwriter.writerow(header)

    # Write the data rows
    for x, y_values in flow_data_dict.items():
        row = [x] + y_values
        csvwriter.writerow(row)


# Optional: Generate and show the plots for each frequency on Screen
for freq in frequencies:
    plt.figure()
    freq_model.plot_pressure_at_freq(freq, label=f'Pressure: Mode at {freq} Hz')
    plt.xlabel('X-axis Label')  # Adjust label as needed
    plt.ylabel('Y-axis Label')  # Adjust label as needed
    plt.legend()
    plt.show()

    plt.figure()
    freq_model.plot_flow_at_freq(freq, label=f'Flow: Mode at {freq} Hz')
    plt.xlabel('X-axis Label')  # Adjust label as needed
    plt.ylabel('Y-axis Label')  # Adjust label as needed
    plt.legend()
    plt.show()
```

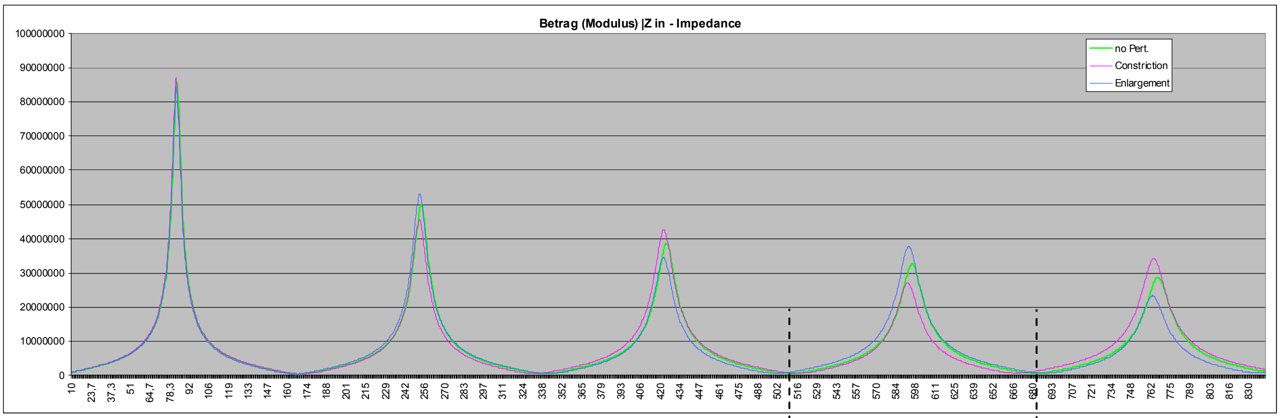
Results from Examination with Excel:

Open Wind - Pressure and Flow Distribution – Changes because of Perturbations

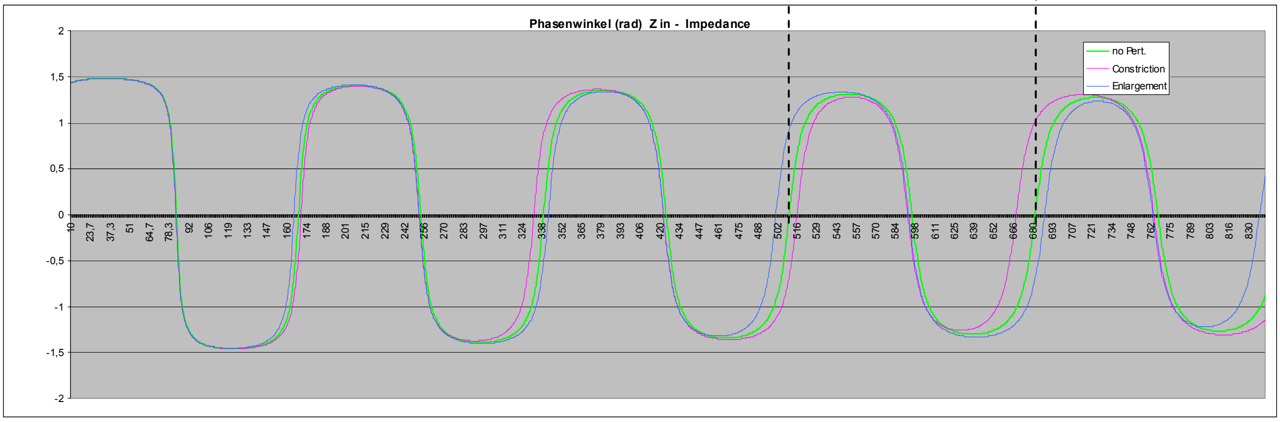
The simulated closed-open tube has a length of 1,0m and inner diameter = 11,0mm Room Temp. = 23°C
The Perturbations applied are q0=1,33 and 1/q0=0,75 ratio of cross section, with a perturbation length of 2,2% tube length, giving an enlargement to Dia = 14,66 mm or an inv. prop. Constriction to Dia = 8,25mm. This perturbation resembles the tests with a bolt, Dia 7,0 mm inserted. This very “heavy” perturbation was choosen to intenser show how the acoustic fields inside the tube are changed with these disturbances.

Remember: OpenWind spectral data is exported as real an imaginary parts,
and has to be rewritten to Modulus and Phase Angle of the input Impedance |Z|in.
OpenWind exported peak magnitudes are already Modulus (Z Betrag), where the phase angle is zero.
Green curves show the unperturbated reference tube.

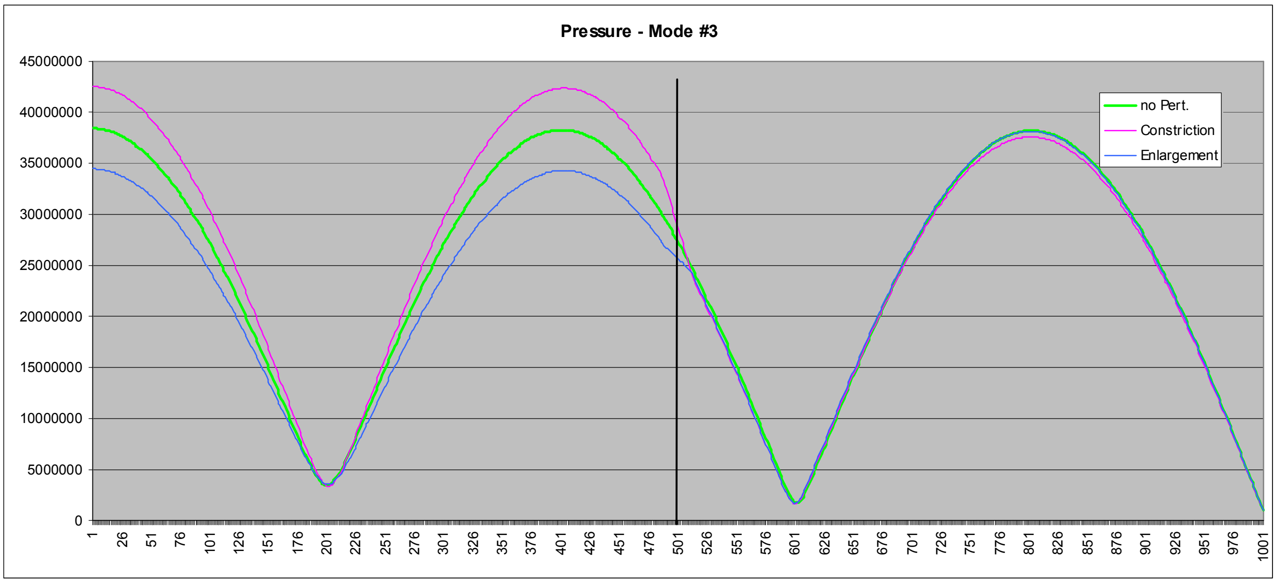
At first, perturbations are exactly centered in the middle of the tube. What we find is, that any disturbance has a frequency lowering potential. Although this place is definitely a Pitch-Pot node, there is an offset down, all resonant frequencies are lowered somewhat, i refer to this effect as pitch-pot offset down.

