Stimmung und Intonation bei Blechblasinstrumenten

Tuning and intonation of brass instruments

Sideletter #5: Measured Input Impedance Potential of cylindrical tubes vs. simulated results

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The latest revision of this document can be found at the project site:
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Accompanying documentation of the project / topic.
Development, Work, Calculation and Copyright:

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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!!

Content

Abstract - Description of discrepancies

It is April 1, 2024 and I have been carrying out impedance measurements on trumpets and mouthpieces, as well as on cylindrical tubes, for many years now using a self-built measuring head and software. Unfortunately, there are significant differences between the measured values and the simulation software available to me. These are Bias© and Bios© copyright by ARTIM, each in the demo version, the Acoustical Research Toolkit (ART) see Sideletters #2 and #3 as well as other parts that were created before 2024, and now also OpenWind - see Sideletter #4.

With the help of numerous experiments, I was able to shed some light on the matter, but the values of the input impedance |Z|in at the closed end determined by simulation are overestimated compared to measurements, or the entire potential found does not match in some cases, and the solutions found are therefore not suitable for practical use, or many statements and conclusions - even fundamental ones - have to be revised for practical use, which I am not very happy about, but what good is it if it is not true?

However, I have the privilege of not having to work academically. I take the liberty of pointing out differences found without having to reconcile anything with various physical laws and theories at the same time. Others are welcome to do that after me. I think there are currently still many parameters missing that could make simulations more suitable for practical use in the future.

My measurements – Sources of errors

On the other hand, practical measurements are very prone to errors and there are relatively large deviations and error spread. The measured values now determined on a cylindrical pipe with a diameter of 11 mm and a length of 1000 mm were therefore mostly repeated up to 5 times, again on around 5 different days, so that the measured values are now available as arithmetic mean values that can be assumed to be realistic and no longer contain any random outliers.

Nevertheless, random deviations in measurements must be accepted. The deviations for the reference pipe in 5 subsequent individual measurements are around +/- 1% (max.), with bolts 5 mm around +/- 0.5% (max.), with sleeves (positioning problem, necessary movement of the measuring head, etc.) higher. If you now have a very low magnitude potential – with low modes or near the open end of the pipe - deviations inevitably occur that can easily amount to 10%. Higher modes with more potential therefore also have smaller deviations in the measurements. The same applies to stronger disturbances - i.e. local perturbations with bolts, for example. However, here the magnitude potential shifts strongly towards the lowering (frequency and magnitude) and a back calculation therefore would produce - since these are only approximations - stronger deviations due to the back calculation.

Another weak point is the measuring head. The built-in loudspeaker is hopelessly overwhelmed below around 100 Hz, at around 1400 Hz in combination with the pressure chamber it has its strongest first resonance, which can be largely corrected by adjusting the signal amplitude, but a wandering "today" effect remains. The necessary correction of the loudspeaker resonance limits the possible volume = sound level. Ideally set, the excitation signal fluctuates by only 0.2 dB in the frequency range of 100-2500 Hz, but this corresponds to a deviation of 2.3% of the sound level. In the region around the loudspeaker's natural resonance, the wave impedance at the measuring microphone is higher, i.e. the impedance minima magnitudes found are somewhat higher. For a 1m long cylinder, this is the case in the mode #7-10 range. In the case of a Bb trumpet, this would only affect the 13th mode and upwards.

In the other case, mode #1 (strong) and mode #2 tunnel back through the capillary, i.e. with the tube plugged in, the resonance frequencies of the mode #1 and mode #2 tube are noticeable as a negative bend in the frequency FFT of the control microphone inside the measuring heads loudspeaker chamber. This means that in the low range the capillaries are an acoustic "leak" in both directions, there is transmission and flow – at the “closed” end. In the lower frequency range, the measurements are therefore very quickly off and the measured impedance of the lower resonance peaks is lower.

Another weak point is the FFT with windowing and spectral leakage, as well as the need for averaging. However, this is not an averaging, but a "peak hold" function. This means: Smaller values may be filled in, values that are too high remain too high - or are added - possibly as outliers. The number of averages determines how smoothly the measured points fit together, with the disadvantage that long measurement times are again sources of error, which leads to further measurement errors, as is the case here with the peak marking function used by the FFT program. Unfortunately, the "random" function is simply at play here.

Since the individually measured peaks were often averaged here, I decided not to smooth the measured spectrum. When measuring on instruments, the spectrum is corrected for the Today curve, smoothed with a Salvitzky-Golay filter and then the peak and statistical alternatives to it are searched for again.

Small temperature fluctuations change the frequency, a lower frequency results in a higher magnitude, a higher frequency produces a slightly lower magnitude (at least theoretically); however, temperature differences between the reference measurement and the measurement with perturbation cannot be ruled out.

The excitation signal is no longer completely sinusoidal - the harmonics found are >> 3000 Hz and very small, the room is not anechoic - there is background noise, so overall there is a really large portfolio of sources of error for the measurements and results. Furthermore, the test object is not 100% centered and clamped with the same intensity on the measuring head. This allows for a slight leak in some measurements. However, acoustic leakage is already present through the capillary. But I have already dealt with such problems in detail in the chapter on the measuring head. It should be pointed out that the measurements cannot and are not perfect.

Losses

What would be considered a loss - from the perspective at the closed end?

I would expect a loss at resonance peaks to be a lower impedance magnitude amount |Z|in, the angle phi() =0 would be +/- smaller before and after. However, whether a lower resonance frequency represents a loss or gain depends on the reference or the expectation.

The sum of the losses is frequency-dependent, with individual categories having different weights, the order without weighting them:

1 within the transmission medium itself (air)
2 friction on walls
3 smoothness of wall (absorption / reflection)
4 vibrating tube wall = random principle: constructive+ / destructive- / parasitic~~
5 acoustic leaks
6 unwanted, small cross-sectional changes = perturbations
7 losses in the excitation signal
8 sound radiation
9 measurement method & measurement error (impedance measuring head) / simulation basis
10 systematic errors / simulation basis

Measurements inevitably result in much higher losses, in contrast to simulations, but these cannot be named individually, they result in a total sum.

In pure cross-section calculations, losses are not taken into account
although the inverse prop. cross-section change plays an important role, so yes.

In simulations, these are modeled according to physical assumptions, whereby
many factors are used here that are not conclusively proven, especially wall friction and radiation.
However, a loss in the excitation signal is completely missing here, as are leaks, measurement methods, measurement errors and systematic errors.

It therefore seems logical that measurement results should deviate from local cross-section deviations on the one hand due to higher losses, while simulations tend in the other direction, although they also take losses into account in one way or another... so not?

Conclusio:

It therefore seems appropriate to compare the deviations of the physical measurements in relation to cross-sectional proportions (no losses taken into account) and also to consider the deviations from simulations – the latter has already been done and should enable an approximate calculation.

Input Impedance Magnitude Potential – Simulation and reality factors

The measurements are compared with the results of simulations and an approximate formula is found for how the changes calculated and simulated from the cross-sectional change can be adapted to the measurement results, so that changes based on the simulation results can also be checked with measurements and thus the desired change actually occurs. It is clear that although simulations usually roughly match the position of a maximum change, the potential of this change itself and thus all zero crossings = impedance nodes at other locations - or do not occur at all.

In principle and greatly simplified, the measured potential is always lower and a potential offset occurs: In the case of local expansions, this offset is in the direction of an increase in magnitude, and in the case of local constrictions, an offset in the direction of a reduction in magnitude. Constrictions reduce more, expansions increase more, but unfortunately it is not quite that simple. Fortunately, there is the "concept q", which is discussed in detail in sideletters #2 and #3.

Input Impedance Magnitude Change Potential – Results of Simulations

In the various parts of my work I use abbreviations to describe certain functional positions in the instrument or pipe. If you find DB, it’s a Druckbauch = Pressure Antinode, DK is a Druckknoten = Pressure Node.

XM means "nearest an acoustic center". Pot. for possible change or max. change,
N stands for node or zero crossing or change equal to 0, PN stands for pitch node,
Shared XM-PN thus describes the frequency-dependent position of the pitch change zero crossing in the acoustic center of the QWR = quater wave resonator = closed-open pipe or brass instrument.

All such nodes and potential are searched for and found using disturbances. Disturbances are local pipe enlargements or pipe constrictions that correspond to a cross-sectional area change factor $q0^2$. All disturbances have a length, the arithmetic center of this disturbance length describes the local center of the disturbance = perturbation. Evaluations compared to the undisturbed pipe show differences at discrete positions of the respective disturbance center(s), connected to a curve thus result in nodes (zero crossings).

Two variable quantities are observed: global frequency changes = "pitch" pot. of the resonance frequencies, as well as input impedance magnitude changes |Z|in (Modulus) at the closed end due to perturbations.

Pitch = frequency or tuning (deviation) has a global effect = radiated frequencies at input impedance maxima (peaks). Pitch potential has hardly any position potential in the closed-open cylinder, local perturbations result in maximum potential at pressure antinodes as well as at pressure nodes. If cross-sectional area changes are inversely proportional to each other, it can be determined that frequency increases are smaller by a factor of $1/q0^2$ than frequency depressions, both at pressure nodes and at pressure antinodes.

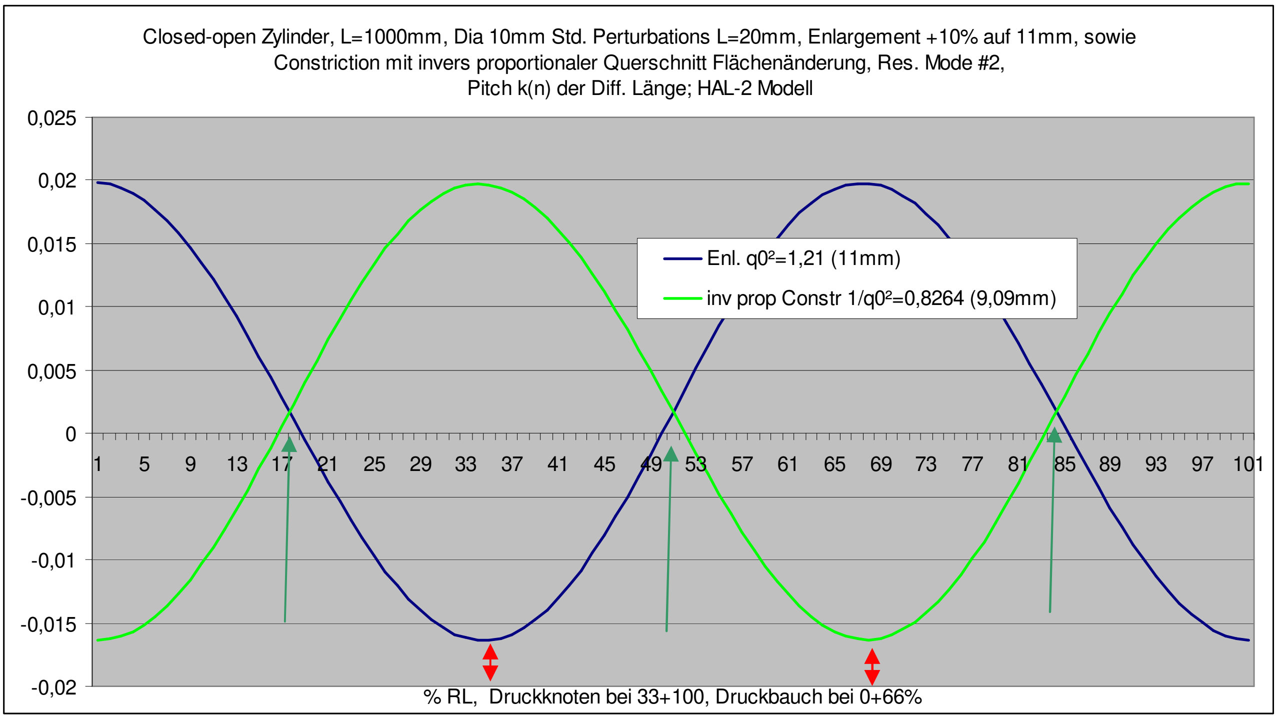
At every opportunity it is claimed that a cylindrical tube represents the simplest geometry, is scientifically completely understood acoustically and can be perfectly described. Related to pitch changes, simulations, cross section calc and measured values do not deviate much, if the perturbations are comparable small.

It are the inevitably arising magnitude changes, which are very different to that found by measurements. It is also the “stepmotherly existence” of those changes. In most publications they are omitted or not discussed in detail or at all, because it seems to be the very difficult part of the game. And as will be pointed out, they are not easy to understand at first sight.

All acoustical simulation software is based on physical laws, and in this case also derived from electromagnetic waves and their behaviour on coaxial lines TMM, and so on. Its my conviction, that there are missing parts in this underlaying math. People who found such physical laws had not the possibility at their livetime to countercheck if the theories will hold in practical tests with low tolerances, and many (all other) hold these theories as “carved in stone”.

So I would be very happy, if anyone has the possibility to countercheck my measurements. Therefore I try to describe each setting to the smallest detail and try to figure out how the measurements deviate from simulations. I am in joyful anticipation that someone can find the missing parts and help in the developing of more usefull results.

Local Cross Section Area Factor q0² at Pressure Antinodes ist prop. to wavelenght:



y-Axis: +k: Diff acoustical extralenght =X+ -k = Diff. acoustical minderlenght = X-
+values mean here lower resonant frequency, -values mean higher resonant frequency.

Every disturbance - regardless of whether it is a local enlargement or constriction - causes additional losses to existing losses and these losses have a global, slightly lowering effect on resonance frequencies.
Or this can also be explained with the "lowering excess potential".
The positions of the zero crossings found using constrictions therefore differ from the zero crossings caused by enlargements. The "shared" pitch node position lies between the two zero crossings found on one side and describes a zero crossing with infinitesimal small changes = referred to as the origin of the pitch nodes.

Here, the change in cross-section is primarily responsible for the deviations, the additional length potential of the disturbance only reinforces the effect. This results in a pitch offset downwards (wave length upwards) for all shared pitch nodes = lowering tuning of the resonance frequencies due to perturbations (any sort).

Input Impedance Peak Magnitude Change by local Perturbations – ART Simulation results: *(Open Wind and measured results are different, especially at low modes!)*

XM-IN1 stands for impedance node and number 1 for the pipe section closed end to the pipe center, XM-IN2 thus the closest input impedance magnitude zero crossing after the center towards the open end.

However, this XM center must be seen as the acoustic center, which varies with frequency and is therefore only at ~50% of the pipe length for a closed-open cylinder, but then for all resonance modes.

~50% because even a closed-open cylinder already shows inharmonicity (losses, correction open end).

In closed-open cylinders, this acoustic center is also the "shared" XM-Pitch Node position of resonances = the (input magnitude peaks) and is found at

1st pressure antinode at the closed end + ({(Mode# *2) - 1) } * 1/8 wavelength peak frequency)

In closed-open cylinders, the 1st pressure antinode is at position 0 at the closed end and XM-PN is therefore at ~50% of the tube length (all resonance modes). I usually define the positions as the distance from the closed "effective" end. Here therefore, at 0 + ~0.5 * RL (tube length).

Phys. Position acoustic center instrument - ({(Mode# *2) - 1) } * 1/8 wavelength peak frequency) therefore provides the 1st pressure antinode of each resonance frequency, which is useful for pitch changes, as well as for the starting positions of the magnitude node positions that are located at pressure nodes, because the magnitude changes that occur in position and actual zero crossings near pressure antinodes are unfortunately complex. Magnitude potential and nodes do not correlate with pressure antinode positions and thus not with wavelengths.

It was found that in the simulation with plane wavefronts on the closed-open cylinder, half of the magnitude zero crossings occur at pressure nodes, i.e. at a distance of 1/2 WL and at positions of pressure nodes there are also magnitude zero crossings, with the exception of the last pressure node at the open end. The 1st pressure node after the closed end corresponds to ¼ wavelength or 2 * 1/8 WL.

So it can be said that pressure nodes - and thus even-numbered magnitude nodes - are found at a distance of odd-numbered ¼ wavelengths from the closed end: (+1, +3), +5), etc.

Total number of ¼ wavelengths = (Mode# *2)-1
Total number of pressure nodes = Mode# Total number of pressure nodes = Mode#
For magnitude nodes, the last pressure node at the open end no longer applies:
Total number (even #) magnitude nodes that are located at pressure nodes: Mode # -1
Total number (odd #) magnitude nodes that are located near pressure nodes = Mode#
Total number of magnitude nodes = (Mode# *2), with the last magnitude node appearing strongly offset towards the closed end (ART simulation).

It can therefore be defined that the following XM-IN magnitude nodes can be determined (ART:)
RL = Tube length, DK = Pressure Node, DB = Pressure Antinode. WL = wave lenght

Based on ART Plane Wave Simulation they would occur at:

Mode #1 (1/1) 0+ ¼ WL = 1. DK none *(DB 0%) -6% RL*
Mode #2 (1/3) 1. DK at 33,3% tube lenght = XM-IN1 *(DB 66,6%) +2,33% RL*
Mode #3 (1/5) 1. DK at 20,0% tube lenght, *DB40%,+0,5%RL* 2. DK bei 60,0% = XM-IN2 *DB80% +1,5%*
Mode #4 (1/7) 1. DK at 14,28%, 2. DK 42,85% = XM-IN1 (DB 57,1%) *DB85,7% +1,2%*
Mode #5 (1/9) 1. DK at 11,11%, ... 3. DK bei 55,5% = XM-IN2 *DB88,8%+1,1%*
Mode #6 (1/11) 1. DK at 9,09%, ... 3. DK 45,45% = XM-IN1 (DB 54,54%)
Mode #7 (1/13) 1. DK at 7,69% .... 4. DK bei 53,8% = XM-IN2
Mode #8 (1/15) 1. DK at 6,66% ... 4. DK 46,66% = XM-IN1 (DB 53,3%)
Mode #9 (1/17) 1. DK at 5,88% .... 5. DK bei 52,9% =XM-IN2
Mode#10 (1/19)1. DK at 5,23% ... 5. DK 47,36% = XM-IN1 (DB 52,6%) and so on..

For the closed-open cylinder, the ART Plane Wave Simulation shows that Magn. Nodes
for odd # Modes XM-IN1 after a Pressure Antinode occur, XM-IN2 = exactly at Pressure Node
für even # Modes XM-IN1 exactly at Pressure Nodes occur, XM-IN2 = after a Pressure Antinode

Near pressure antinodes, magnitude zero crossings are always offset towards the open end, which means that at ascending pressure antinodes the distance to these magnitude nodes is slightly longer than 1/4 WL, and at descending pressure antinodes it is slightly shorter than 1/4 WL.

However, in practice this problem only occurs with Mode #1 - Mode #2, with the remaining modes the differences are negligible (XM-IN1 Mode 3) or XM IN2 is no longer close to the last pressure antinode. However, the effects of the last ¼ wavelength = from the last pressure antinode still exist.