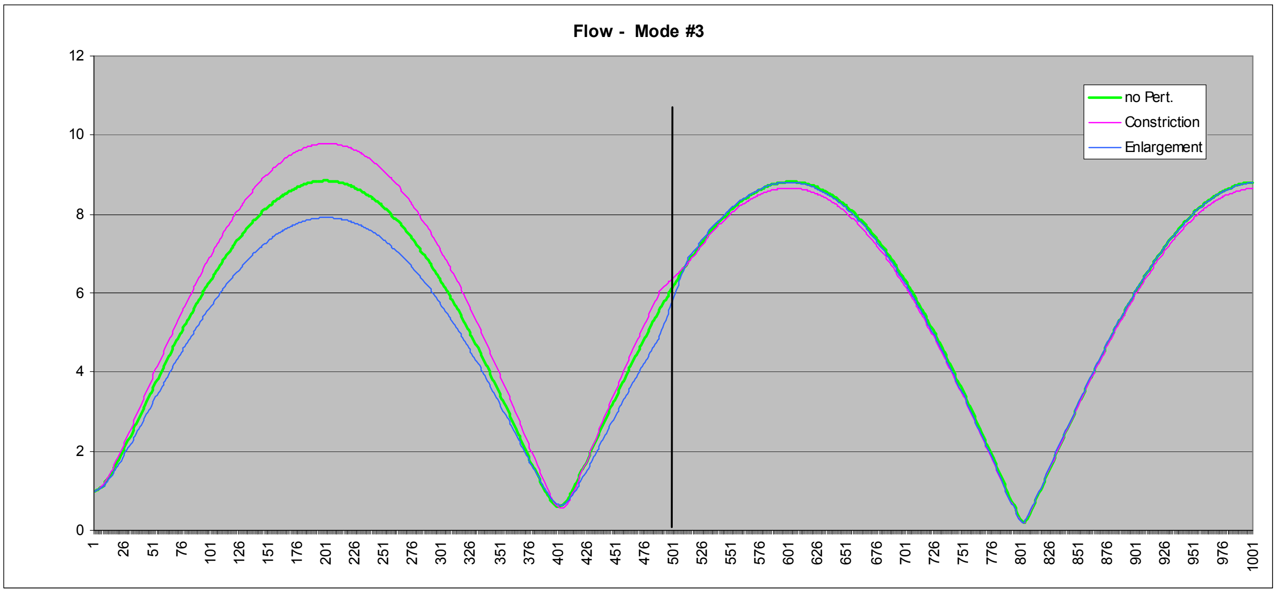


Odd Modes show inverse behaviour, so Input Magnitude is raised with constriction, even Modes are lowered



The greatest differences appear here at / around the minima = anti resonance frequencies, these form a “domain” with peak magnitudes, which means they are changed at the same position. The second domain is shared by peak Frequency with Minima Magnitude changes, as we will see later.





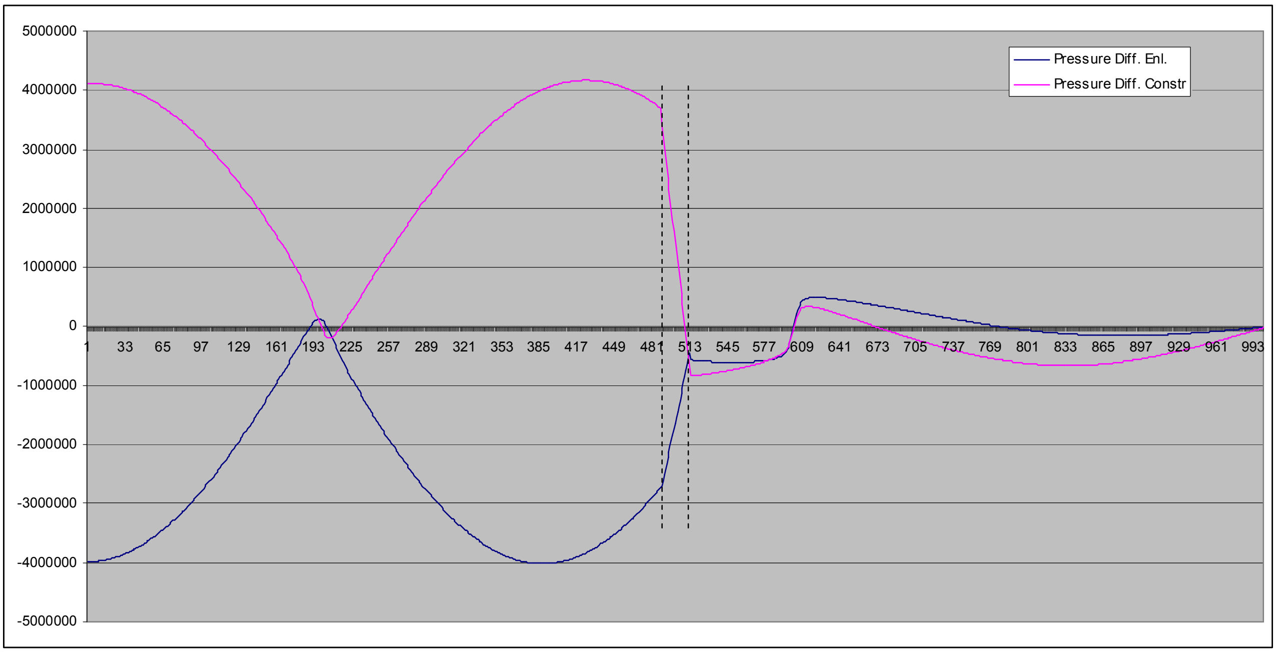
not inverse (odd # Modes): constriction raises pressure + flow + Imp. Magn. – at the closed side, flow at the closed end is not affected

This effect is found at all not inverse positions, being at the right side of a pressure antinode maximum. Seen from constrictions, this has a damming effect (Staumauer Effekt) on the left (closed) side of the tube.