All perturbations result in inverse effects on rising pressure antinode flanks and these are stronger than the geometric mean Xg Pot., provided that constrictions are inversely proportional to extensions and thus have a comparable Xg Pot. On falling pressure antinode flanks, the magnitude potential is generally not inverse and is lower than the Xg potential. At pressure nodes (except open end), magnitude nodes are obviously fixed, so subsequent zero crossings shift behind the pressure antinode maxima positions, since inverse excess potential still prevails here. Mode #1 has only 1 falling pressure antinode flank in the closed-open cylinder, and here too the zero crossing shifts behind the pressure antinode flank.

At 50% pipe length, even modes are on rising pressure antinode flanks (inverse stronger Magn. Pot.)
odd modes on falling .... weaker Magn. Pot. |Z|In

Inverse magnitude pot. means magnitude increase with enlargement, reduction with constriction,
so “inverse behaviour” is opposite to changes that occur with a complete bore size change.

The max. magnitude pot is always closer to the previous pressure node, = <-- closer to the closed end, this is largely caused by the falling position potential and results from this.
The distance from the pressure node (and its magnitude nodes) to the next position max. magnitude potential is therefore smaller than the arithmetic mean of a 1/8 WL, = larger gradient; but since the potential is also inverse and stronger, the gradient is increased again. Since the following magnitude node only occurs after the pressure antinode maximum, the falling flank of the magnitude pot is slightly longer, lower negative gradient, since it is also not inverse, therefore another lower negative gradient. (Very pronounced: Mode #2).

In addition, Z-peak magnitude changes at the closed end have a position potential of the perturbation based on the distance from the closed end, or better a potential based on the acoustically effective open end, which is related to the number and numbering of the ¼ wavelengths (WL), or must be divided into an inverse and a non-inverse behavior. Peak magnitude nodes due to local perturbations near pressure antinodes result in positions that deviate more and more towards the last ¼ wavelength before the open end, but again in a very systematic way.

For the closed-open cylinder, one can say that the change potential - now difference +/-X due to cross-sectional area changes in the acoustically effective center is $(q0^2-1)/q0$ = the geometric mean from which constrictions and enlargements deviate more or less, also depending on whether there is an inverse or non-inverse change potential due to the perturbation. This is again determined by odd and even mode numbers. The actually effective potential depends in turn on a sine function that describes the perturbation length as ratio to ¼ wavelength of the mode, low modes therefore have an above-average change potential than the length ratio indicates.

Input Impedance Peak Magnitude Change due to local perturbations –
OpenWind (OW): Results are different to ART ans measured Result, giving these answers:

Now, the simulation with Openwind comes to a different result.
The differences are so serious that it largely turns the above statements on their head.
I have described this in detail, but the differences to ART are briefly summarized as follows:

Magnitude nodes now appear in front of pressure nodes, but exactly at determined pressure antinodes.
The magnitude potential upwards corresponds almost to Xg, downwards it is stronger in the case of constrictions and weaker in the case of expansions than Xg.

The OpenWind simulation shows that the closed-open cylinder Magn. Nodes
for odd # Modes XM-IN1 exactly at Pressure Antinodes occur, XM-IN2 = before Pressure Nodes
für even # Modes XM-IN1 before Pressure Nodes occur, XM-IN2 = exacly at Pressure Antinode

Another major difference in the simulation is that with ART there is no zero offset of the magnitudes, i.e. zero crossings are always at 0% magn. potential when constrictions and enlargements are superimposed. With Open Wind there is a zero offset, but only with very strong constrictions.

The comprehensive evaluations and attempts to derive formulas or approximations from them can be found in Sideletter #2 + #3 (ART) and Sideletter #4 (Openwind).

In all measurements to date, however, a downward offset was found due to constrictions, which has a significant impact on magnitude node positions and potential, which is shifted downwards as a result, sometimes so that only one-sided pot (downwards) is produced before the open end, i.e. when the offset down is stronger than the magnitude potential up. (Same is true with strong enlargements; offset up).

Input Impedance Peak Magnitude Change due to local Perturbations – physical Measurements:

The following summarizes the results of measurements that were carried out repeatedly in March 2024. The measuring object is a cylindrical tube with an inner diameter of 11.0 mm and a length of 1000 mm. The tube has a wall thickness of 0.5 mm and is made of nickel silver. The measurements were carried out on different days, the room temperatures were in the range of 21 - 23 degrees,
Temperature fluctuations between reference measurements and perturbations were never greater than 0.4 degrees, usually less.

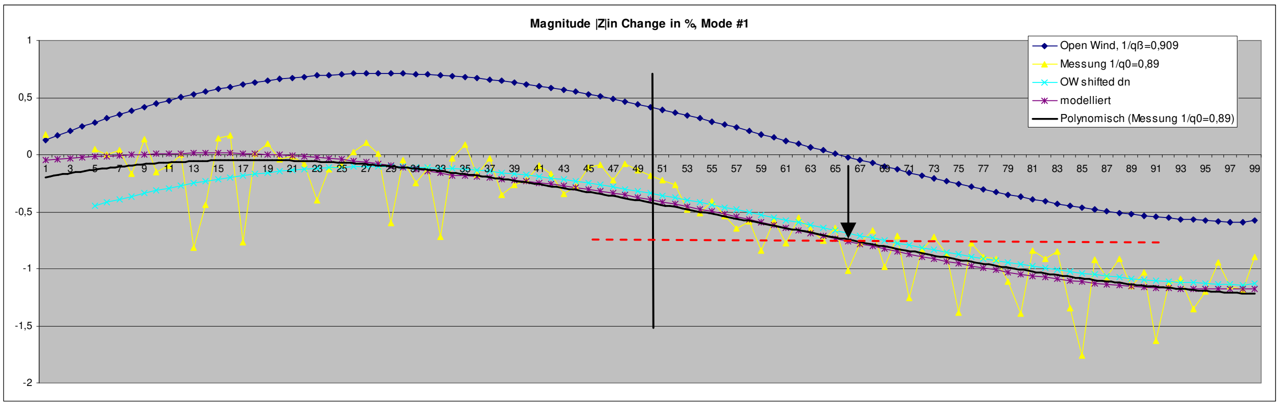
Since physical measurements with the self-made measuring head always produce outliers and the measured excitation signal changes slightly just by screwing on the measuring object, the measurements were averaged. Usually there were 5 individual measurements of the reference tube, the arithmetic mean of which was then determined as a reference, then 5 individual measurements with the respective perturbation and the mean of this was taken as the measurement result. Since measurements with sleeves produce the most (positioning) errors, bolts were also used as constrictions, but for the expansion tests, only a 12mm "gap" was available, centered at 50% of the tube length.

Since the 7mm bolt has a length of 22mm, this length was also used for the enlargement or "gap" 12.0mm diameter and a sleeve with a diameter of 10mm. Only the 5mm bolt has a shorter length: exactly 18.5mm.

In addition to complete runs with each center position per 1% of pipe length = every cm in the pipe with the bolts, the 50% center position was used for the remaining tests, as it has already become clear that this position has very good significance - especially within the higher modes.
It must also be said that measurements of mode #1 at around 87 Hz are not reliable, and mode #1 manages to tunnel back through the capillary of the measuring head, so the flow is not zero at the closed end.

Nevertheless, I will start with this "very unstable" mode to illustrate the situation on the last ¼ wavelength in the pipe, the measurement results with a 5mm bolt, which results in an area difference equal to a sleeve with 9.8mm and 1/q0= 0.89 and is therefore somewhat stronger than the simulations with 10mm = 1/q0= 0.909 constriction.

The OW simulation results were further adjusted: Xg bolt 0.232 / Xg sleeve 0.1909 = factor 1.215 by which the simulation values are too weak; on the other hand, the perturbation length pot is too high by 2/1.8% = factor 1.1, giving OW Sim *1.215/1.11 = OW Simulation * 1.0945 = as the OW comparison values.
(The overview measurements at each single tube position were not averaged, only one run was carried out.)



Bolzen 5mm: turquoise =OW adjusted/q0² and ½ *q0²% shifted down. (higher Modes 1*q0² % shifted down)

With the bolt of 5mm, the magnitude change potential in % within measurements is 100*Xg/1 down and 100* Xg/q0² - offset ~q0² up. With open wind, the pot up is ~ 100*Xg.

The formula (OW Result / q0²) -q0² therefore provides approximately the measurement results found.
At mode #1 however, the offset down is only about ½ as large and corresponds to the OW = Xg pot up.
The offset down through the bolt is approximately the max. possible magn. potential up, so there is only an input magnitude reduction - so it runs completely below zero and therefore does not give a magnitude node, i.e. with constrictions in the first half of the pipe, no increase is possible, as the measurements show!

It should be noted that the frequency changes in the simulation and measurement produce almost identical results, so only the larger differences in magnitude changes are listed here.

However, when measuring sleeves with q0<1.12, the measured pot down is Xg/q0 and this simple conversion formula is not longer suitable. It demonstrates also, that a non symmetrical change has a much higher impact on the impedance changes!

Overview, over whole tubelenght positions, OW vs. Measurements, Bolt 5mm and 7mm, Sleeve 10mm:

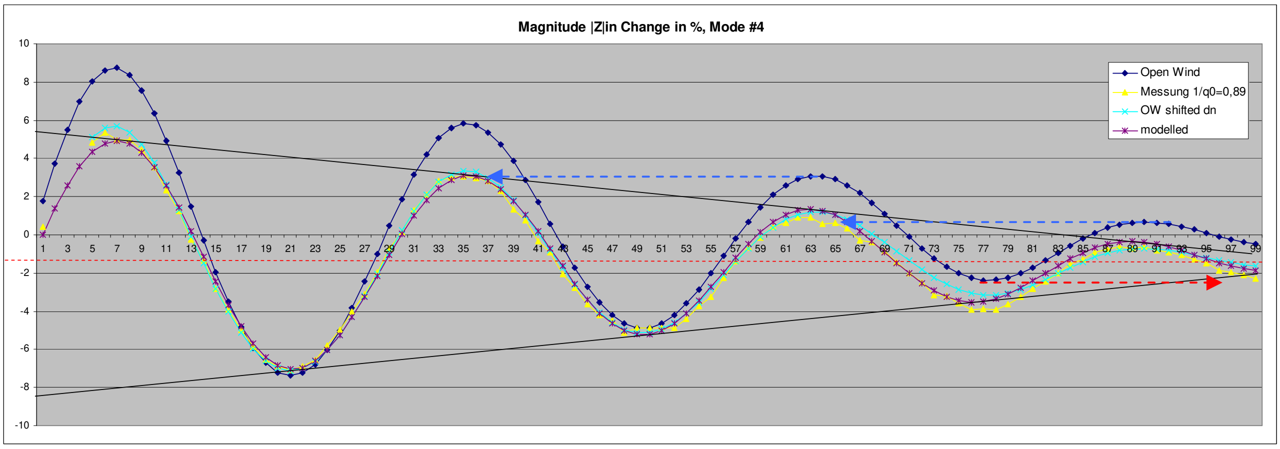
I must now emphasize that every mode in the last ¼ wavelength before the open end behaves the same, but measurements show that higher modes show more offset dn than mode #1. Mode #4 (inverse behavior at 50% RL) and mode #5, as well as mode #9 are shown as examples.

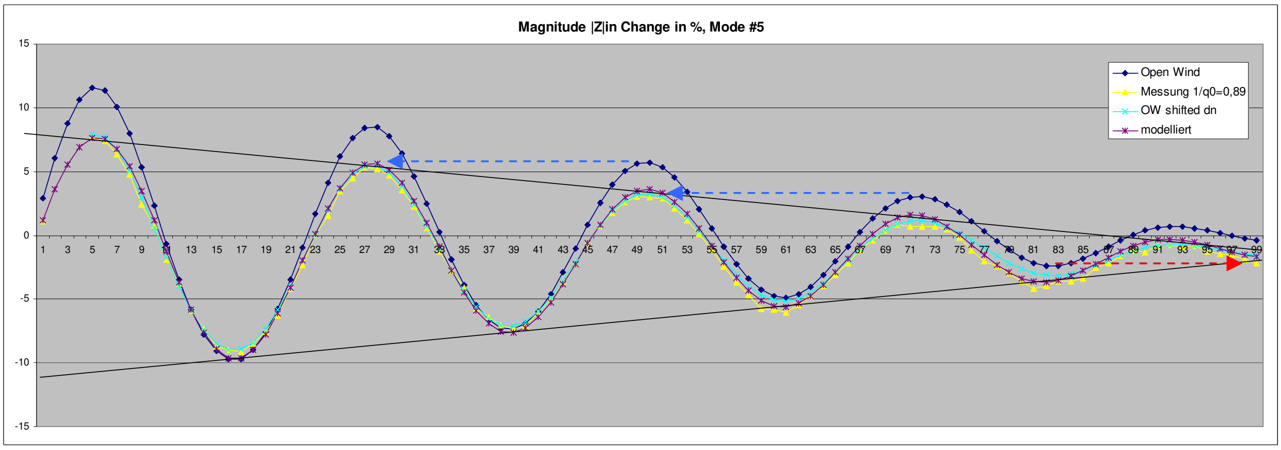
5mm bolt in 11mm tube, corresponds to a sleeve Dia = 9.797 mm 1/q0 = 0.89 q0=1.1226 PL=0.18%
The existing OW simulation data is slightly weaker and has been adjusted.

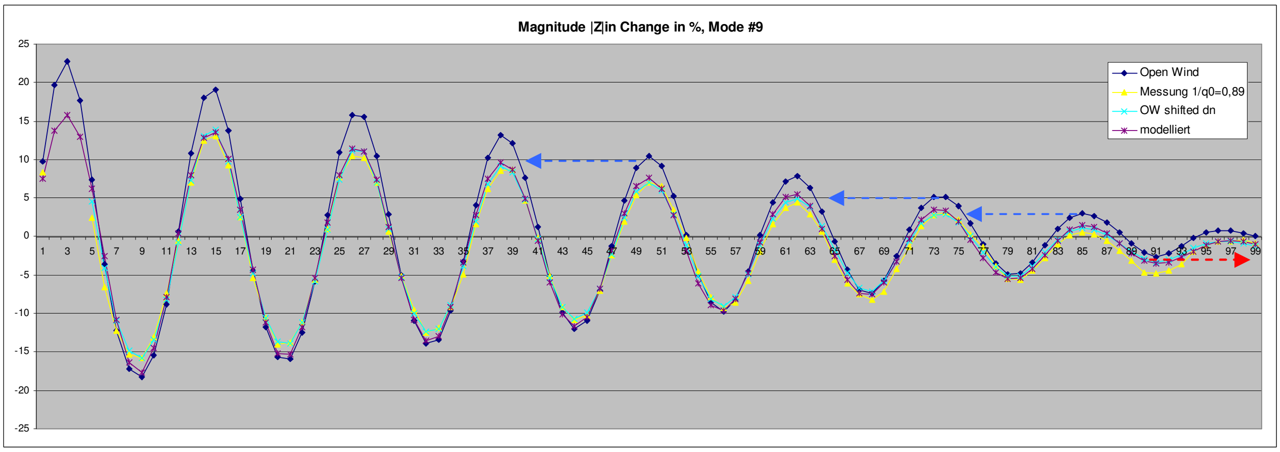
1/q0 = 0.909 q0=1.10 PL=0.20%, gives a factor *1.0945 by which the OW values are here adjusted.

Dashed: The open wind simulation results in a magnitude pot. up that occurs in the measurements exactly ½ wavelength closer to the closed end, except for the 1st pot at the closed end.
With 3/8 WL Pot. dn it is ½ WL closer = to the open end = end pot; Both only apply to bolts 5 and 7mm!

Bolt 5mm; turquoise: OW adj. Magn. % Pot / q0² 1,26 and additionally -1,26% Offset (q0²) down
Mode 2 is only insufficiently corrected with this formula (too much start pot, too little end pot.)

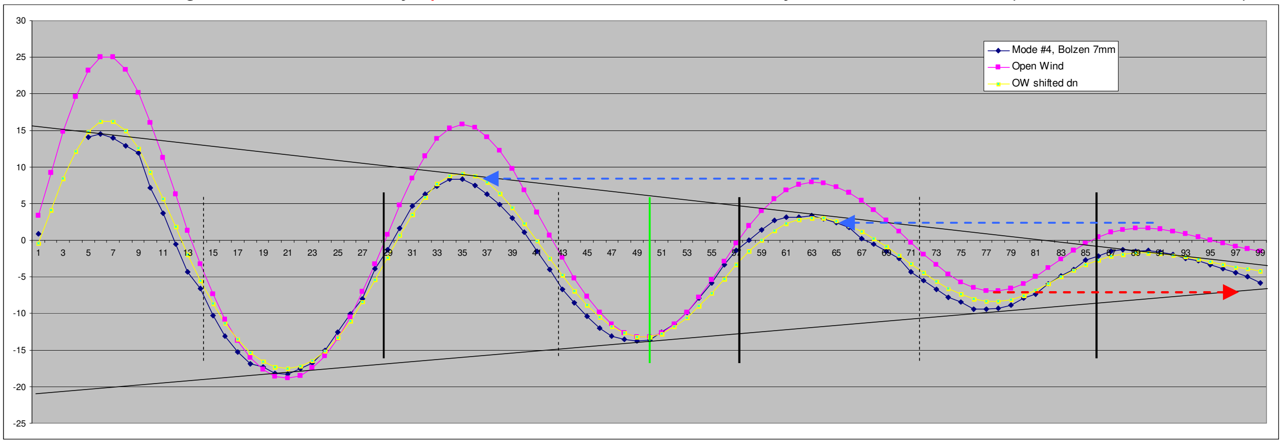


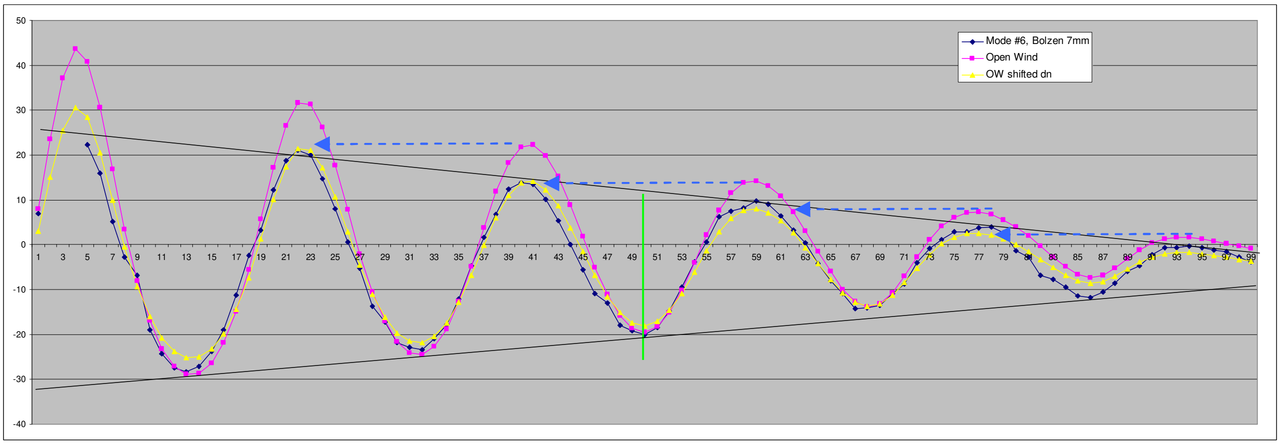




Bolt 7mm in 11mm Tube equals a sleeve with inner diamerter = 8,45 mm 1/q0 = 0,768 q0=1,300 Xg=0,524
The existing Openwind simulation is somewhat stronger here:8,25 mm   1/q0 = 0,750 q0=1,333 Xg=0,578
Xg 0,578/0,524 = Factor 1,1 * the simulation data in the graphics and calculations are therefore to weak.