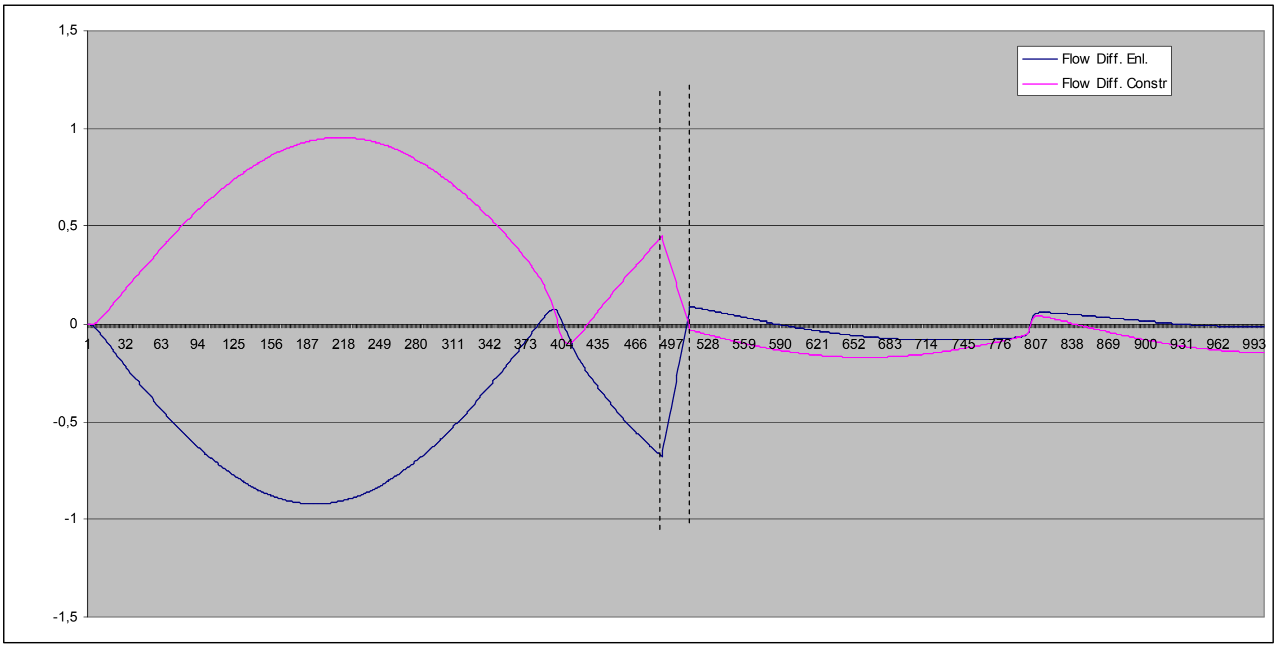
Mode #3 has a ¼ wavelength of 0,2m oder better said 1/ (2n-1) = 1/5 of tube length.
5 * ¼ wavelengths would fit into the pipe, and so 5 * 1/8 WL would fit into either half of the pipe.

Counting from the “open End”, we can define that the Input Magn. Pot. is that of 5/8WL!
At 9/8 WL = Position 100mm from closed end, it will have 9/8 WL Pot. Mode #5 for example would have 9/8 WL Pot at 50% pipelenght. But Mode #3 would here only have to push 1/8 remaining WL damming up at the closed side and so the effect becomes much stronger. At 1/8 WL from the open end therefore the damming up covers 9/8 remaining volume and the effect is therefore much smaller.

This is somewhat oversimplified, but it can be stated, pressure nodes and antinodes keep staying in place, pressure and flow nodes are almost not changed at all.

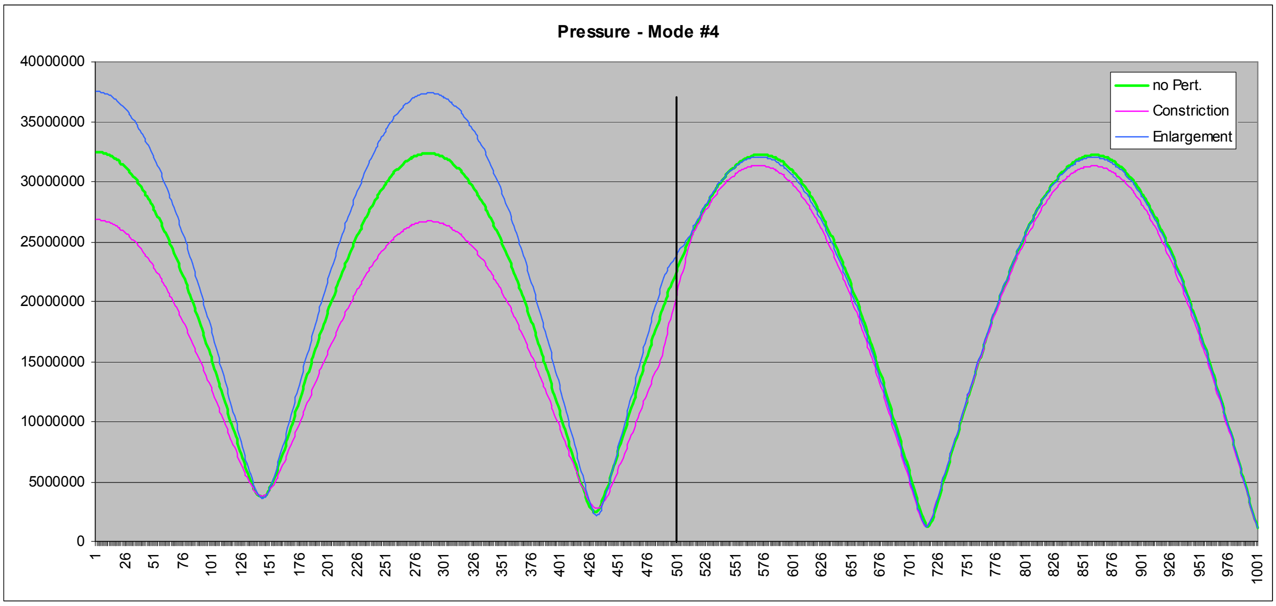


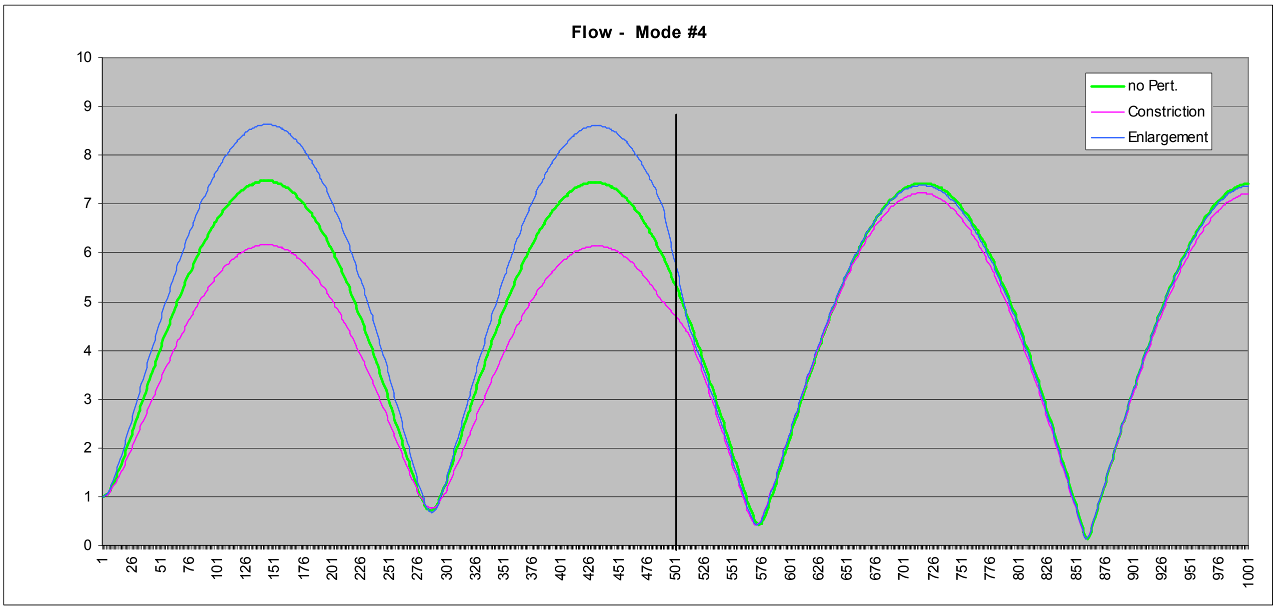
Mode #3, Difference in Pressure due to Perturbation, perturbated region marked with dotted lines,
The not inverse case: Much of the difference is inside the perturbated region



Mode #3, Difference in Flow due to Perturbation, perturbated region marked with dotted lines,
not inverse case: the change of flow inside the perturbated region is comparable small

Both Pressure and Flow are changed in the same direction.





inverse (even # Modes): constriction lowers pressure + flow + Imp. Magn. – at the closed side

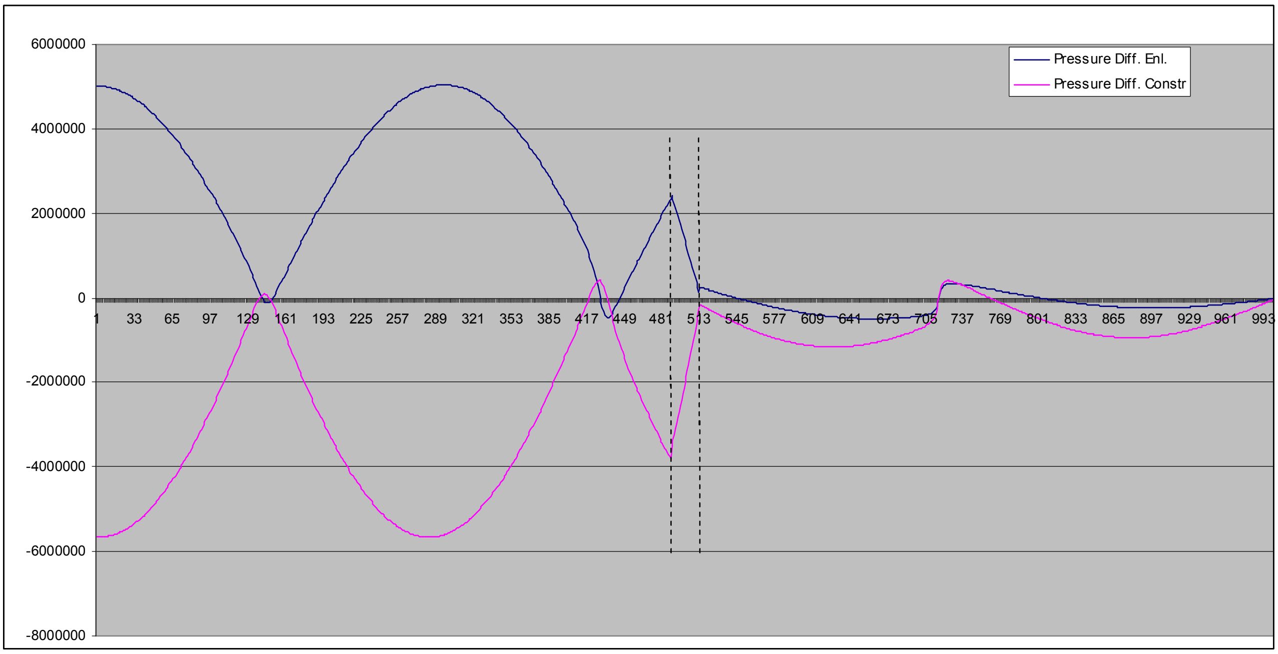
This effect is found at all inverse positions, being at the left side of a pressure antinode maximum. Seen from constrictions, this has an “anti”-damming effect on the left (closed) side of the tube.

Mode #4 has a ¼ wavelength of 0,1428m oder better said 1/ (2n-1) = 1/7 of tube length. 7 * ¼ wavelengths would fit into the pipe, and so 7 * 1/8 WL would fit into either half of the pipe.