With bolt 7mm, the required factor from OW simulation to measurement is only 1/q0, = /1.3 but the offset down is now already around -3%.
Yellow: OW Magn. Pot. in % / only q0 1,3 but additional now heavy -3% Offset down (*no calc base, rated*)



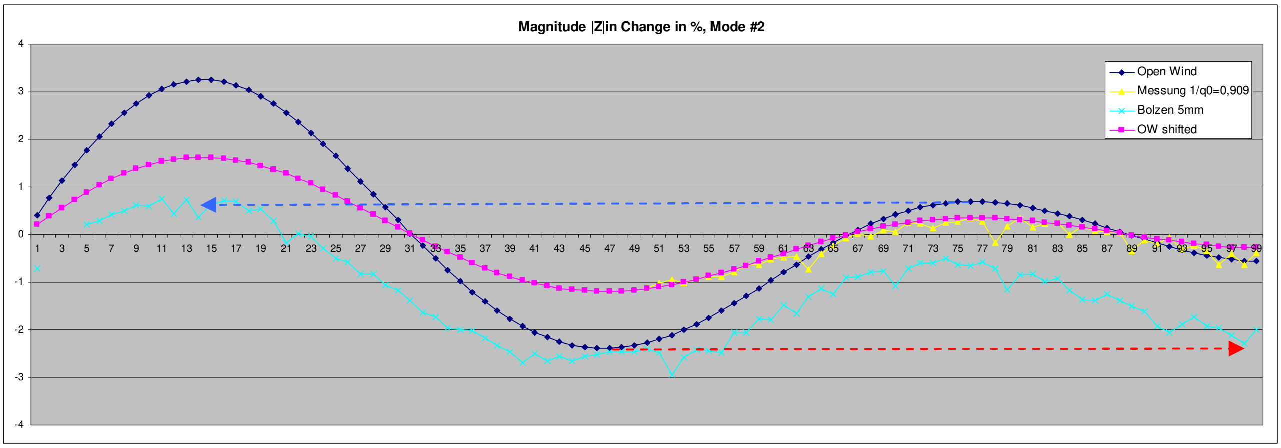


With bolt 7mm there is already a small vertical offset too, which further distorts the results.

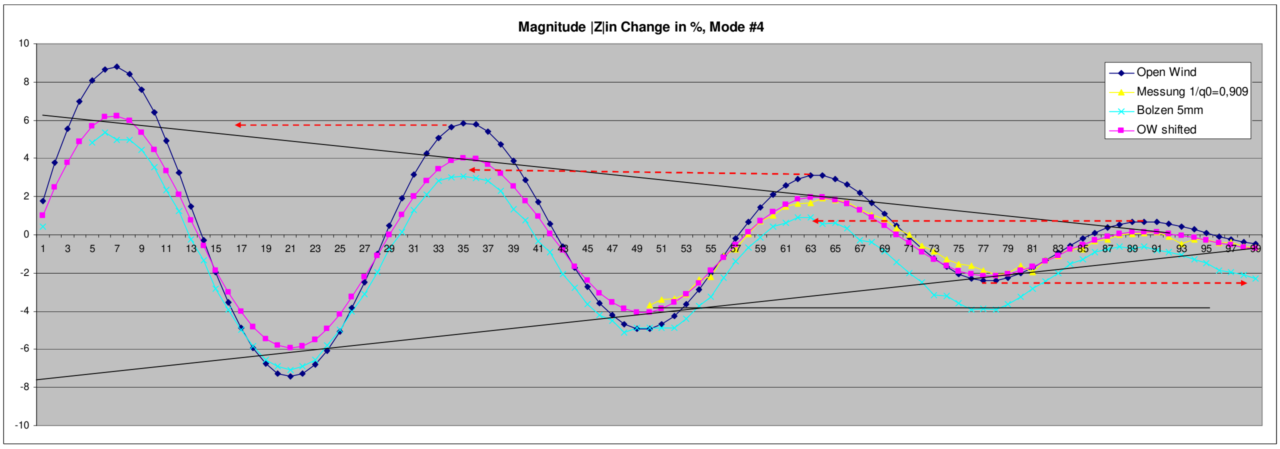
There is also a measuring series for the **10mm sleeve**, but this only covers the last half of the pipe.

OpenWind Data is with 1/q0= 0,909 und PL = 2% RL available, but the measurements have 2,2% PL = 1,1 more length pot., so the Openwind results are adjusted for comparision by Factor *1,1.

For a 10mm sleeve in an 11mm tube, the necessary correction factor for Openwind is basically 1/q0³ = /1.331, but for Mode 2 it is /2 and Mode 3 it is /1.5. These two modes then have an offset = 0 dn, for higher modes the offset dn increases - which now starts low, Mode 4 ~ -q0/3 = -0.3663, rising to -q0^3 = -1.331 for Mode 9. Lower modes are therefore changed much less.



Mode 2: When measuring mode #2, only half the change potential is reached and there is de facto no offset (dn). Bolt 5mm is included for comparison purposes. Since there is no other inverse pot dn except at ~ 50% RL, the exact course (angle) of the envelope curve dn is not important.



Clearly visible: The potential difference between OW and measurement no longer corresponds to ½ WL position difference, the offset and thus the end point are much smaller. The potential increase per ½ wavelength is almost constant here ~ +/-2% = per ¼ WL ~ 1%, per 1/8 WL ~ 0.5%.

However, you will find (only at mode 4 exactly):
1. n. inv. Pot up = same value following inv. Pot dn (after ¼ WL);
from the closed end: +6, -6, +4, -4, +2, -2, +0,
gives a 3/8 WL Pot of -2%; a 1/8 Pot up of ~0%, and an endpot of ~ -0.5%, the endpot is only ~ ¼ Pot compared to the bolt. In higher modes, the endpot becomes stronger due to the increasing offset, the same +/- change at the closed end changes slightly, at the open end inv. Pot. dn then predominates.

3/8 Pot dn is almost identical to the OW simulation from mode #4 onwards.

Approximation of Cross Section Area Changes to changes found by measurement:

So far, every simulation has produced changes in magnitudes that are far too high. While these may be understandable under laboratory conditions with special hardware (has anything like this ever been done?), simulations are unfortunately only useful for me if they produce results that I can achieve (and check) in practice with the equipment available to me. A better method must therefore be found to adjust simulation data to measurable data.

Therefore, the simulation should now correspond exactly to the dimension and perturbation. The simulations were therefore created with Open Wind centered at the position 50% of the pipe length and several measurements were carried out.

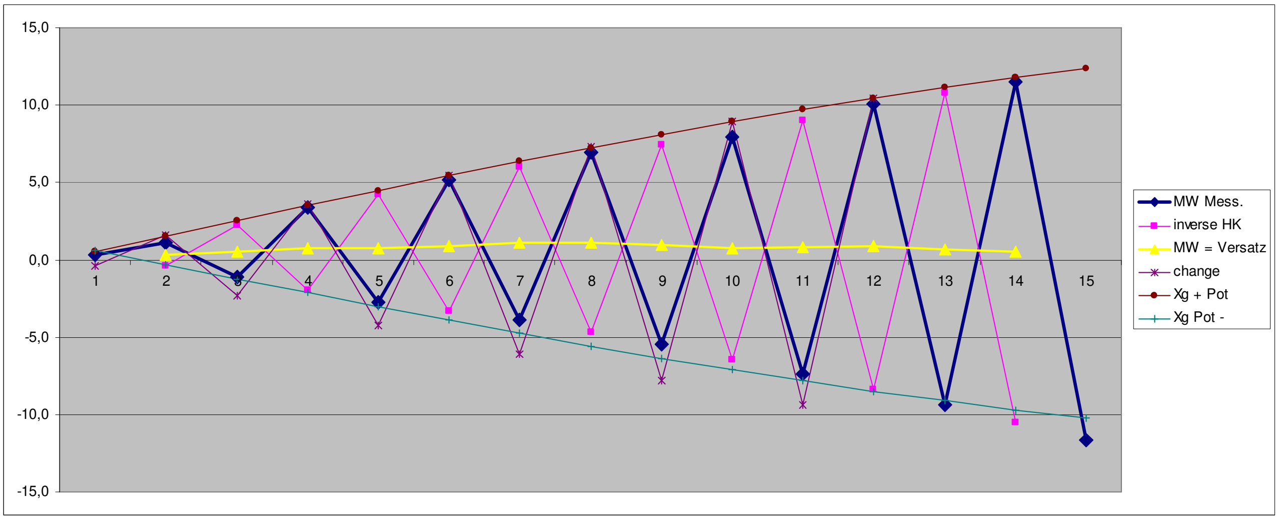
Above all, enlargements must also deviate (significantly) from the simulation results.

In several parts I have pointed out that perturbations can only be compared if the cross-sectional changes are inversely proportional to each other. This is the case without any restriction for frequency changes, but only to a limited extent for magnitudes, as it seams.

This is usually not easy to do with sleeves on brass instruments. Expansions - e.g. tuning slide gaps - are determined by the wall thickness, and constrictions to a certain extent as well. The wall thickness of a sleeve has a lower usable minimum and in addition, prefabricated standard tubes are often available. On the other hand, the results are of course not limited to sleeves. Any local change in bore size must be considered, also major changes such as existing dents and of much more interest the existing prominent constriction in a cup mouthpiece.

Enlargements:

Results of measurements vs Open Wind simulation, cylinder L 1000mm, Dia 11mm
Enlargement centered at 50% Pipe lenght, perturbation lenght 22mm, inner Dia 12mm q0=1,0909



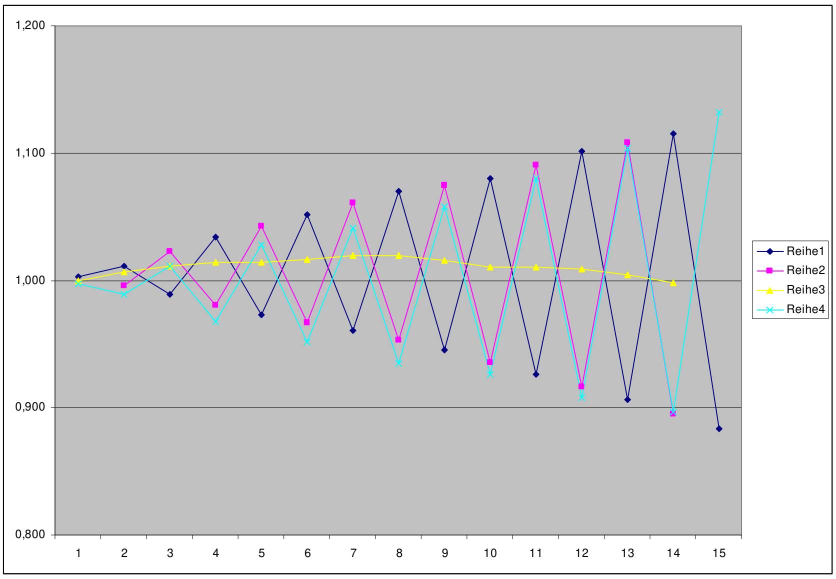
The calculated Xg Pot up 0,174*100 in % (+Envelope) is here with the factor $1/q0^2$ = * 0,84 already weaker ploted.

In first approximation, Enlargements:
inverse Pot up with Enlargement, measured: xg/q0 /q0 = xc /q0 = **$xg / q0^2$**. bzw. $xe/q0^3$
Magn. Pot up equals in OW simulation nearly Xg, Measurement equals Openwind result Pot up = $Xg / q0^2$.

XG Pot- down *100 in % is here factor $1/q0^3$ = * 0,77 weaker ploted (-Envelope) = Xe / q0^4
and is additional ~ +1,1 % shifted upwards

However, the lower non-inverse change is not a straight line but a curve;
the maximum reduced potential is approximately where PL to ¼ WL Ratio is 0.33; above and less below.
*Change = Openwind Simulation Data * 0.84 --> the additional necessary upward offset is still missing here.*

The measured potential up is a factor of $q0^2$ = 1.19 lower than the calculated XG potential at 50% pipe length.
the non-inv. pot. down is a factor of 1/q0 less than pot up, and an additional ~ -1.1% less pot. dn



blue: Measurement, Magn. Change Factor, Enlargement
pink: arithmetic mean (average, for envelope curve)
yellow: blue*pink = max 1,02 shows the overpot to the raising behaviour (with enlargements)
turquois: this would be invers prop. values to the measured values: in the case of enlargements, high modes show inverse prop. behavior, low modes do not (the opposite is the case with constrictions)

Measurement results = changes *dy* are inversely prop. to each other with enlargements from mode 13 onwards, i.e. if the initial magnitude is high, less reduction occurs with enlargements, with high modes it is inversely proportional.

Mode 3: inv prop. Pot would be 1,1% – but is 2 time to much (2,2%) = * 2,0 up
Mode 2: inv. pop. Pot would be ~ 1%, but is 0,5 times (-0,5%) = * 0,5 dn in contrast to inv. prop. Pot.
Mode 8: inv prop. Pot would be -6,5% but is only ~0,7 times (-4,7%) = * 0,7 dn in contrast to inv. prop. Pot.
at ~ Mode 14 it is 1,0 times = invers proportional.

Alternative Perturbation lenght Factor for magnitude changes, solution for short perturbations, physical Measurements

The sine factor of the perturbation length to 1/4 wavelength provides suitable values in the simulation, and one finds in the simulation that small perturbation lengths have a higher potential than longer perturbation lengths. This is the case with frequency changes, so a given perturbation length has mostly the same change potential in Cents for all modes.

This means, conversely, that higher modes show less potential with the same perturbation length to pipe length. In general, the potential without the sine function would be odd# * Potential Mode 1, but with the sine function it would be less, since the pot Mode #1 is pi/2* times larger than the perturbation length potential - and ratio to ¼ wavelength: Sin Pot Mode 1 = 2.2% PL to ¼ WL* 1.57 = 3.45%. With higher modes the pot decreases, with Mode #10 it is only 1.46% stronger than the perturbation length potential.

The sine pot, therefore, viewed as an envelope, causes a curve in which the slope decreases increasingly. Without a sine pot, a straight line (constant gradient) results, but less potential.

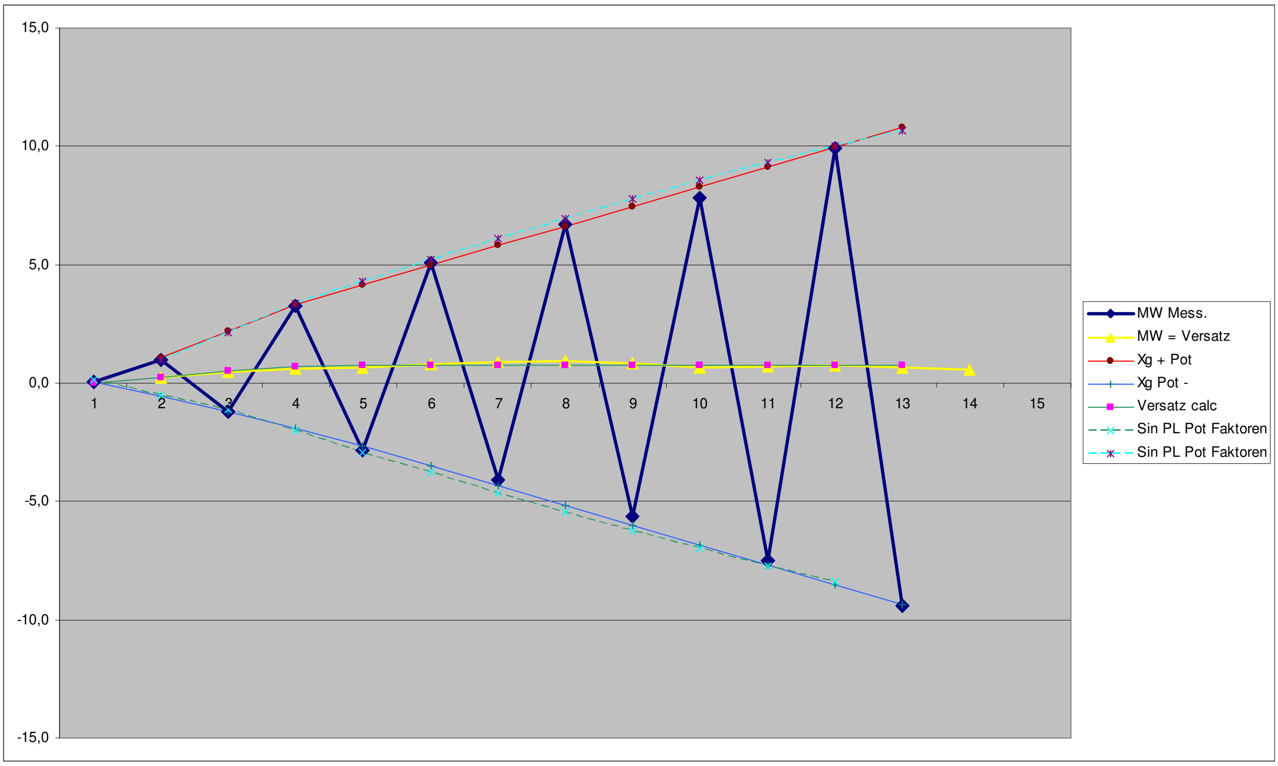
If you look at the previously found envelope curves of the measured values, you can see that this sine potential actually works against it, and it turns out that deep modes show less magnitude change potential in measurements.

On the other hand, it turns out that sleeves and bolts have different effects. Bolts, as objects that change the cross-sectional area in the same way, show different results, especially at low modes, and therefore have to be treated slightly differently.

At the search for better results, the following conversion factors and offset values were found, with individual low modes being specially corrected. All correction factors were chosen so that they are factors based on cross-sectional changes. Factors with sine perturbation length potential (Var. A) and factors with perturbation length potential (Var. B) are obtained, with the latter mostly coming closer to the measured values, but the factors used do not seem entirely sensible at first glance. A factor compared to Xg Pot indicates the slope (angle); a additional correction to this indicates the offset.

Var. B. only works with the selected factors for sleeves within q0 1.07 – 1.14, above that it is too strong!