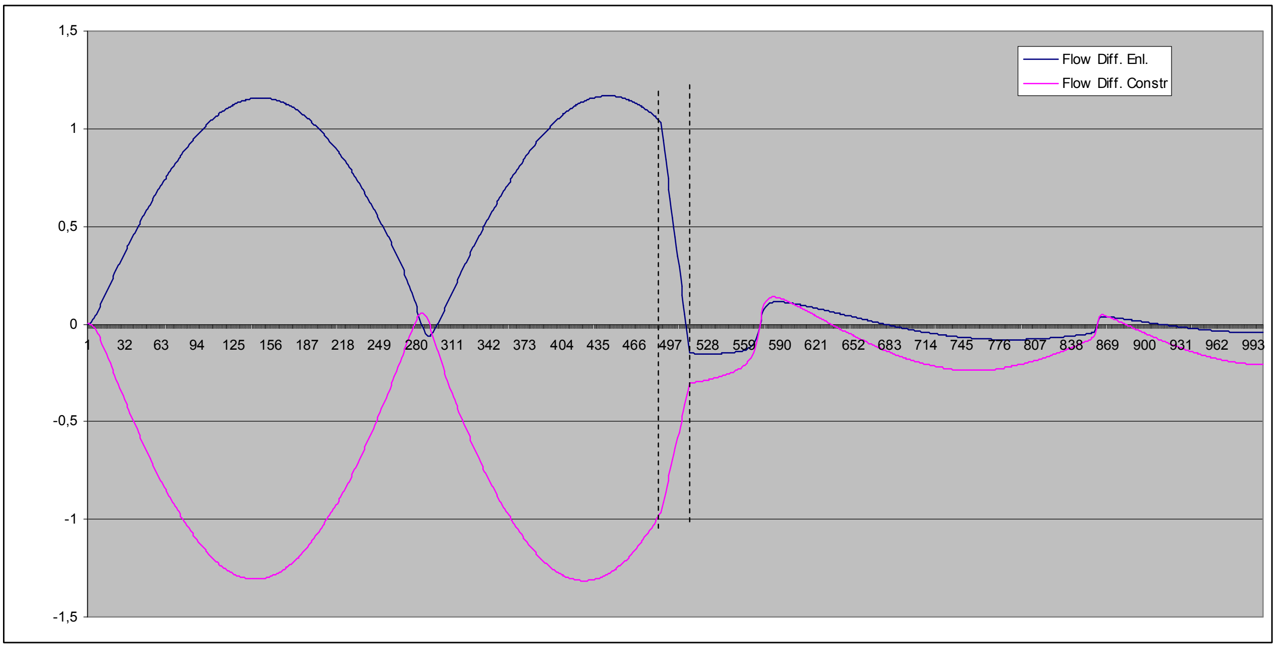
Counting from the “open End”, we can define that the Input Magn. Pot. ist that of 7/8WL! At 11/8 WL = Position 214mm from closed end, it will have 11/8 WL Pot. Mode #6 for example would have its 11/8 WL Pot at 50% pipelenght. But Mode #4 would here only have to push 3/8 remaining WL damming up at the closed side and so the effect becomes much stronger. At 3/8 WL from the open end therefore the damming up covers 11/8 remaining volume and the effect is therefore much smaller.

This is somewhat oversimplified, but it can be stated, pressure nodes and antinodes keep staying in place, nodes are almost not changed at all.

Both Pressure and Flow are changed in the same direction.



Mode #4, Difference in Pressure due to Perturbation, perturbated region marked with dotted lines,
The inverse case: The difference (change) is inside the perturbated region is comparable small



Mode #4, Difference in Flow due to Perturbation, perturbated region marked with dotted lines,
The inverse case: The change of flow inside the perturbated region is compareable large.

To put things together, in the perturbated region itself changes are
in the not inverse case (left side of a pressure antinode) = larger pressure change, smaller flow change
in the inverse case (right side of apressure antinode) = smaller pressure change, larger flow change

Now its time to examine what happens when a perturbation is exactly center-placed on a pressure node.

Since q0=1,33 is really strong and so the pitch offset is really strong down, I switch to a slighter Perturbation: Enlargements q0=1,1 and inv. prop. Constrictions = 1/1,1 = 0,90909 which means, the tube is enlarged from 11,0mm to 12,1mm or constricted to 10,00mm at the centered perturbation with length = 50 mm.

The longer perturbation length should give some more Pitch Pot. to see the differences clearer, rather than the used perturbation lengths of 2-2,2% in the other examples found in my former writings. The perturbation length itself has no effect on the pitch over-pot. and pitch offset dn, it's a sin(PL Pot.) multiplicator.

As i know, we can say, that pitch Changes are invers proportional to wavelength changes – as long the phase velocity is not changed =it's the proportionality constant in this case. It's the wavelength changes due to the perturbations. And if perturbation cross sectional changes are invers prop. to each other (what is here the case); we can forecast, that a pitch pot up = shorter global wavelenght would be q0² weaker than the pitch change Pot. dn = longer global wavelength. So there is a fairly good match to the boresize changes.

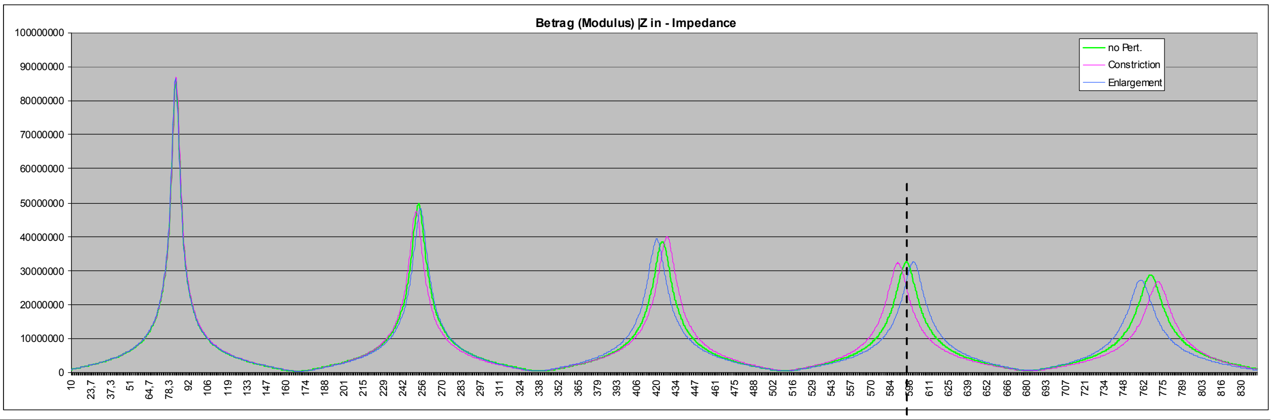
A constriction center-placed at a pressure node will lower the global resonant frequency (longer WL),
a constriction center-placed at a pressure antinode will raise the global resonant frequ. (shorter global WL);
Now it is the case, that the tubelenght ist not changed at all, and 2n-1 quarter wavelengths must fit the tube.

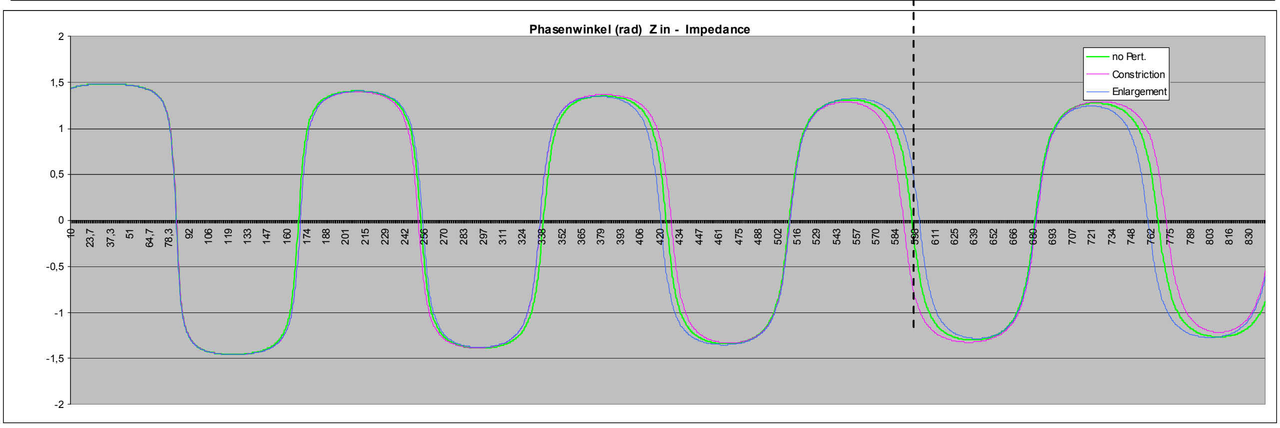
And when the global frequency is raised (shorter wavelenghts) there is a remaining length. This remaining length is added at the local perturbation position, having the effect, that pressure nodes at the right (open) side get now somewhat smaller spaced, the 2 neighbour pressure nodes distances are slightly larger and their position is shifted away, leaving 1 longer distance around the perturbation position. The inverse case is when the global resonance frequency is lowered (longer WL, 2x shorter distances to neighbour pressure nodes. So let see if this is correct and how pressure and flow distribution is effected from such perturbations:

I choose resonance mode #4 and these Positions, that refer to XM-IN1 and XM-IN2, Positions where Input Magn. Changes |Z|in would be nearly zero.

Pressure Nodes are 1/(2n-1) parts of the tubelenght apart, Pos. are ¼, ¾, 5/4 and 7/4 WL from closed end.
= 142,8mm 428,6mm 714mm und 1000mm (the open end itself).
Press. Antinodes =0mm 285,7mm 571,4mm 857,1mm

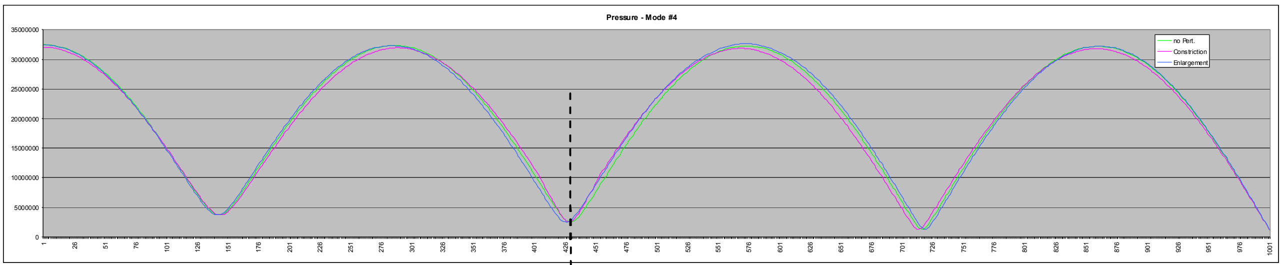
Perturbation centered on a Pressure Node of Mode #4 (~ XM-IN1) at 428,6 mm:

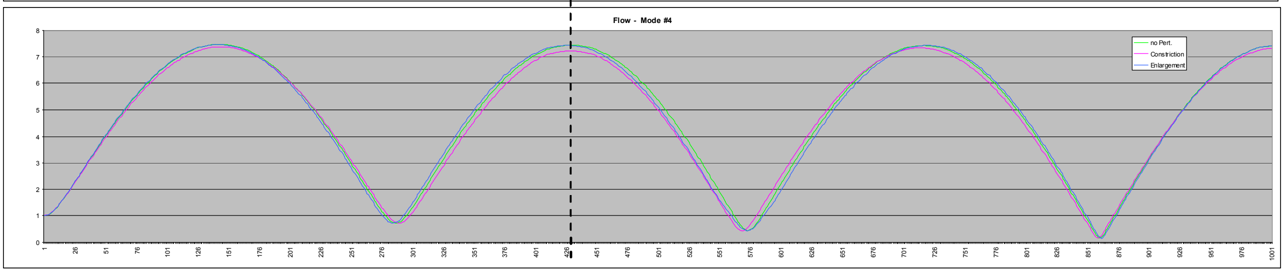




Since zero phase angle determinates Peak frequency, Minima Frequ Domain has nearly zero changes!

Frequencies for Pressure Distribution are the altered Frequencies found by Simulation with the perturbation
Mode #4 unperturbated: 595,469 Hz
Constriction: 589,436 Hz = -17,6 Cent
Enlargement: 600,503 Hz = +14,6 Cent = ~ 1,2 = q0² smaller pitch pot. up

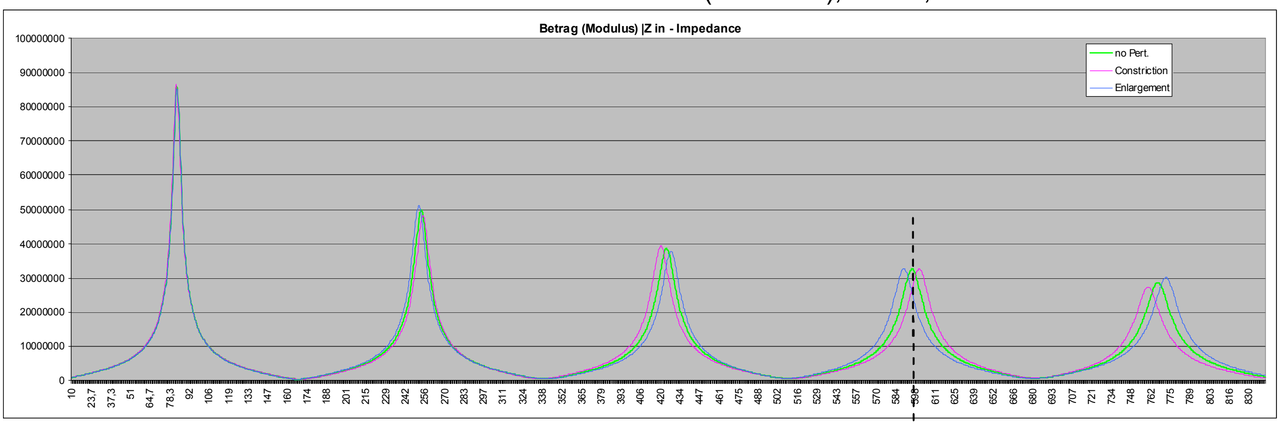


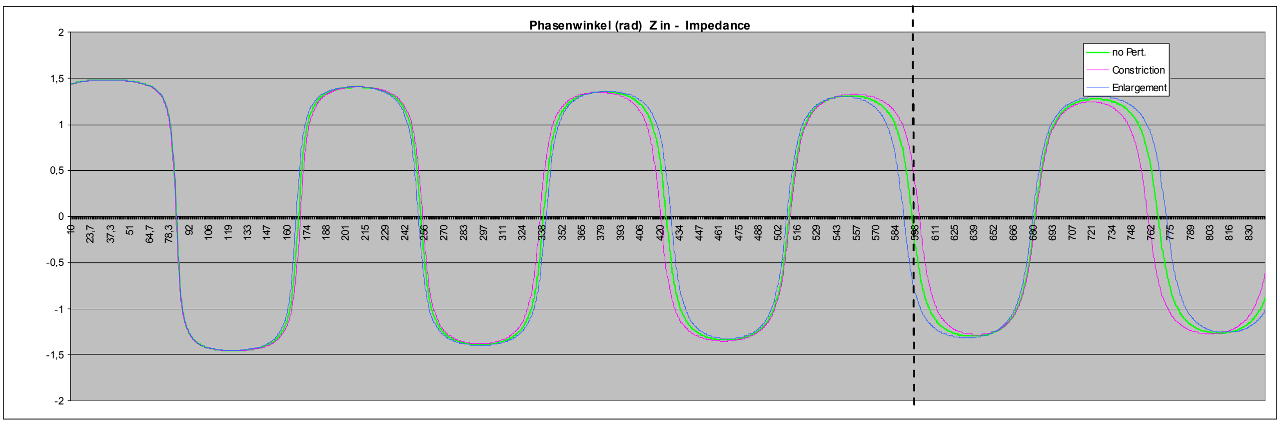


Constriction on Pressure Node lowers the global frequency = longer ¼ WL; the distance from the perturbated pressure node to his neighbour pressure antinodes is smaller, also the distance to the next pressure node towards the open end. So here only the last distance between the pressure nodes is definitely longer.