Enlargement Sleeve 12mm in 11 mm tube, lenght 22mm, tube lenght 1m,
Magnitude Change |Z|in % with perturbation position centered at 50% tube lenght:



Approximation Enlargements (negative sleeves):

In first approximation to Enlargements:

inverses Pot up with Enlargement found by measurement: Sin (PL Pot) * 100 **Xg / q0²**

Pot. dn: Sin (PL Pot) *100 Xg / q0³ - q0² (less dn)

= (pot up / q0) -q0²

More accurate (with small q0):

Var. A (dotted curves): Sin(PL Pot) * 100 * Xg Pot

* Pot. up Factor +1/(q0^2,5) + 0 offset up
* Pot. dn Factor -1/(q0^3) + q0² offset up (gives less pot dn)

additional corrections: Mode 1 Pot dn: + Xg
Mode 2 Pot up: * 2/3
gives new average values Mode 2+3

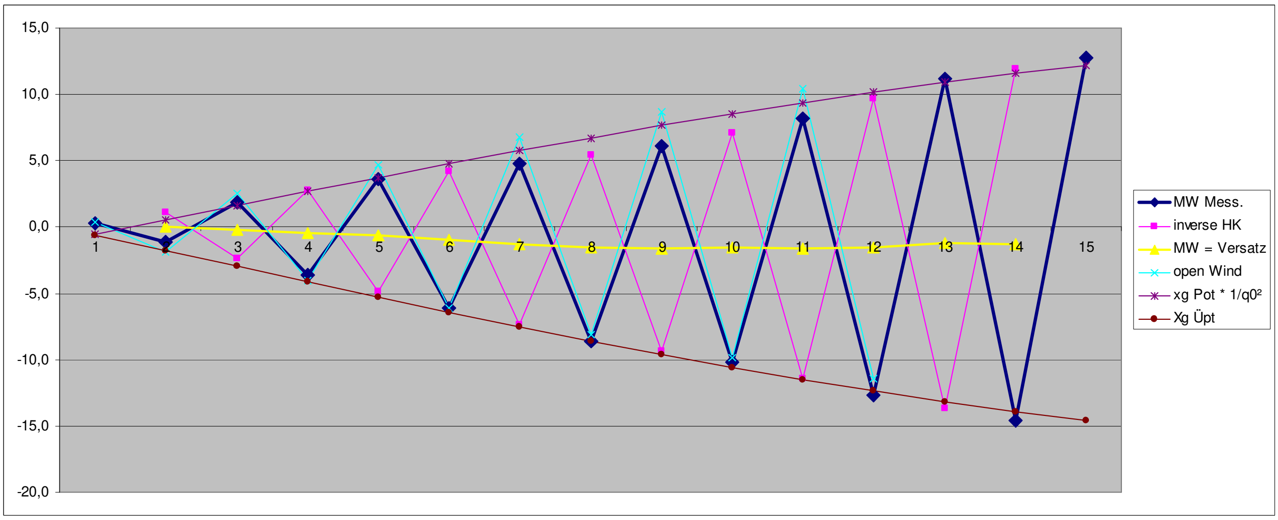
Var. B: (red+blue Curves) PL Pot * 100 * Xg Pot

* Pot. up Factor +q0 + q0/3 offset up
* Pot. dn Faktor -q0 + q0 offset up (gives less Pot dn)

additional corrections: Mode 1 Pot dn: - (1/q0^5)
Mode 2 Pot up: * 2/3
gives new average values Mode 2+3

Constrictions (Sleeves):

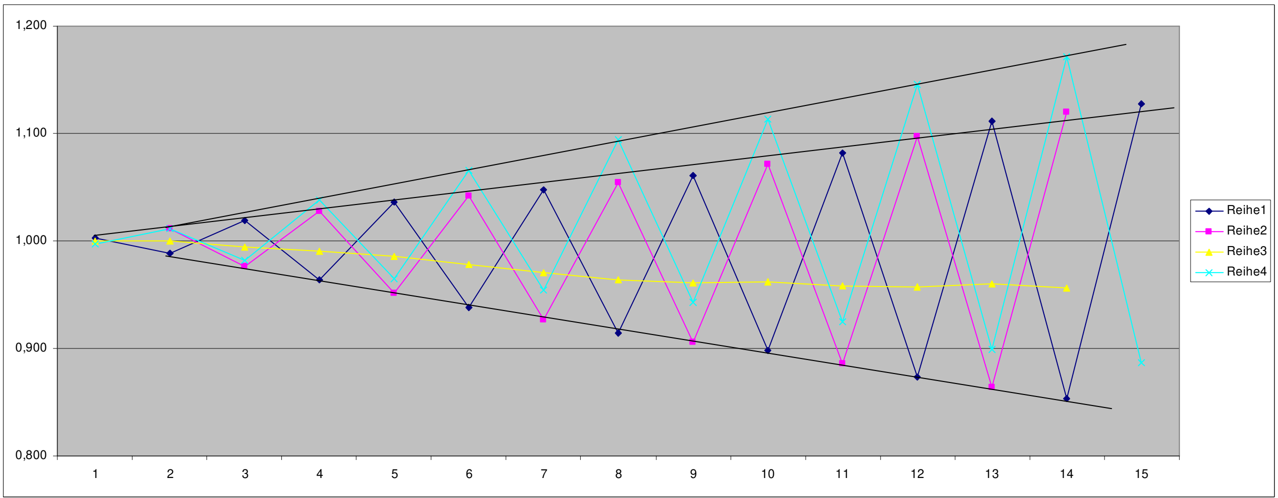
Results of measurements, vs. simulation Open Wind, cylinder L 1000mm, Dia 11mm
Constriction centered at 50% tube lenght, Pertubation lenght=22mm, Dia 10mm 1/q0=0,909



inverse Pot. is with constr. down (even Modes), MW Mess = measured average with constriction 1/q0=0,9090 (sleeve)

In a first approximation:
measured inverse Pot down is ~ Xg * 1/q0 = Xc. *(Open Wind result ploted = * 1/q0² = * 0,8264)*

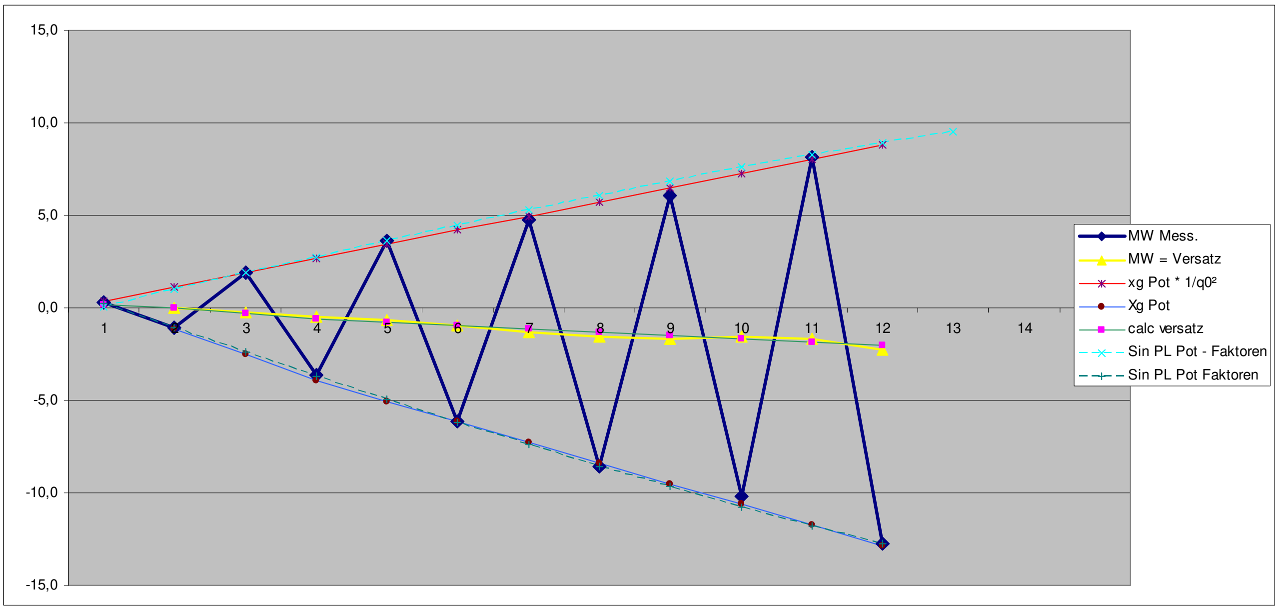
measured non inverse Pot up ~ = Xg * 1/q0² = Xc* 1/q0 and additional –1,19 = q0² % Pot less up.
Here too however, a curve results with Pot up – at ~ Mode 8 the additional offset is higher, but less at the ends.



In the case of constrictions, it can be seen that the changes here are inv. prop at low modes and then deviate greatly, the lowering potential increases strongly with higher modes

blue: measured mang. change factor, due to constriction
pink: average – (for envelop curves)
yellow: blau*rosa = max 1,02 zeigt den Potentialüberschuss in Richtung Erhöhung
turquoise: would be inverse proportional values to measured values,
with constriction, low modes show approximately inversely proportional behavior,
high modes do not, which is the opposite behavior to enlargement (at 50% pipe length).

Constriction, sleeve 10mm in 11 mm tube, PL= 22mm, tube lenght 1m,
Input Impedance Magnitude |Z|in change in % with perturbation centered at 50% tube lenght:



Approximation Constrictions:

In a first approximation:
Inverse pot down is ~ Sin (PL Pot) * 100 Xg * 1/q0
non inverse Pot up is ~ Sin (PL Pot) * 100 Xg * 1/q0² an additional -1,21 % = q0² Pot less up.
= (pot dn / q0) -q0²

More accurate (with small q0):
Var. A (dotted curves): Sin(PL Pot) * 100 * Xg Pot
* Pot. up Factor 1/(q0^4) - (q0/3) offset up (gives less Pot up)
* Pot. dn Factor -1 +(1/q0) offset dn (gives less Pot dn)

Additional corrections: none

Var. B: (red+blue curves) PL Pot * 100 * Xg Pot

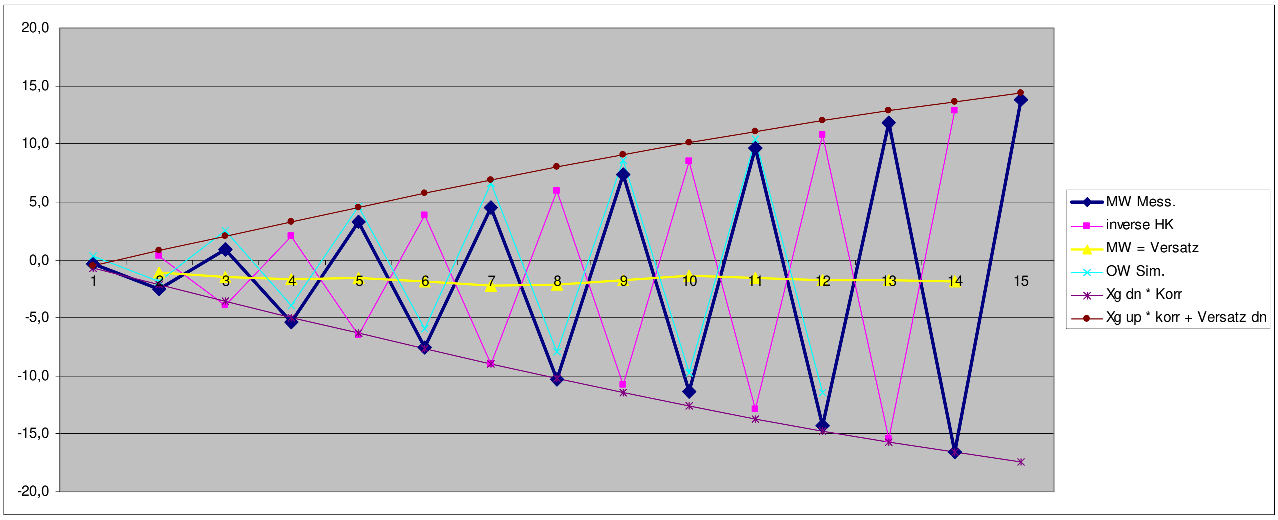
* Pot. up Factor q0 + 0 Versatz up
* Pot. dn Factor -q0^3 + 0 Versatz dn

Additional corrections: Mode 2 Pot dn: * 2/3
gives new average Mode 3 (dn)

Constriction with bolts:

Constriction Bolt 5mm: Cross section area change equals that fo a sleeve with 1/q0= 0,89
So with the Dia 11mm tube a sleev with inner diameter = 9,8mm.

The measured bolt with Dia 5mm and (simulated equiv. sleeve) has a perturbation lenght of 18mm instead of 22mm.
The perturbation length should not play a role for the potential offset down, as long it is smaller << ¼ wave length.



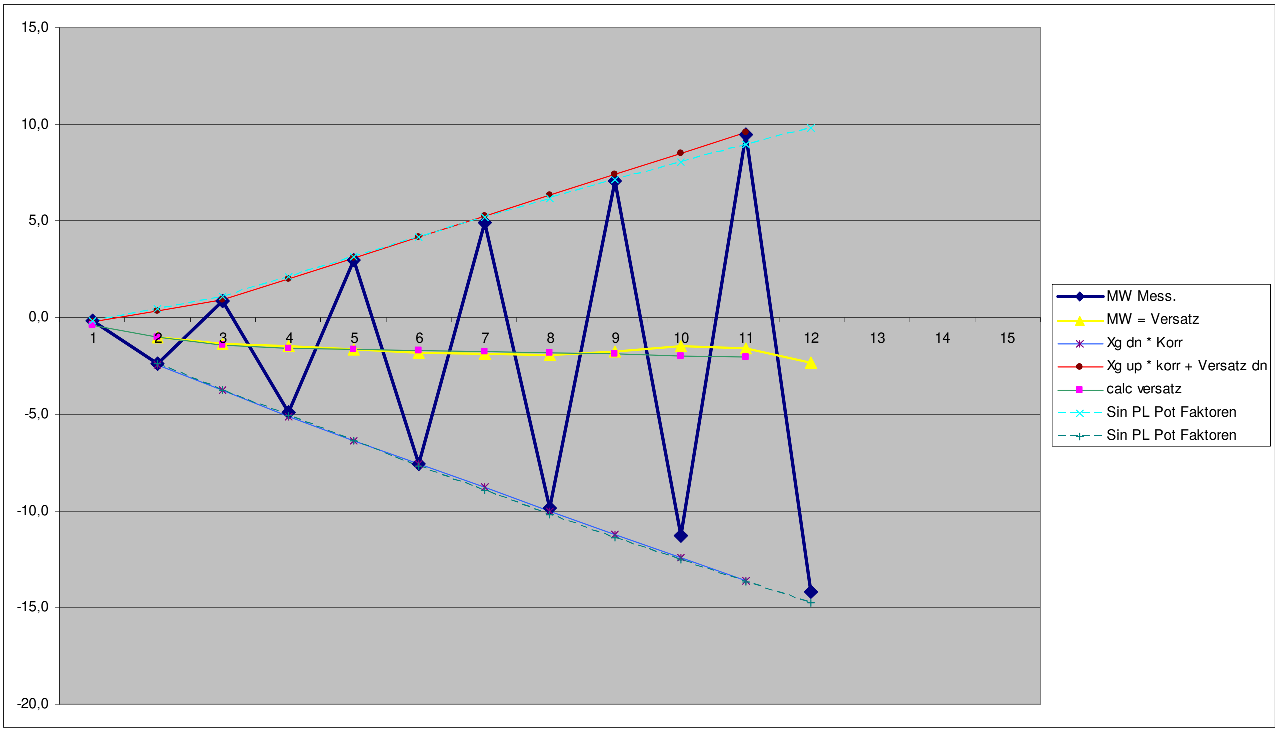
inverse Pot is with constr. down (even modes). *(ploted OW-Sim result = * 1/q0²)*
the measured results are with constriction 1/q0=0,89

In 1st approx.: Inverse Pot down with Bolt is Xg * 1 = Xg
none inverse Pot up = Xg * 1/q0² = Xg * 0,7933 = Xc* 1/q0 bzw. Xc /q0
and is additional about -1,26 q0² % Pot less up.

Here the additional attenuation upwards = Magn. Pot. Offset down becomes almost a constant value

The offset with bolt 5mm is already so strong that mode #1 no longer develops any pot up and #3 almost no pot up.
The same applies to (low) pot at the open end of all modes, i.e. the question of the behavior on the last ¼ WL in the pipe changes, and where "shared" magnitude nodes should occur.

Constriction, Bolt 5mm in the 11mm tube, PL= 18,5mm, Tube length=1m,
Impedance Magnitude |Z|in Change in % with perturbation centered at 50% tube lenght:



In a 1st Approximation:

Inverse Pot down is = sin(PL Pot) *100 Xg * 1
non inverse Pot up = sin(PL Pot) *100 Xg * 1/q0² and add. -1,26 =q0² % Pot less up.

More accurate:

Var. A (dotted curves): Sin(PL Pot) * 100 * Xg Pot
* Pot. up Factor +1/(q0²) - (q0^4) offset up (less Pot up)
* Pot. dn Factor -1 +(-q0/3) offset dn (more Pot dn)

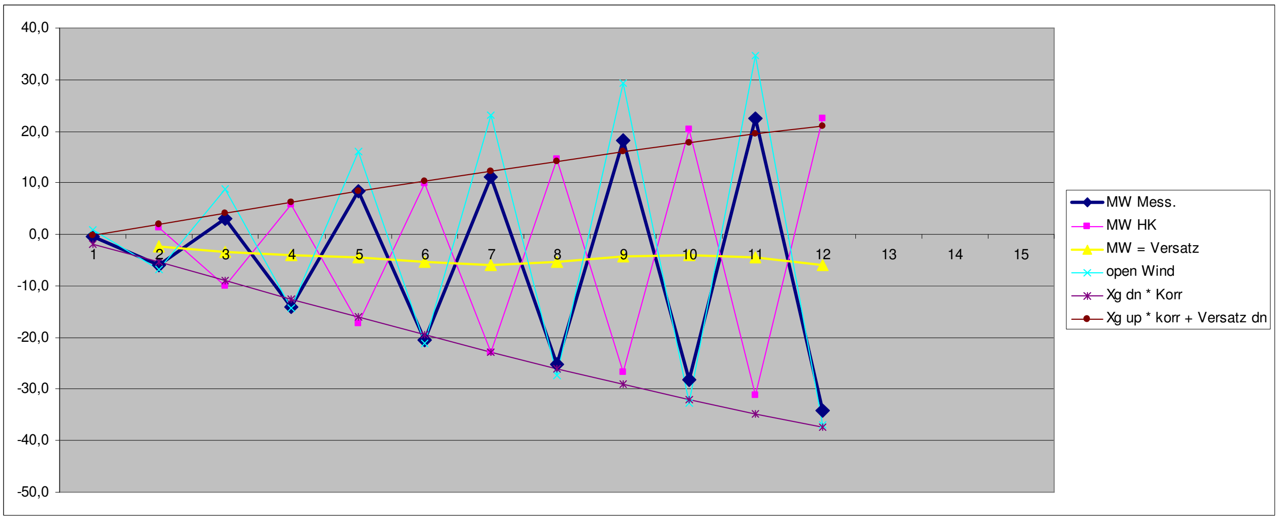
additional corrections: Mode #1: + 1/q0 (more Pot up, bit stays minus)
Mode #2 new average value (up)

Var. B: (red+blue curves) PL Pot * 100 * Xg Pot

* Pot. up Factor +q0^2 - q0^5 offset up (less Pot. up)
* Pot. dn Factor -q0^3 + (-1/q0) offset dn (more Pot. dn)

additional corrections: Mode 1 Pot up: +1,0% Pot. (but stays minus)
Mode 2 Pot dn: * 1/q0 (less Pot dn)
gives new average values Mode 2+3

Bolt 7mm: Cross sectional area change equals to that of a sleeve with 1/q0 = 0,77



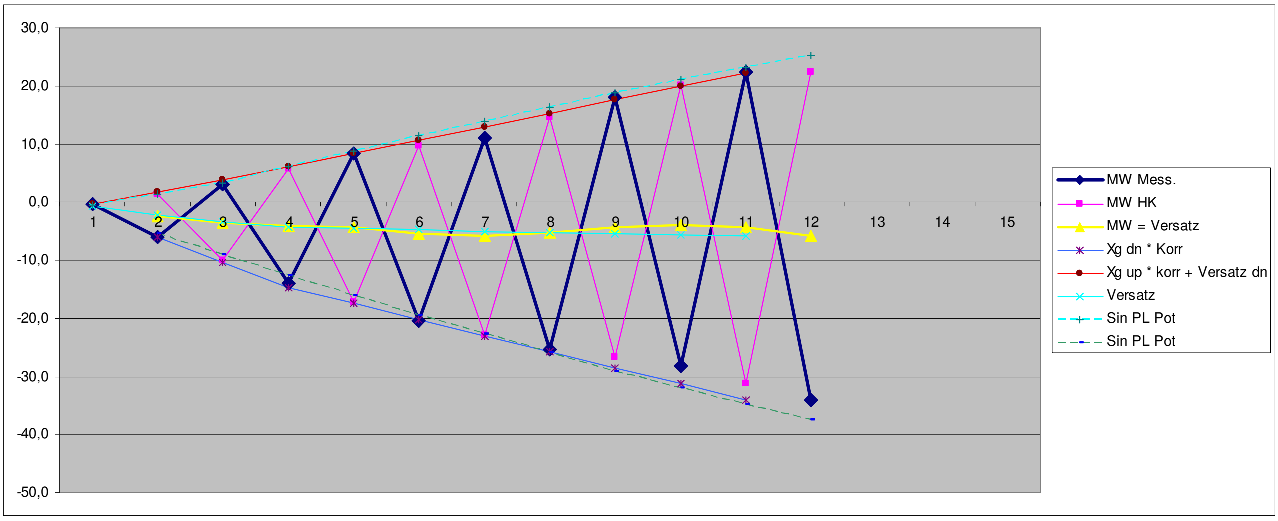
inverse pot is here with constr. down (even Modes). *(OW-Sim. result * 1/q0² = * 0,595 ploted)*
the measured results are with constriction 1/q0=0,77 Inverse Pot down = Xg * 1 = Xc*q0 = Xg!

In a 1st approximation:

Here is OW Pot down *1/q0² und measured results = Xg*1.

non inverse pot up = Xg * 1/q0² = Xg * 0,595 = Xc* 1/q0 bzw. Xc /q0
and additional about -1,69 = q0² % Pot less up.

Constriction, bolt 7mm in a 11 mm tube, PL=18,5mm, tube length = 1m,
Input Impedanz Magnitude |Z|in change in % with centered Perturbation at 50% tube lenght:



In a 1st approximation:

Pot. dn	=	Sin(PL Pot) *100 * Xg * 1
non inverse Pot up	=	Sin(PL Pot) *100 * Xg * 1/q0² and add. -1,679 =q0² % less up.

More accurate:

Var. A (dotted curves): Sin(PL Pot) * 100 * Xg Pot
* Pot. up Factor +1/q0 — - q0^5 offset up
* Pot. dn Factor -1,0 — +0 offset dn

Additional corrections: Mode #1: +(whole sin(PL)*XG Pot*100); more Pot up, but stays minus
Mode #2: new average value (up)

Var. B: (red+blue curves) PL Pot * 100 * Xg-Pot

* Pot. up Factor +1,0 — - 2,0 offset up — = less Pot. up
* Pot. dn Factor -1,2 — + 5,0 offset dn — = more Pot. dn

Additional corrections: Mode 1 Pot up: * (1/2) (but stays minus)
Mode 2 Pot dn: *(2/3) = less Pot dn
gives new averages Mode 2+3

Summary – Input Impedanz Magnitude Changes found by physical measurements:

In 1st approximation, perturbation centered at 50% tube lenght, but low modes need considerably add. corrections:

Enlargements:
inverse Pot. up, even Modes =Sin (PL Pot) * 100* Xg / q0^2 = Xc / q0
non inv. Pot. dn, odd Modes =Sin (PL Pot) * 100* Xg / q0^3 and add. -q0² % less = -(up/q0)-q0²

Constrictions:
inverse Pot. dn, even Modes =Sin (PL Pot) * 100 * Xg / q0^1 = Xc = Xe/q0²
but with bolts =Sin (PL Pot) * 100 * Xg / 1 = Xg = Xe/q0

non inv. Pot. up, odd Modes =Sin (PL Pot) * 100 * Xg / q0^2 and add. -q0² % less = (dn/q0)-q0²
but with bolts = (dn/q0²)-q0²

It follows: If area changes Xc and Xe are inversely proportional to each other, then the geometric mean area difference Xg results, which is set equal to the mean expected magnitude change, example q0=1.1

q0^2 = 1,21 Xg / q0^2 = 0,1577 *100 = +15,77% (Enl. up) - 1,21 % = +14,56% (Constr. up)
q0^3 = 1,331 Xg / q0^3 = 0,1434 *100 = -14,34% -1,21% = -13,13% (Enl. down)
q0^1 = 1,1 Xg / q0^1 = 0,1735 *100 = -17,35% (Cnstr. dn) =Xc, with bolt = -19,09% = Xg

measured Pot dn with Constrictions = Xc is 1,33* stronger than Pot dn with enlargements (~< q0³)
measured Pot up with Enlargements is 1,083* stronger than Pot up with Constrictions (~< q0)
measured Pot dn with Constrictions (~Xg/q0) is q0 stronger than Pot. up with Enlargements ~(Xg/q0²)
The max. possible Pot dn with sleeves = Xe/q0² =Xc (Constr. dn), but with bolt = Xe/q0=Xg.
up = Xc/q0 (enl. up)

Low modes deviate from this simplified scheme, including the observation that enlargements develop inversely prop. potential up & down with high mode numbers, whereas constrictions develop this with low modes. A factor describes the potential increase of the modes per ½ wavelength, and additional corrections describe the potential offset based on these phenomena. The more precise approximation formulas were given to be able to determine the magnitude potential at 50% of the tube length.

However, a final potential at the open end is still missing. The envelope values and thus the potential at the closed end and along the tube can then be determined from the potential difference to the center.

Convert Open Wind results (in % magnitude change)
to approximate measurement results:

OW: Enlargements: inverse Pot. up at 50% tube lenght, even Modes =+ ~Xg,
Correction needed: = 0+ (OW / q0²)

OW: Non inverse Magn. Pot dn equals with slight perturbations and 50% Centerposition Pot. nearly
with enlargements: [Sinpot (PL) * Xg] - [(Xc* Pertub. length to pipe length ratio)]

Corrections: Xg is stronger; 1st: get to level Xg Pot: - OW + (Xc* Ratio PL) = ~Xg
Correction needed: =0 – [(~Xg*100 / q0³) - q0]

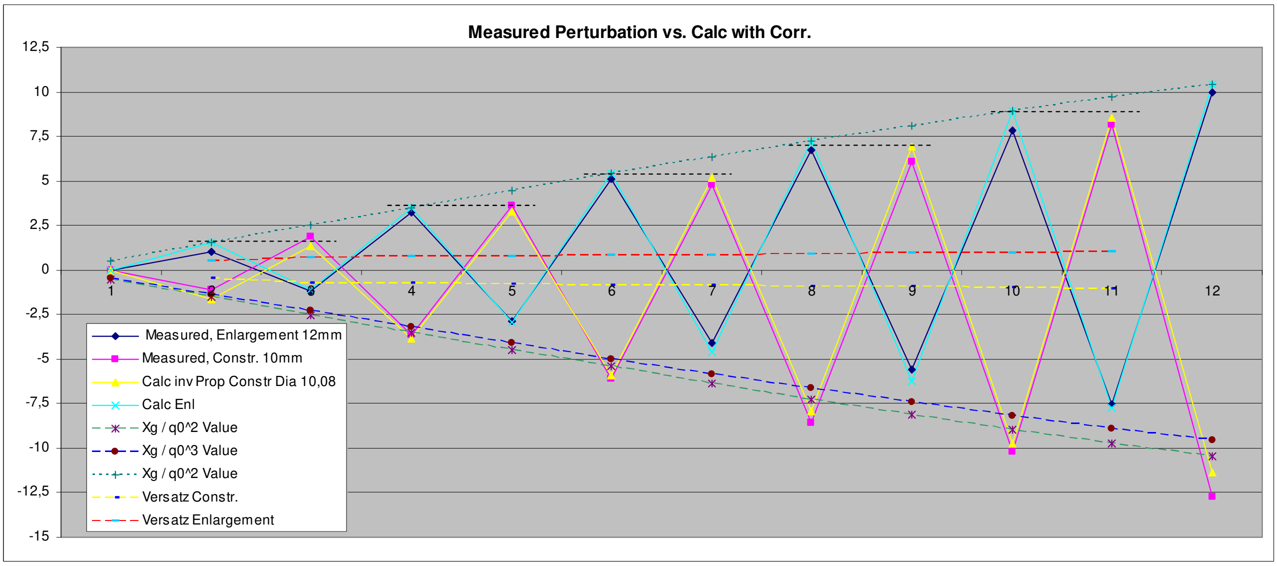
OW: Constrictions: non inv. Pot. up at 50% tube lenght, odd Modes
Corrections needed: = 0+ [(OW (=Xg)*100 / q0²) -q0]

OW: Inverse Magn. Pot dn equals with slight perturbations and 50% Centerposition Pot. nearly
with constrictions: [Sinpot (PL) * Xg] + [(Xc* Pertub. length to pipe length ratio)]

Correction: Xg is weaker; 1st: get to level Xg Pot: - OW - (Xc* Ratio PL) = ~Xg
Correction needed: = 0 – [(~Xg*100 / q0)]

OW bolt 5mm: simplified with a 11mm tube:
OW Data Magn Pot in % Diff. / q0 1,1226 and additional -1,26% (q0²) offset down.

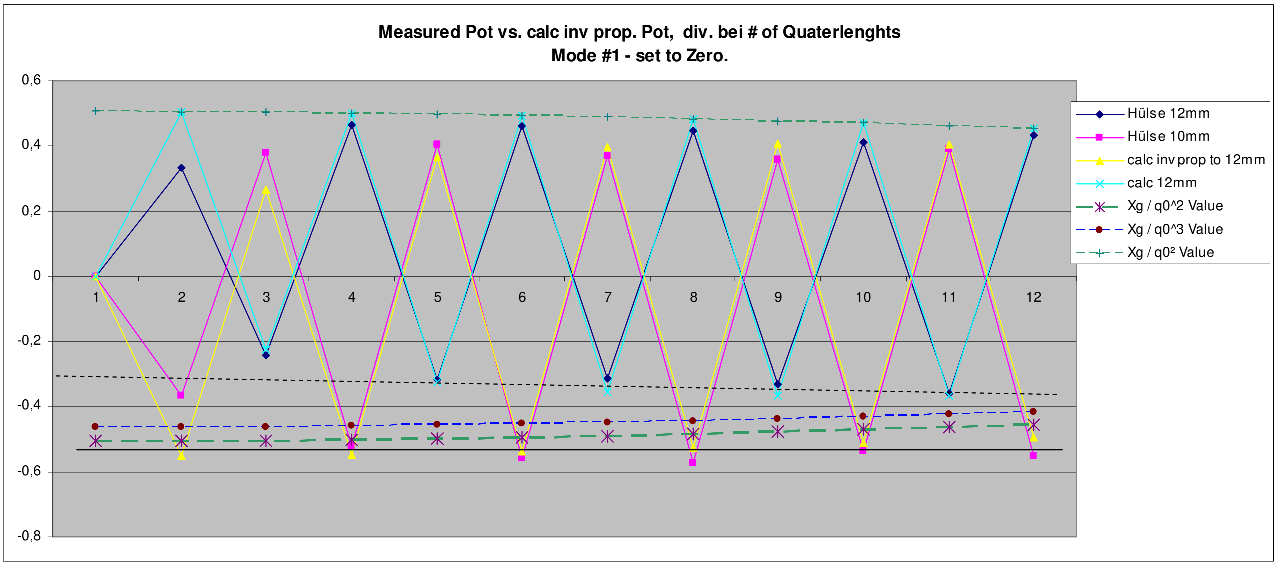
Further special features:



The calculated pot based on Xg and corrections delivers, with inversely proportional area changes, a magnitude pot upwards, where even modes have inverse pot. with enlargements, 100*Xg/$q0^2$. Odd modes do not have inverse pot. with constrictions (100*Xg/$q0^2$) - $q0^2$. This correction is so strong, that odd modes up have comparable pot to even modes up with the next lower mode number. Now here there is always 2/8 WL difference = $q0^2$ = dy -1.21%.

Mode 1 has at 50% tubelenght	1/8 WL	distance to the open end,	resp.. ¼ WL fits in the tube
even Mode 2 has at -„-	3/8 WL	-„-	resp. ¾ WL –„-
odd Mode 3 has at -„-	5/8 WL	-„-	resp. 5/4 WL –„-

Even modes are found here on rising pressure flanks, (inverse = stronger pot.); odd modes on falling DB flanks. The difference is ¼ wavelength - but the wavelengths are of different lengths. Therefore, the idea was born to divide the determined pot by the number of ¼ WL = (2n)-1:



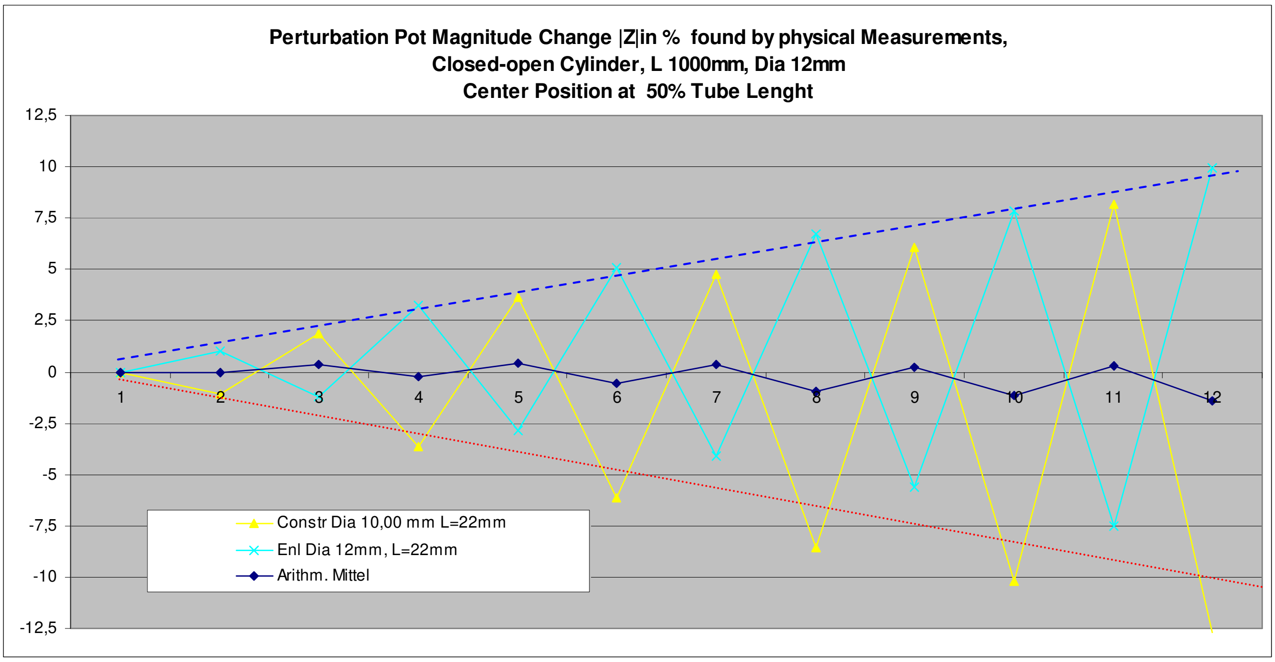
Apart from the fact that mode 2 shows much less pot. in measurements and mode 3 shows more pot up, you can see that the magnitude pot from mode #4 onwards has a fairly constant value per ¼ wavelength. You find an inverse pot. up with enlargements of ~ +0.5% which drops to +0.45% at high modes, a non-inverse pot dn. of -0.3% which rises to around -0.35%.

With constrictions, the inverse pot dn is around -0.55% - falling to -0.50%, the down remains ~ q0 times stronger than enlargements up, non inverse pot up at ~ +0.4%, which results in around 25-12% less pot than enlargements. With pot down however, enlargements result in a non-inverse pot dn that is up to 40% less than the inverse pot dn with constrictions.

On rising pressure antinode flanks (inverse behavior dn, = Xg/q0), constrictions have a stronger lowering effect by ~ q0 than enlargements have an increasing effect (inverse behavior up = Xg/q0²).
At 50% tube lenght, this affects all even modes.

On falling pressure node flanks = non-inverse behavior, constrictions up have a stronger effect than enlargements dn, around q0² (falling to ~q0), but themselves have less potential than at rising pressure flanks (not inverse ~ q0² (falling to ~q0 at high modes). At 50% RL, this affects all odd modes. A fictitious mean value - which cannot exist - would be a mean value on an envelope curve that is not reached.

This results in the measured effect that perturbations on rising pressure antinode flanks have significantly more potential than on falling pressure antinode flanks, with the exception of mode #2.
This manifests itself in the fact that at position 50% of the pipe length, even modes have significantly more total potential than odd modes and this with an overhang to reduce the magnitude |Z|in.



Such envelope curves would look something like this (dotted, drawn freehand); Magn. Pot up varies only very slightly, but down very strongly. The (non-existent) middle pot would be about the same up / dn at high modes. (*Here, measured values wich are not inv. prop. to the other, were used for the graphic, i.e. Constriction = 1/q0=0.909 and Enlargement q0= 1,0909 instead of inv pro. 1,10*)

Modelling input magnitude potential based on measurement results

A possible solution for how a model can be found based on the measured changes;

I have divided it into 5 individual steps, here is a systematic brief overview, although steps 1 and 2 have already been largely described.

Step 1: Calculate the input magnitude pot. at x= 0,5 * pipe length and mean pot. for the envelope values at 50% pipe length. This step has just been described in detail.

Step 2: Define the inverse final potential using 1/8 WL extra Pot determined at 50% pipe length. From this, the gradient per mode is determined (mode #1 is treated differently)

The envelope values are now already available. As an intermediate step, an average must be calculated again, this results in equally large dy values = the amplitude for the sine function in step 4 - shifted by the offset, which is than finally corrected back in step 5.