With Constriction at the Pressure Node there is no great change in Pressure and Flow Maxima.

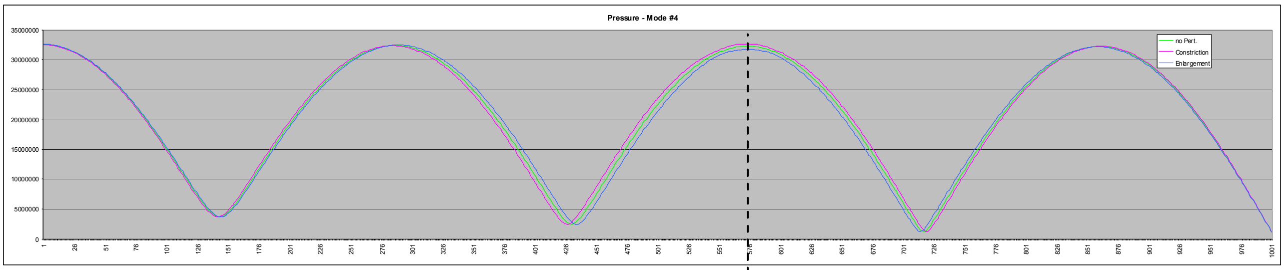
Enlargement on a Pressure Node raises the global frequency= shorter 1/4WL, the distance from the perturbated pressure node to his neighbour pressure antinodes is longer.

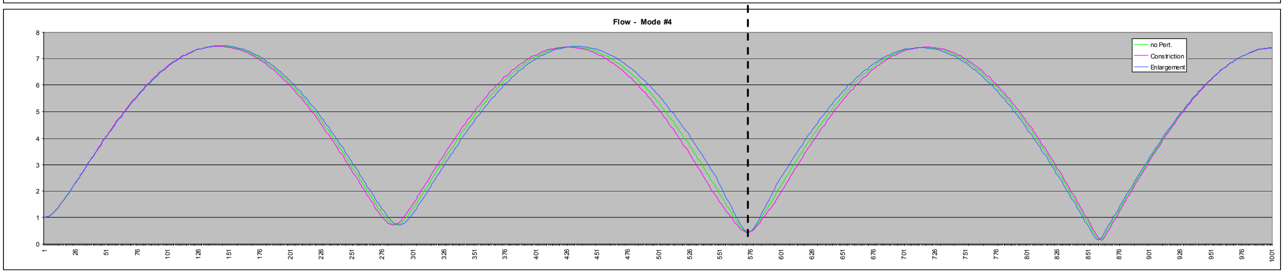
Perturbations centered on a Pressure Antinode of Mode #4 (~ XM-IN2), at 571,4 mm:





Frequencies for pressure distribution are the altered frequencies found by simulation with the perturbations
Mode #4 unperturbated: 595,469 Hz
Constriction: 600,503 Hz = +14,6 Cent
Enlargement: 589,642 Hz = -17,0 Cent = ~ 1,17 = ~ ~ < $q0^2$ larger pot dn as pot up





Constriction on a Pressure Antinode raises the global frequency = shorter ¼ WL; the distance from the perturbated Pressure Antinode to his neighbour pressure nodes is longer. So here only the distance from Perturbation to neighbour pressure nodes is really longer, giving room for a global shorter wavelength.

Enlargement on a pressure antinode lowers the global frequency = longer 1/4WL,
So here only the distance from Perturbation to neighbour pressure nodes is really shorter, giving room for a global longer wavelength.

General comparison with other simulation software:

So, this check is in general agreement with my experiments made with Bios© Artim and the ART simulated Bb-Trumpet, where additional opposite effects from Mouthpiece and Bell must be considered since they change their effective acoustical length with frequency – (compared to a cylindrical tube of same lenght). Bios © by Artim Tests show a larger change in Pressure after the Perturbation in direction to the open end, but this is not the case with Openwind, here changes after the perturbation position are almost unchanged and at the perturbation position itself there are changes. This difference is because the Bios © Artim pressure amplitude data was normalized to the pressure value at the perturbation center (with no perturbation).

The Bios © by Artim results are presented in part 2C-Virt-Cyl-frustum.pdf Page 5, and in more detail in Part 3-Pert-Virt-Simulate.pdf Pages 27-55, but note, this parts have to be rewritten due to the new understanding!

However, it should be also mentioned, that changes found by measurements, FFT-Transform and Analysis of the results are much smaller and there is an offset not only in the frequency but also with magnitude changes of the input Impedance. Therefore also the placement of magnitude nodes is different, especially at the last full wavelength fitting into the pipe and finally at the last quaterlenght fitting the pipe. So the real pressure and flow distribution data along the tube (must) also deviate from those found by the simulations!