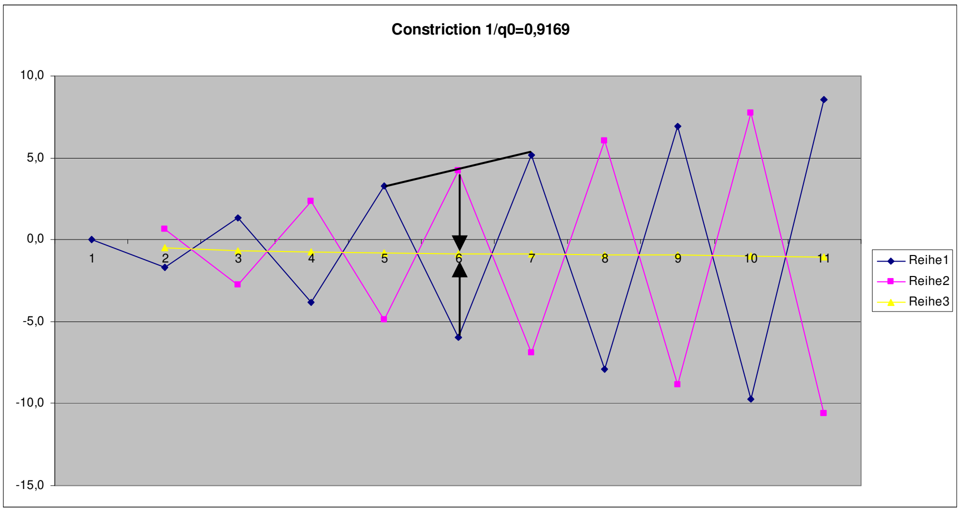
Step 3: Sine function with a suitable acceleration on the last 4/4 wavelengths in the pipe (Mode #1 is treated differently)

Step 4: Amplitude from Step 2 * Sine function Step 3 gives the approximation, shifted by the offset

Step 5: Add offset from Step 2 = result of the modeling.

Now in detail, based on constrictions:

Step 1: Potential based on cross-sectional change and appropriate approximation:

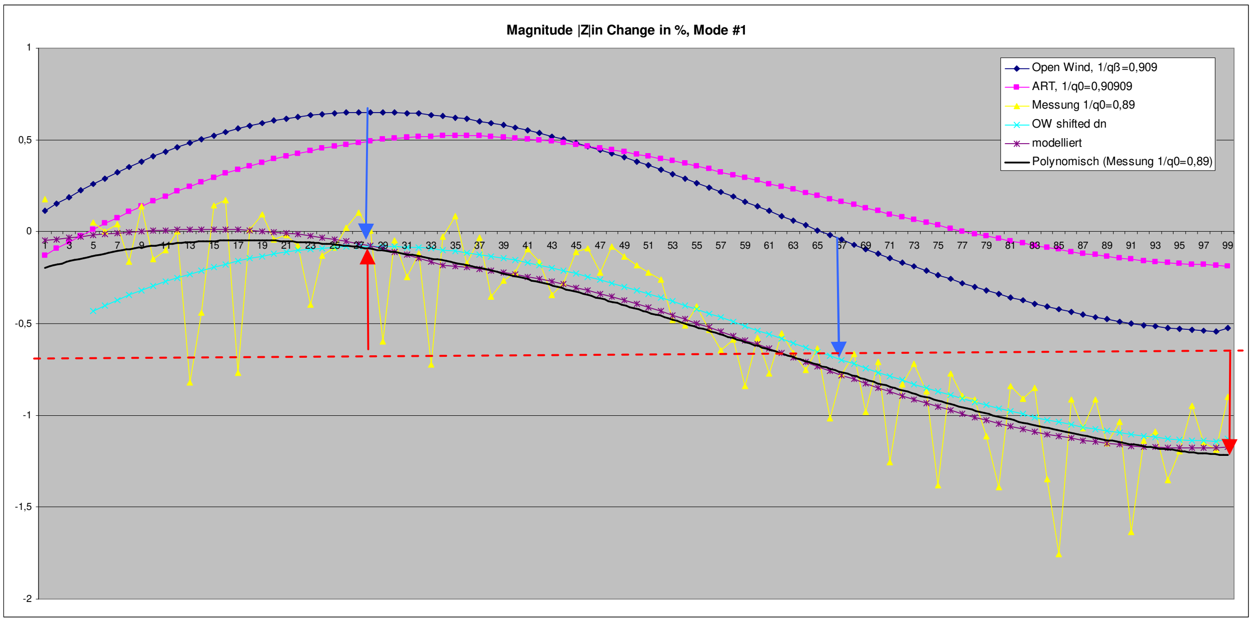


The potential offset is obtained, (using Mode #6 as an example), at Pos. 50% RL:
Pot up: arithmetic mean of Mode #5 and Mode #7 results in an auxiliary value (envelope values, pink) at 50% pipe length, the pink values are a pure envelope potential - without hits at 50% tube lenght.
The arithmetic mean of these auxiliary values with the calculated pot values dn results in the potential offset dn (yellow). This can be omitted for Mode #1.

Step 2: Define the inverse end potential using 1/8 WL Pot determined at 50% of the pipe length.
The amplitude envelope can then be defined over the entire pipe length.

*The position potential of such envelopes based on the ART simulation would be approximately at pipe length x=0 twice the value compared to pipe length 0.5: +/- 2.378% * 2 = 4.756% (Mode #3) and at the open end around 0%, without any offset up/dn.*

This is not true based on the measurement results, however. There is a change in the speed of the sine function and thus an end potential, and also a linear offset over the entire pipe length, which produces completely different results than the ART and OpenWind simulation models.



Although Mode #1 is treated differently below, this graphic (5mm bolt) shows what happens. There is a division into three on the last ¼ wavelength in the pipe, it starts with a pot. up, which is still below 0 due to the offset, an arithmetic center / node, which is reached at ~2/3 of the pipe length and which gives the offset, and an inverse pot dn at the open end of the pipe.

The pot. of Mode 1 is only theoretical (open wind) +0.7% up, since ~ the same amount of offset down is found (measurements).

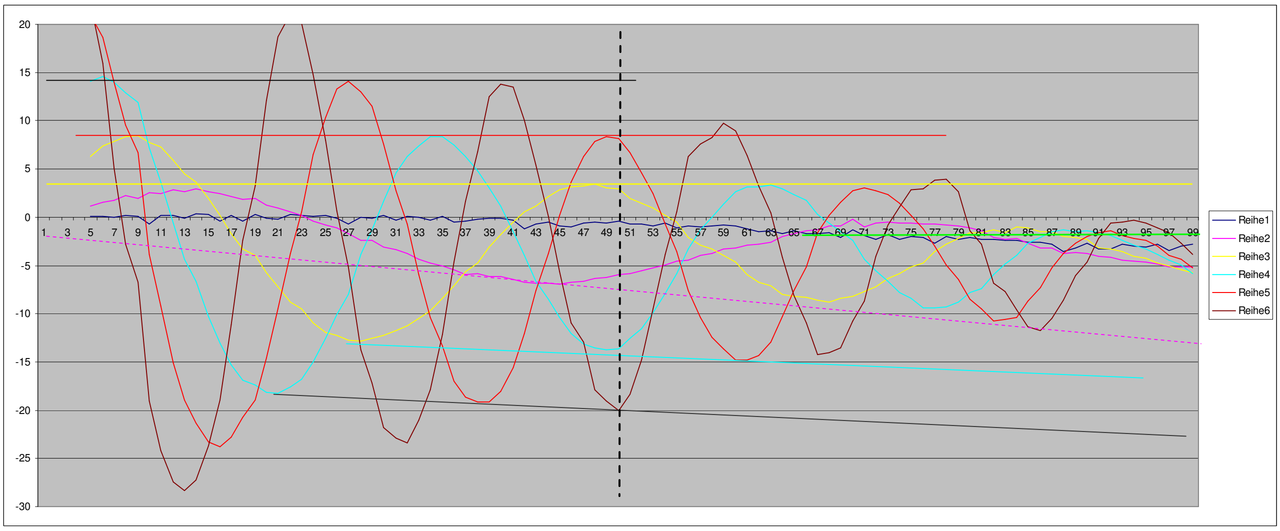
At 2/3 RL the measured pot is therefore -0.7%, that is the magnitude node offset downwards,
the inv. end pot dn~ -1.0%, so offset change dy +0.5%, the non-inv. pot up is -0.5%.
Mode #1 has the same inverse pot dn as the higher modes, but a much smaller offset and, including the extra pot, an end pot down that is about ½ of the higher modes.

Mode #1 is considered differently in this model.
The calculated Xg pot up at 50% RL assumes 1/2 motion of the sine function. In reality, however, it is ¾.
The calculated XG pot up at 50% RL is therefore found at almost 1/3 of the pipe length, the inverse pot down at 3/3. At 2/3 of the pipe length, the "magnitude node" or sine value = 0, which should only appear at 3/3 when correlated with the wavelength (without accelerating the function), and has calculated 1/3 of the pot of mode 2 at 50% RL = 1/8 WL pot.

Mode #1 reaches an inv. end pot down at the value where higher modes ~ have their end pot up. So it is almost the same pot up and down. However, the offset is not half, but slightly less:
The calculated inv. Xg Pot dn at 50% pipe length ... which is an auxiliary value would be ~ -0.67%, half the offset to higher modes would be -1.5% / 2 = -0.75%, ultimately it is equal to inv. Pot. dn calc. Mode #2 = ~2.0% / 3 = -0.67%, which ultimately gives the same result.

Higher modes – deviations of the inverse pot. dn compared to simulations:

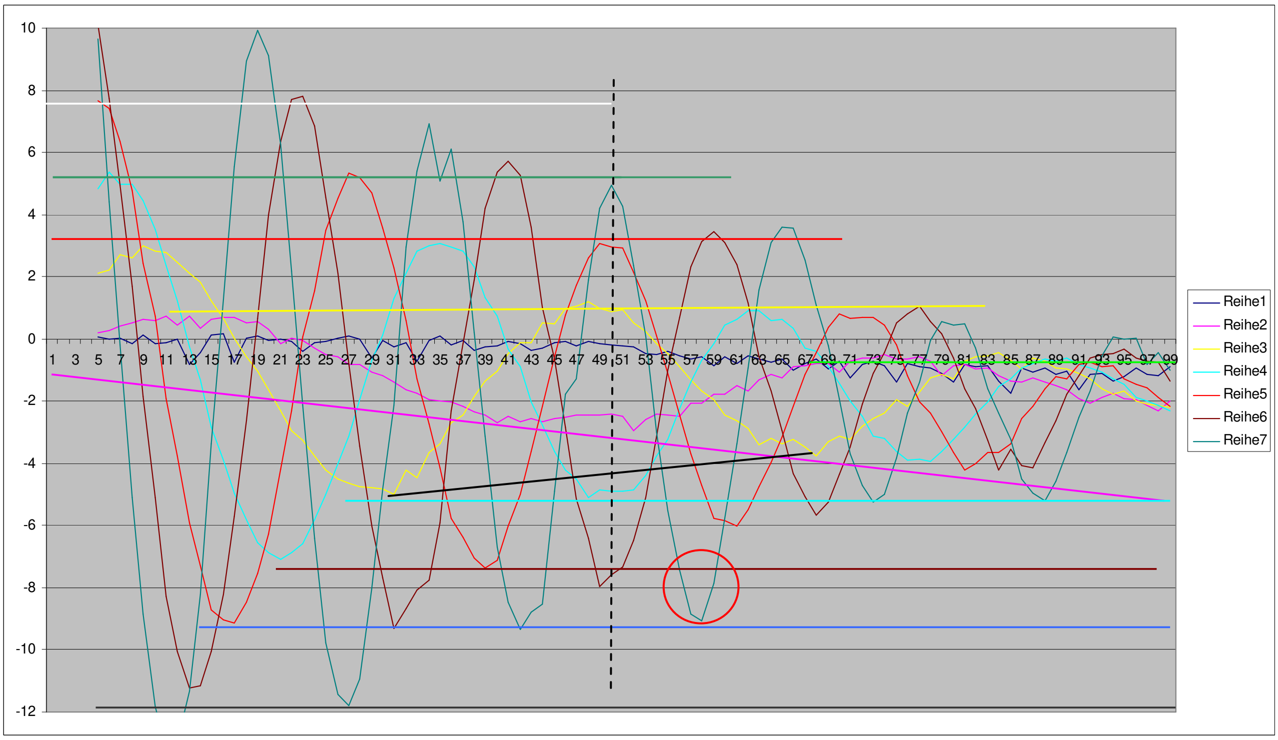
7mm bolt in a tube with 11mm diameter:



The odd#/8 wavelength potential is shown at 50% tube length.
Green = Mode #1, half pot. at 66% RL = offset down and ~ non-inv. pot on the last ¼ WL in the tube for all modes. The offset stronger dn than the pot up results in, therefore in the minus range.

Mode #2 only reaches around 2/3 of that instead of 3/8 WL pot. dn (pink) and that earlier, too.
High modes exceed this pot. dn. and it can be seen that low modes have less lowering pot than high modes. 7/8 WL pot = mode 4 dn and 11/8 WL pot = mode 6 dn also show this behavior with 7mm bolts. With pot up = not inverse, on falling pressure antinode flanks, this pot. is stable as in the simulation, and it is the potential down that shows the most deviations.

5mm bolt in a tube with 11mm diameter:



Bolt 5mm has ~2.5 times less magnitude change potential than bolt 7mm.
The weaker Pot dn at 3/8 WL = Mode #2 is here also very pronounced.
At 7/8 WL Pot. dn = Mode #4 a curved curve downwards would be more likely,
at 11/8 WL Pot. = Mode #6 the pot of Mode #7 is probably an outlier.

This also results in a non-linear position pot. The last inverse pot dn 3/8 WL before the open end is simulated too low for higher modes, and too high for mode 2 at 50% RL.

This results in the effect that the last inverse pot in the pipe = 1/8WL pot. = on rising pressure antinode flanks is stronger the closer it is to the open pipe end, or the more pressure antinodes there are in front of it.

The same applies to the remaining inverse modes 7/8WL, 11/8WL, etc. With the 10mm sleeve, however, the 3/8 WL pot is almost identical for modes #2, 3 and 4, but then increases rapidly.

The simulations apparently do not take this observed effect into account at all, just as the calculation using the cross-section proportionality does not take this into account. This means that in measurements, a further potential is added to the position potential, which has the opposite effect, i.e. it weakens based on the position of the closed end, but in the opposite case increases with a smaller distance from the open end. The pot. at the open end is not zero - and the size is determined by this effect.

This results in an end pot that is almost equally strong for bolts of 5 mm in all modes from #2 onwards. The end pot ultimately consists of the potential offset down, which is fairly constant + an extra potential at the open end, which is also fairly constant. This extra end pot corresponds to 1/8 WL pot, which now appears "earlier", at 0/8 WL.

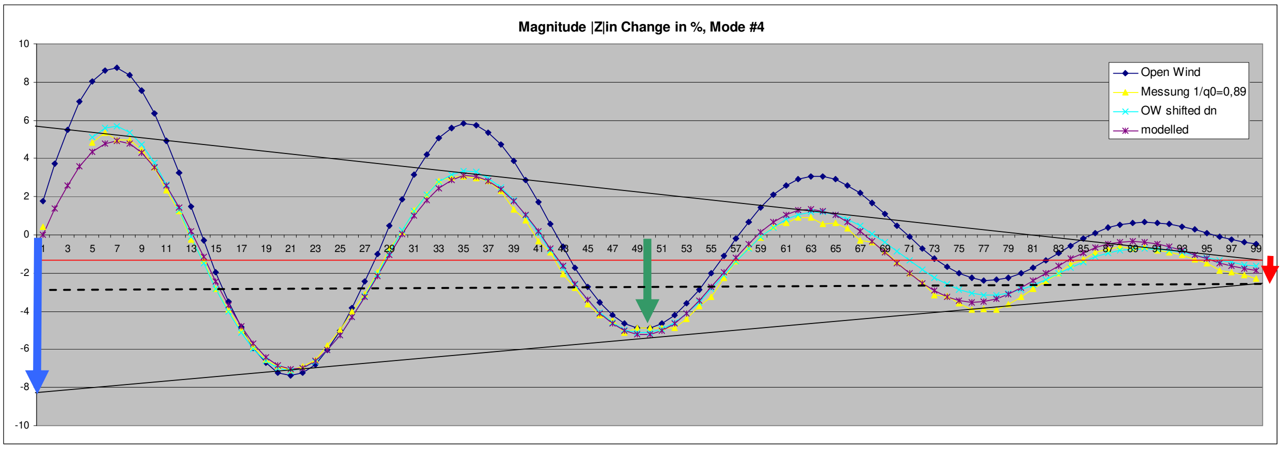
With sleeve 1/q0= 0.909, the offset at mode #2 is de facto 0, the end pot = 1/8 WL pot, with increasing modes # the offset becomes increasingly stronger and only half the value of the 1/8WL pot was determined for the extra end pot.

If the extra end pot is too large, the magnitude changes at the closed end would be too small to the same extent (and vice versa). The middle is considered the pivot point and is not changed. This uncertainty results in maximum deviations at the pipe ends of max. +/- 0.3% magnitude change in mode #8.

With enlargements, the magnitude potential offset is upwards, which increases relatively quickly to an almost constant value compared to constrictions. However, this value remains comparatively low.

Mode #2 and Mode 3 show significantly less potential than the higher modes and also less offset. For the time being, I'll leave it at 0.5* 1/8 WL pot for the calculation attempts.

The End-Pot. Problem:



Bolt 5mm: The XM pot in the middle is known (green), here -5.2%. The potential offset dn with constrictions is known, red line here -1.5%. The extra end pot is the pot that goes beyond the offset (red). The envelope and the start pot dn (blue) are also determined from the size of the end pot. For bolts 5mm and 7mm it can be determined that the extra end pot corresponds to 1/8 WL pot down (red arrow).

In mode 4 the XM pot in the middle of the tube = 7/8 WL pot (calculated from the open end).
XM pot here is -5.2% / 7 = -0.742% 1/8 WL extra end pot + the existing offset -1.5% = end pot = -2.24%. This results in a gradient dy of 5.2-2.24%=2.88% on 7/8 WL =dx. The start pot has the same gradient, dx is twice as large, resulting in 5.2% +2.88% dy = -8.08%. The lower envelope is: start -8.08% middle -5.2% end pot -2.24%.

The non-inverse end pot up is de facto = 0+offset, i.e. -1.5%. For XM the value is the arithmetic middle 7/8 pot up = +2.1%, resulting in a gradient dy of 2.1% + offset 1.5% of =3.6% on 7/8 WL dx, the start pot up is twice the value, as the distance is twice dy = +7.2%, whereby the reference (base) is still the offset, which must be subtracted: = +7.2 - 1.5 = upper envelope start +5.7%, middle +2.1% and end -1.5%.

The sine function can now be calculated, but for this it is necessary that + and - add up to a maximum of 1.0. Therefore, an arithmetic mean must now be calculated again, from which up and dn deviate equally. This auxiliary value is only needed temporarily for the sine calculation.

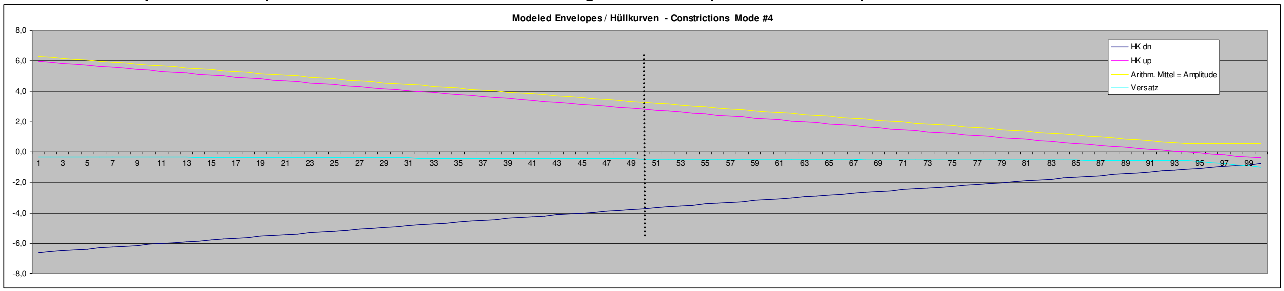
The arithmetic mean of the envelope curves up/dn is -1.19% at the beginning, -1.5% in the middle and -1.875% at the end. The mean must now be calculated for each dx value, = (total pot up + pot dn) / 2.
Envelope up mean = offset for the following sine calculation. dy for the offset now results in the same values up and down = amplitude value for the sine calculation. After the sine calculation, the offset must be added again: Up - offset at x, Dn + offset at x. It is known that the inclination in the sine calculation results in small deviations. However, since the measurement results only approximately follow the sine curve, I have to accept this.

The calculation changes slightly for constrictions in the form of sleeves. Here it can be seen that low modes do not develop an offset, but have an endpot. Higher modes show an offset dn, but have a much smaller extra endpot. The experiments show that for mode #2 the endpot = 1/8 WL is approximately correct, but for the higher modes only half the 1/8 WL pot as an extra endpot delivers approximately good results.

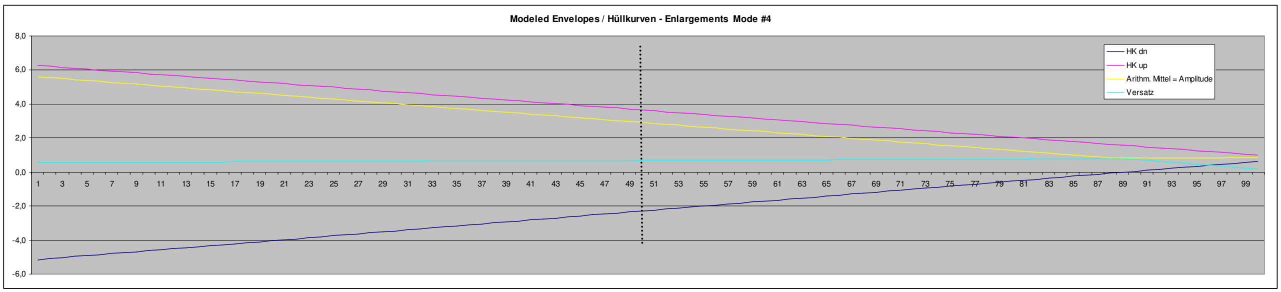
Enlargements have the well-known problem that experimental measurements are difficult. Enlargements quickly show an offset up, with the exception of modes 2 and 3. When in doubt, I assume that enlargements in the best case only develop an extra pot (now upwards) that is no stronger than with constrictions, i.e. 1/8 WL pot at the end * 0.5. I do not plan to calculate strong enlargements. In modes #2 and #3, the pot up is much lower than in higher modes, the offset is also lower and I assume that it can remain at the same (half) 1/8 WL end pot.

Mode #1, unlike the other modes, does not have a falling envelope slope from the only and last non-inverse pot at 33% RL, i.e. a constant amplitude of a differently calculated speed in the only and last ¼ wave position in the pipe. Based on the measurements, however, it can be assumed that the pot at the beginning of the pipe has approximately the same value as at 33% pipe length. This correction is taken into account in step 4 for mode #1.

Mode 4, Step 2: Example Constrictions and Enlargements, q0=1,1 = 1/q0=0,90909



Perturbations with sleeve inner Dia 10mm und Lenght 22mm in the 1000mm tube with inner Dia 11mm =1/q0=0,90909



Perturbations as enlargements to Dia 12,1mm und Lenght 22mm in the 1000mm tube with inner Dia 11mm =q0=1,1

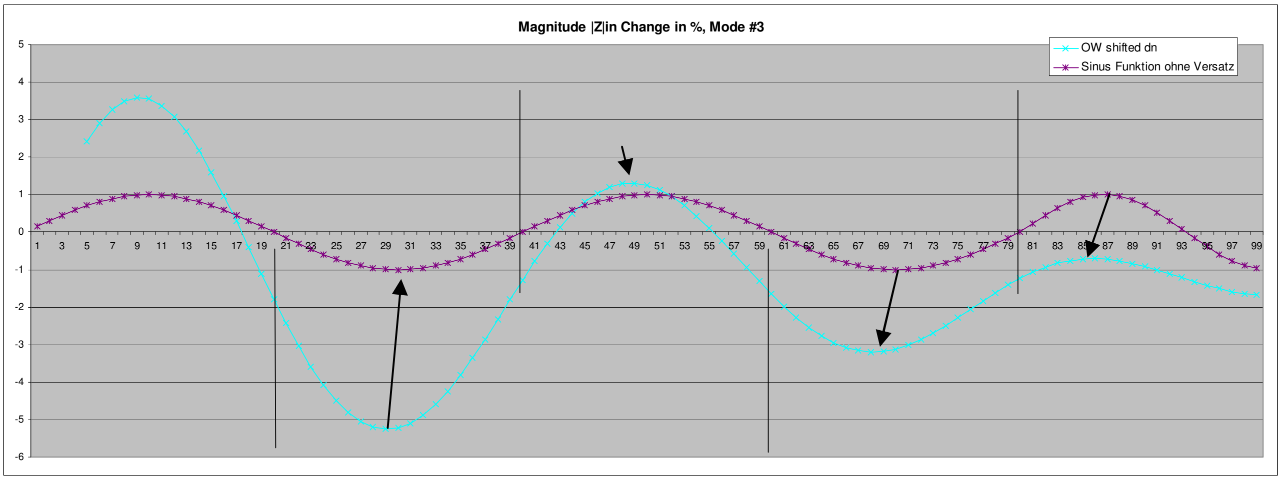
Step 3: Sine function with a suitable acceleration on the last 4/4 wavelengths in the pipe
(Mode #1 is treated differently)

Calculation of the closed end section up to the position 4/4 WL before the open pipe end, the speed of the function correlates with the wavelength of the mode, 1 whole sine oscillation corresponds to ½ WL and is shifted by 90 degrees compared to frequency changes:

sin [pi /2 * 2 * (2n-1) * Positionfactor x]

Mode #1: The function changes 1.5 times faster and has a small phase shift

Modelliing Step 3, Mode #1:	sin [(pi / 2 * 3 * 1 * Positionfactor x) + (pi/16)]



Sine function, where the last ¼ wavelength = ~¾ oscillation instead of ½ oscillation.
Pressure antinodes and pressure nodes are shown at a distance of ¼ WL. So if the speed of the function does not change, there would be magnitude zeros exactly at these positions and 1 additional "advanced node" before the open end and then an inverse pot.

OpenWind results show hardly any offset, but the speed deviations are close to the measured results, so the above sketch is usable.

It turns out that the angular velocity based on measurement results, as with OW, increases from 4*1/4 WL before the open end, resulting in the lag of the sine function (horizontal shift) based on the wavelength. In mode 2, this position is already "fictitiously" ¼ WL beyond the closed end, in mode #3 this acceleration of the magnitude potential curve begins at the 1st pressure node after the closed end, at 0.2 * pipe length.

For the modeling, I used a linear increase in the angular velocity, which increases from position: length of a ¼ WL = (1/odd#); [(number odd#-4) /odd#] = a pressure node and magnitude node without offset.
The necessary increase was determined using the "best fit" of the overall curve. It turns out that in mode #8 the correction factor is 1.0 - so it no longer accelerates on the last wavelength, mode #10 has a negative acceleration of the function.

Calculation of the closed end section up to position 4/4 WL before the open pipe end:

sin [pi * (2n-1) * Positionfactor x]

The number in brackets is an angle in radians.
Total number ¼ WL = odd mode # = (2n)-1 = 5, - 4 = remainder = ¼ WL = 0.2m.
On the last whole wavelength in the tube = 0.8m the acceleration will start with a factor of 1.

We have a remaining length (in mode #3) of 0.8 * pipe length.
At normal angular velocity, this remaining length fits 2 * 1/2 wavelengths, i.e.
2 sinusoidal oscillations = 2*360 = 720 degrees = 2* Pi()*2 = 4 Pi = 12.56 rad.
Every pi() times = 180 degrees, the sine value will be 0, i.e. exactly 4/4 WL before the open end.

To keep the formula clear, let

Start pos	= [(number odd#-4) /odd#]
Remaining length	= 1- (start pos. last wavelength in the pipe)
Slope	= 1 / remaining length
Final speed factor	= 1+ [% change / (remaining length*100)]

The formula for the last whole wavelength from mode #2 before the open end in the tube is, variant 1:

Step 3 Var.A =	-sin (2pi * 2 * x-(Startpos) * Slope * Final speed factor)

x-(Startpos) 0,2-0,2 =0 with Mode3
und remaining lenght =0,8 = dx.
Slope dy/dx= y=0 ...->....y=1, dy=1 / dx 0,8 = =1,25
Slope =5 odd# / 4 (Remaining lenght)
with Mode 2 it is 3 /4 =0,75
Mode 4 it is 7 /4 =1,75
Mode 5 it is 9/ 4, =2,25 and so on

The angular velocity increase can be described as a difference:
at the beginning the increase is 0, at the open end of the pipe a value >0

This means that per percentage point the change (increase = difference) in mode #3 is 1/80 of the angle dy=4pi = 12.56 /80 = 0.157 rad gradient. In fact, the speed increases, the resulting extra pot at the open end results in around ¼ sine oscillation = pi/2 = 1.57 rad which would result in a final angle of 12.56 +1.57 = 14.13 rad, dy = 1.57 / dx = remaining length 80% = 0.0196 rad per % Pos x,
14.13 / 12.56 corresponds to factor 1.125 / 80 parts = 0.0140625
but also factor 1.125 * gradient 1.25 = 1.40625 / 100 = 0.0140625
-Sin from this = ~ -1.0 so magnitude pot. dn with constriction.

gives:	Pos. Factor	- (1/odd#)	dx	*	Final speed Factor (Mode #3) =1+dy	
	0,2	- 0,2	=0	*	0,0140625	=0
	1,0	- 0,2	=0,8	*	0,0140625	=0,0125 *100

where the position factor now increases linearly.
x gives the angle based on wavelength,
the increase in speed gives a larger angle
at the same position. dy/dx and from this a factor.
At the beginning the factor Pi()/2*2 means 3.14 rad = 180 degrees = sine of which 0 = will be a node. Pi * number ¼ WL * position factor in the pipe.

This variant results in an increase in the angular velocity, which is approximately

Mode2:	10%	
Mode3:	10%	
Mode4:	7,5%	
Mode5:	5,6%	
Mode6:	4,0%	
Mode7:	2,0%	
Mode8:	0,0%	
Mode9:	-2,0%	
Mode10:	-5,0%	meaning the change decreases with higher mode #.

However, in this variant, Mode #2 is already changed at the closed end.

There is another variant that reveals surprising connections for me:

To keep the formula clear,

odd# = number of ¼ wavelenghts fitting in the tube (2n)-1

Startpos = [(number odd#-4) /odd#] *(of last whole WL in the tube)*

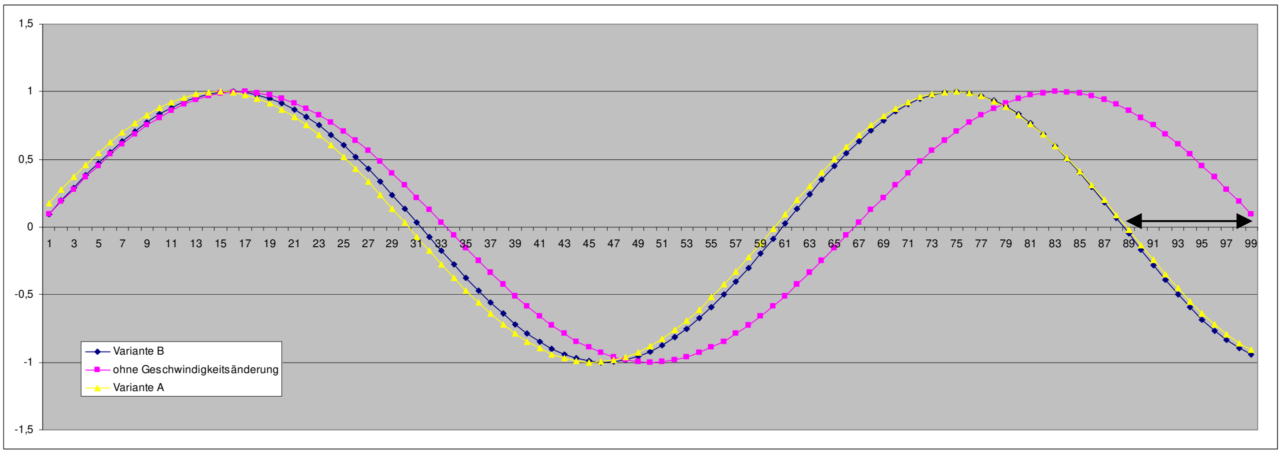
Remaining lenght = 1 - Startpos

Variable A: = [(appropriate Changefactor -1) / Remaining Lenght]
Remaining Lenght*100 * odd# *... is / Remaining L^2*

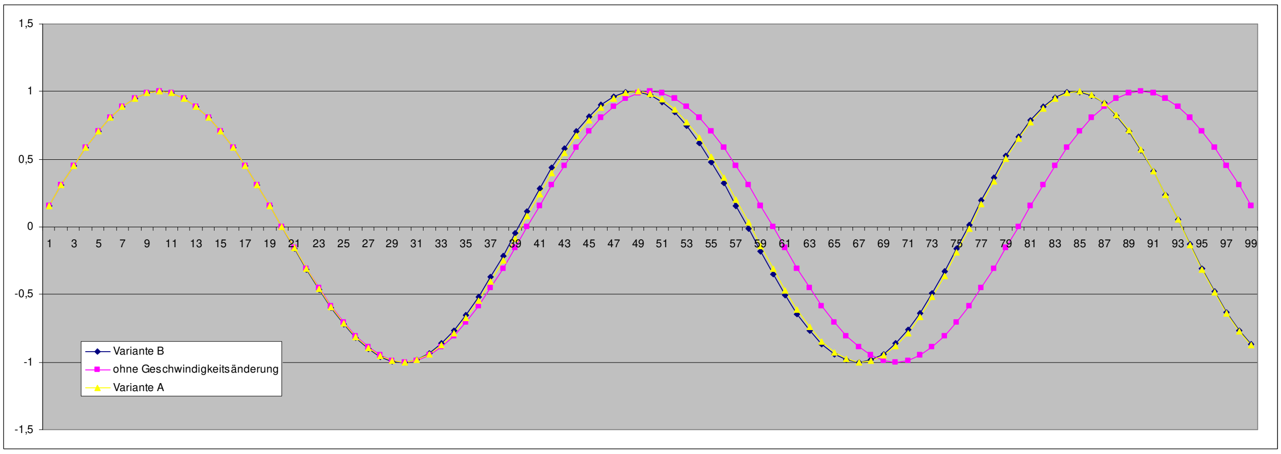
Factor B: = 1+ (x - Startpos * Variable A)

Modelling Step3, Variant B =	sin [(pi / Factor B) * x * odd#]

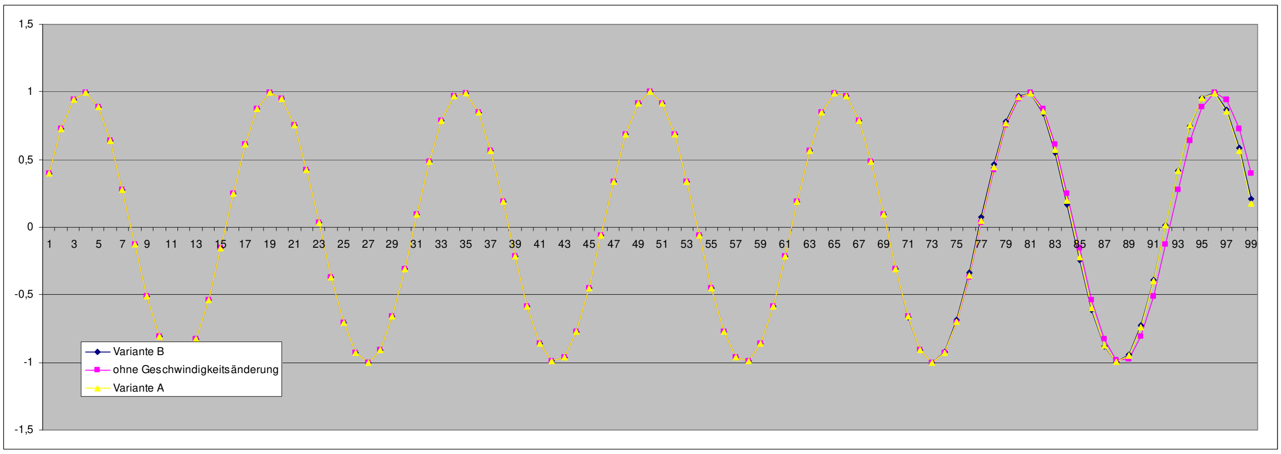
How I came up with this formula is trial and error, but here mode #2 is also better.