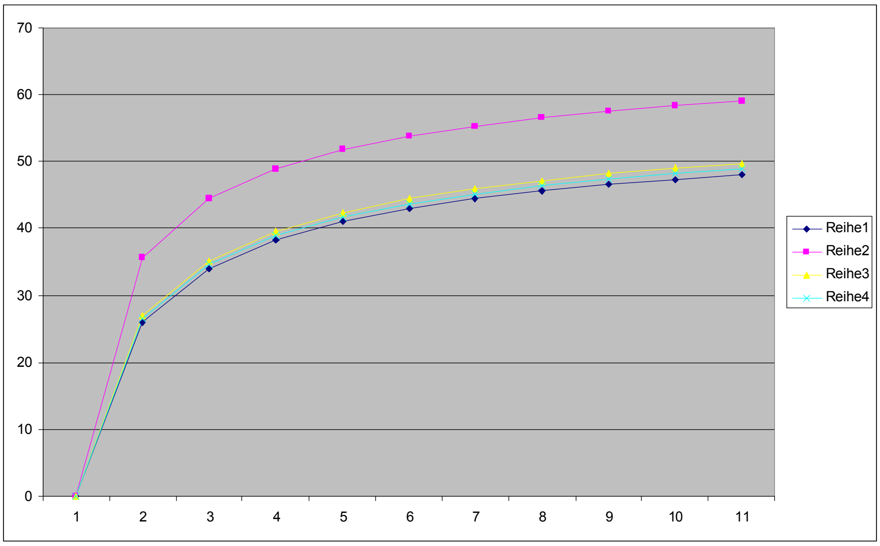
Evaluating temperature changes in the pipe, + / - and drop towards open end:

In simulations and impedance measurements, there is no temperature gradient in the pipe, the air humidity and CO2 content correspond to the ambient values. Nevertheless, I have always been interested in how the temperature gradient of the exhaled air would affect the resonances (or the inharmonicity). ART Simulation also offers the possibility of varying the temperature, air humidity and CO2 content, but it is easier with the Python script and Openwind.

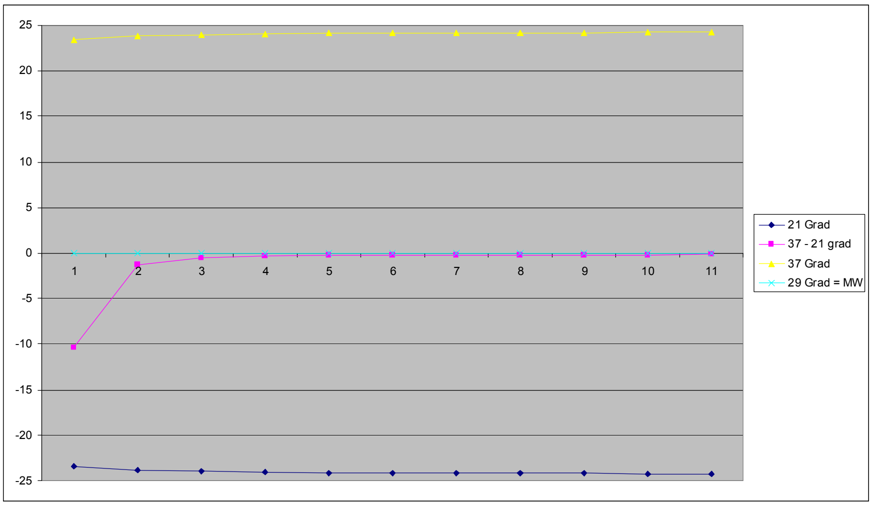
Please note:
A short pipe is more inharmonious than a long pipe, a narrow and long pipe is more inharmonious than a pipe of the same length with a larger cross-section (see Sideletter #2).

Test linear change of air temperature in the pipe:

	closed end	-> open End:
blue:	21°	-> 21° C = constant -8 degrees compared to the average
turquoise:	29°	-> 29° C = constant, arithmetic mean = average
yellow:	37°	-> 37° C = constant +8 degrees compared to the average
pink:	37°	-> 21° C = linearly decreasing, results in 29° C at 50% pipe length



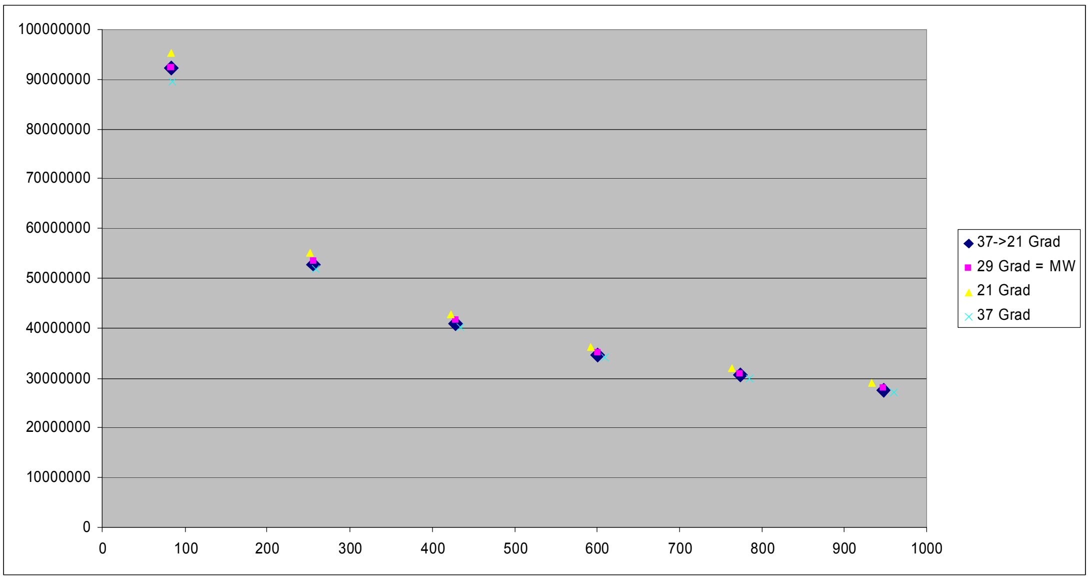
x = Mode #, y = deviation Cents to frequency of harmonic = Mode #1 * (2n-1)
Inharmonicity to Mode #1 in Cent, Equal tuning



Difference in Cent to the average temperature, Modes # 1-11

Including the exhalation temperature and a linear gradient to the ambient temperature, there is an additional inharmonicity, especially mode #1 is increased in frequency much less, -10.3 cent deviation, but with mode #2 the inharmonicity is only -1.3 cents stronger.

Conclusion: Lowest modes become deeper than average, with higher modes the resulting frequency stays almost unchanged. Higher temp. results in less increase in deep modes, lower temp. results in less deepening of the lower modes, so: At lower temperatures the harmonicity increases.



x = Frequency in Hz, y = Input Magnitude |Z|in given in acoustic Ohm

The input magnitude peak maxima change as expected with the frequency change, i.e. lower with higher resonance frequency (see Sideletter #2).