Mode #2



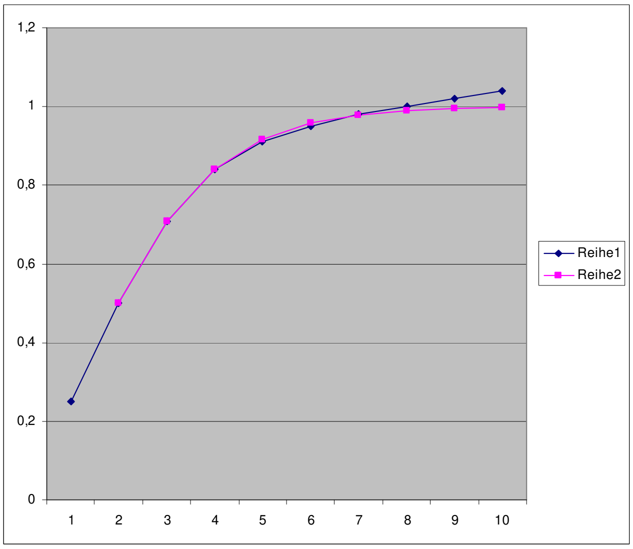
Mode #3



Mode #7

The particularly exciting thing about this variant B is that the appropriate changefactor is =

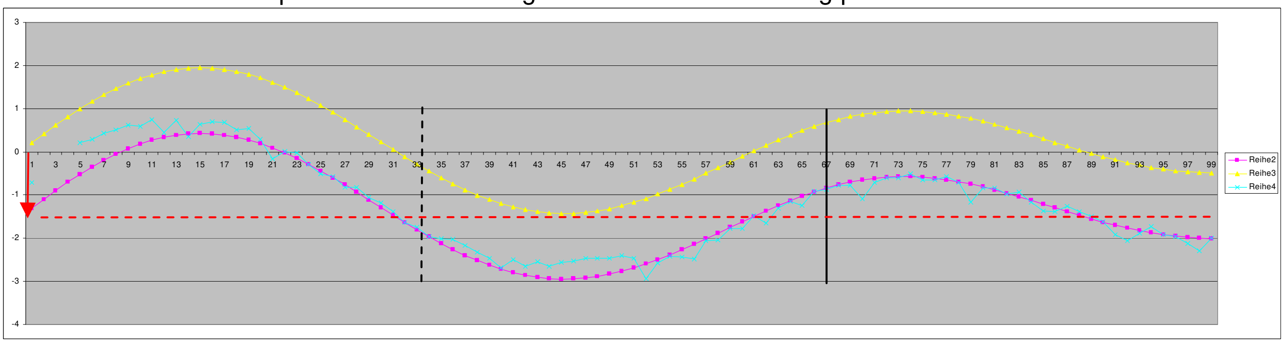
Mode 1:	0,25	(not in use)	
Mode 2:	0,50	= 2. (square root) of 0,25	=0,25^(1/2)
Mode 3:	0,7071	= 3. root of 0,25	=0,25^(1/3)
Mode 4:	0,8408	= 4. root of 0,25	=0,25^(1/4)
Mode 5:	0,91	~	=0,25^(1/5)
Mode 6:	0,95		
Mode 7:	0,98		
Mode 8:	1,0		
Mode 9:	1,02		
Mode 10:	1,04		



x = Mode #
y= pink: (¼) ^(1/Mode #), blue: determined using "best fit", change factor variant B.
This cannot be a coincidence. The reason that the higher modes deviate is obviously that they are not exactly integer multiples of Mode #1.

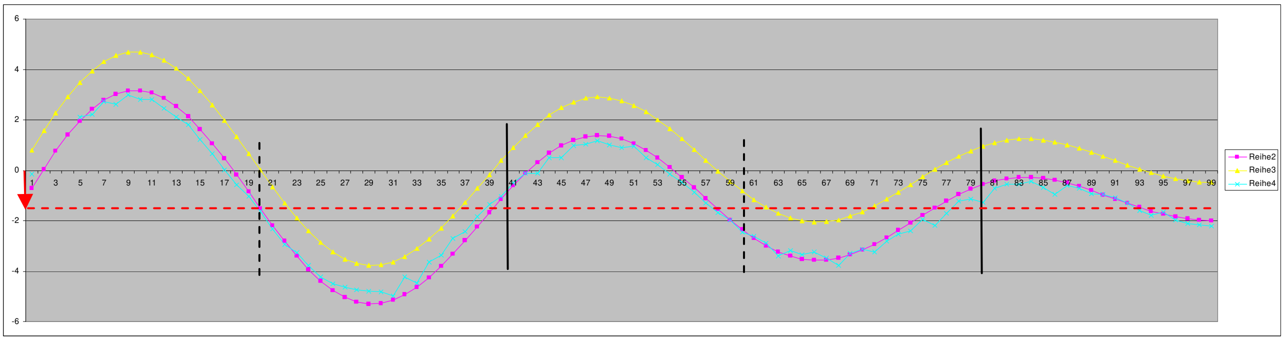
Modelling, Step 4:
Envelope potential Step 2 as amplitude * sine function Step 3 results in the yellow curve (below):

Modelling, Step 5:
Now the offset from Step 2 must be added again and the final resulting pink curve is:

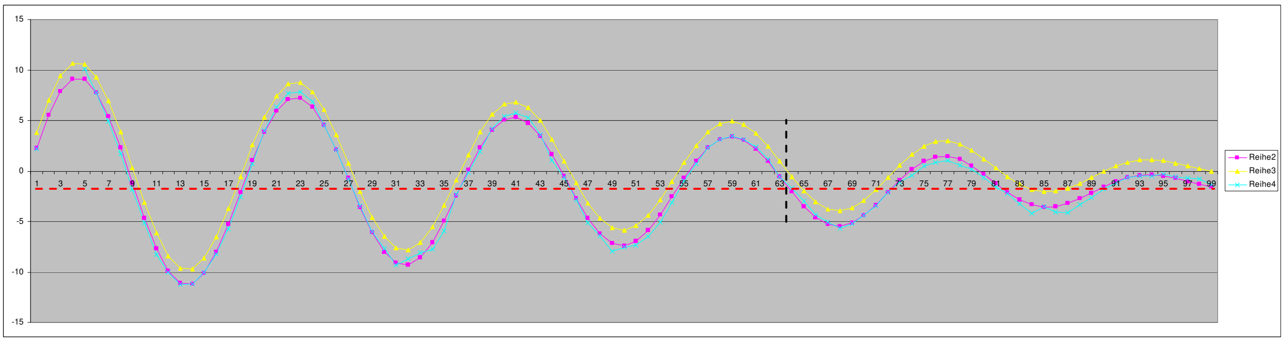


Mode #2, turquoise=measured value of magnitude change, pink=modeling result, yellow=without offset dn
y = magnitude change in %, x = centered perturbation position of bolt 5mm in 11mm tube with length 1m.
As you can see, it is almost impossible to increase the magnitude.

Magnitude nodes and maximum values are not aligned with pressure antinodes and pressure nodes due to the acceleration of the change and the potential offset dn, as they are within the last whole wavelength before the open end. The offset with bolt 5mm in mode #2 corresponds approximately to the pot. dn offset at 50% RL.



Mode #3, turquoise=measured value of magnitude change, pink=modeling result, yellow=without offset dn
Mode #3, last 4/4 WL starts at 20% tubelenght = a pressure node, (dotted lines);



Mode #6, turquoise=measured value of magnitude change, pink=modeling result, yellow=without offset dn
Mode #6, last 4/4 WL starts at 63,36% tubelenght

Mode #1 must be treated differently:
Here the measurements show that the almost max. Pot up already exists at the closed end, but this was only determined with the sine function at 33% of the pipe length. A correction is therefore necessary at the start of Pot+ at 33% of the pipe length: ~0.5% dy / 33 percent steps dx = 0.01515% increase or corrective push up per % pipe length up to position 33%:

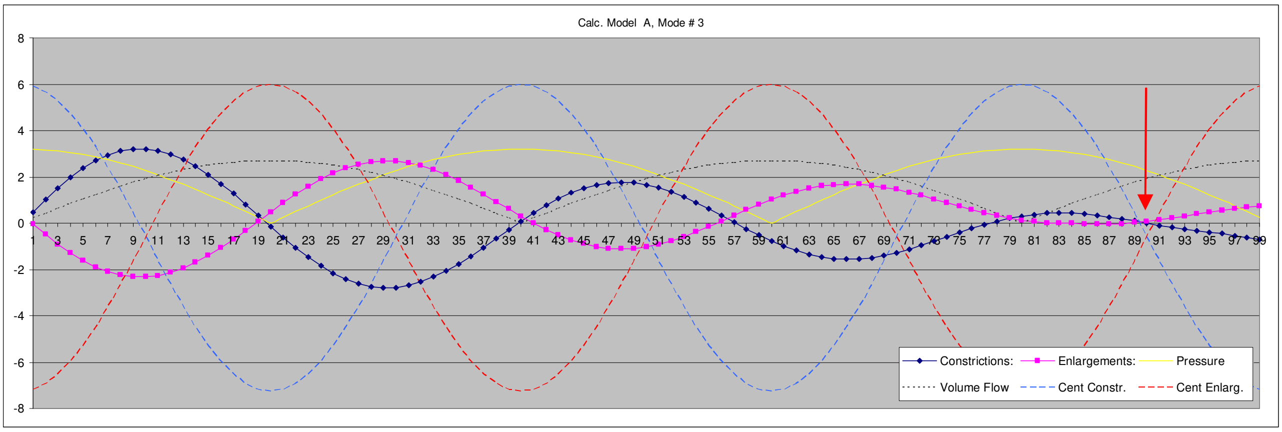
If x < 0.33 pipe length; (0.33*100 –x) *Slope = Extra push Magn. Pot up.
This simple method creates a small kink at 33% pipe length, which is negligible.

Since Mode #1 does not actually develop a significant magnitude pot and is of no importance for brass instruments, this was omitted from the modeling and a much simpler model was therefore used. An effective magnitude node in Mode #1 results here at around 50% of the pipe length.

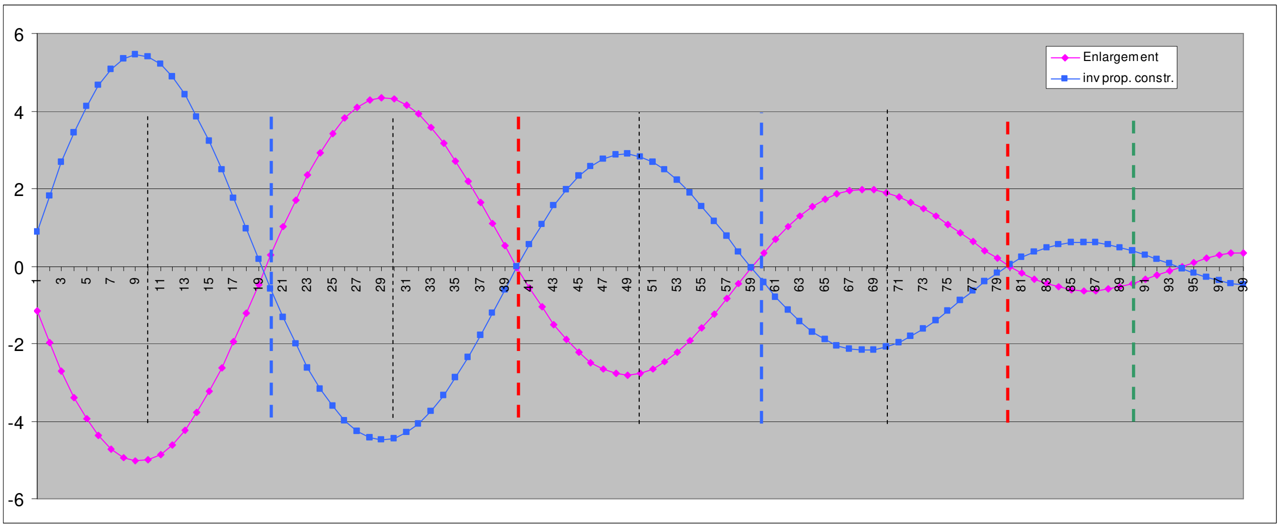
Based on the steps mentioned above, I have created an Excel file which calculates the modeling for sleeves (constrictions and enlargements). Bolts have already been covered in this documentation and are not modeled further at the moment. Below are some special properties that are found compared to the simulation models; some deviations have already been highlighted.

For sleeves, it can be seen that Var. A sin(pl Pot) * factors and corrections to Var. B pl Pot * factors deviate quickly if the perturbation length and the cross-section factor change too much. If in doubt, Var. A is therefore more suitable.

Modelling the behaviour of closed-open cylindrical Tubes to local perturbations,
using approximated targets found by repeated experimental phys. Impedance Measurements – Results:



Cylinder L=1000mm, Bore =11mm, Constrictions =10mm, Enlargements =12,1mm, Pert. Length = 20mm.
y-Axis: Magnitudes = % Change |Z|in, Pitch: Cent Deviation from the unperturbated closed-open Tube.
x-Axis: Center-Position of each single local Perturbation applied, in % of tube length (Example Mode = #3)



|Z|in Magnitude Change %, result of OpenWind Simulations with same perturbations as repeatly measured.
blue dottet lines: expected Position of Pressure Nodes, red dotted lines: Pressure Antinode Positions

Pitch Change Pot., measured and modelled:
Max. frequency changes caused by perturbations “max. Pitch Pot” occur at the places considered to be Pressure Nodes und Pressure Antinodes, they do not vary and stay on this positions. Mode #3 has a 1/8 WL = 100mm. Pitch Pot down equals to sin(pot PL) * Xe, Pitch pot up ist $q0^2$ less strong = Xc. This ratio is subtracted from the k = Wavennumber (ratio) of the mode, giving a Δ k of a Δ Wavelenght. From the different wavelenght, the invers prop. frequency change is calculated, here shown in cents. (See HAL #2)

The systematically less potential up of the pitch changes results in shared Pitch nodes with an offset dn, also being Δ k of Δ WL = Pitch Pot up – (TL Pot /2) = Xc – ((Abs Xe + Abs Xc)/2)

The pitch change Pot. is almost similar for all modes, and so the pitch pot offset dn over the tubelenght.
A very slight increase found in pitch pot toward the open end is here ignored to hold things simple.

The Pitch Pot. found by Measurements is very nearly the same as simulated and calculated using HAL #2).

Input Magnitude Changes, measured and modelled:
Because of the found and needed increasing oscillation speed of the sin function at the last whole wavelength before the open end, “shared” Magnitude Nodes as result of Enlargements and Constrictions, but also magnitude change maxima are generally found closer in space to the closed end side of the tube.

Mode #1 or ¼ Wavelenght Resonator has only one pressure antinode at the closed end, and one pressure node at the open end. So the complete tube would be at the “falling” right side of a pressure antinode. Magnitude Pot. is in this case i call “not inverse”, and much smaller compared to the situation at the ”inverse” left “rising” side of pressure Antinodes which appear at the higher Modes. Measured Pot found at 50% tubelenght ist larger (inverse side) oder smaller than Xg/q0 =Xc, found by measuring results.

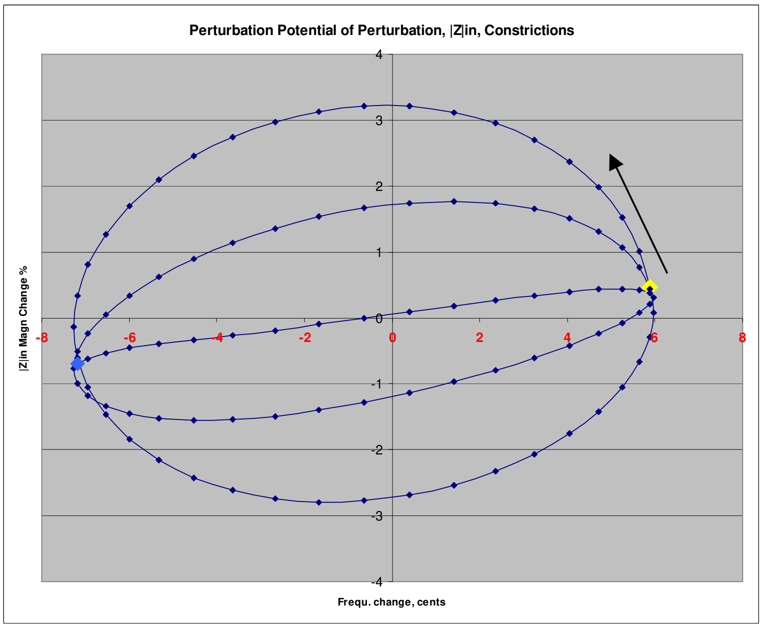
The found Magn. changes do not anymore correlate to changes in cross section and perturbation positions. So the measured results have generally less pot. than simulation results, but the difference between inverse and not inverse behaviour are much stronger and more complicated as simulation results imply. We find an endpot at the open end also with small q0 values of perturbations which means, that there ist an effective Magn. Pot. offset down with constrictions and a offset up with enlargements, both having “inverse endpot”, increasing with mode number, but also with increasing q0 factor of the perturbation to the bore.

This gives quite interesting results over the whole tube, having regions with “inverse” high magnitude pot. followed by regions of having very much less pot. than expected by the simulation models. The “shared” magnitude nodes do not appear anymore at places half between Pressure Antinodes and Nodes, and so not at places where the pitch pot. is max., they have no “shared” offset up/down, but an offset left/right, which seems to be difficult to handle in an easy way.

Red: 1/8 Wavelenght before the open end, there is a point with nearly no change, both pitch and magnitude, and at the open end, the changes of magnitude and pitch are “in phase”. On the closed side the stay out of phase by 90° and magnitude changes start all with not inverse Pot., this is the case with any of the modes.

The most deviation between Open Wind Simulation and my physical Measurements can described as:
Input Magnitude Changes found by measurements are much smaller, however, if a local constriction becomes very large, measured values with pot down converge with the simulated values in the area after the closed end, near the open end, measured Pot dn is stronger, while Pot up keeps being much less.

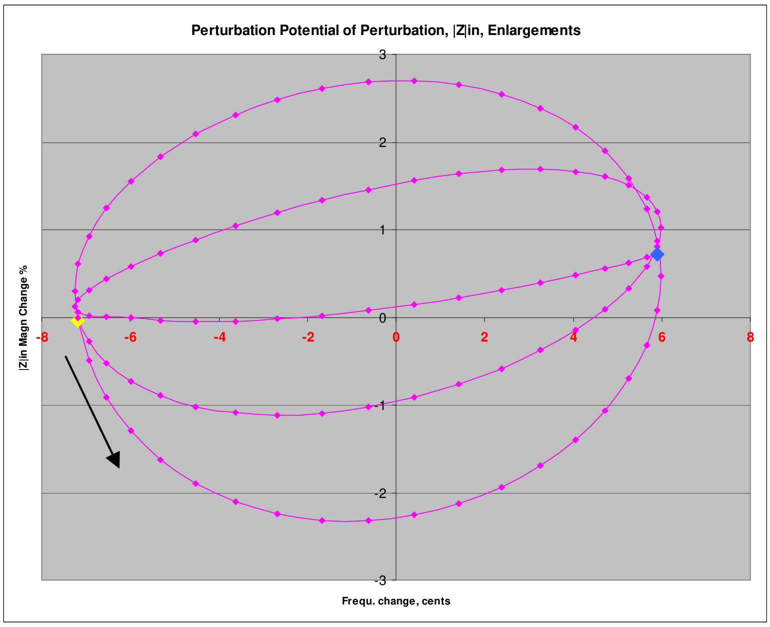
Smaller Perturbations (q0 ratio) show much more quickly an pot offset (down with constrictions). So the found Magnitude Pot. offset down starts much more quickly with small constrictions, compared to the Open Wind Simulation, and also to other (TMM Simulations like ART available for me), possible Magn. Pot up with constrictions are “oversized” in the simulation Modells.



Result of measured data, mode #3
A 2D "Spiral View", shows the alteration of Peak Mode #3 both in Input Magnitude and pitch, when a local constriction (a sleeve, here being 2% of tubelenght and Diameter Ratio =1/q0=0,909 here) is moved stepwise trough the cylindrical closed-open tube.

Each Point is +1% tubelenght position, the centered Startpoint at 1% from the closed end is marked "yellow", stop at the 1% before the open end ist marked light-blue. The arrow shows the direction of movement of the peak magnitude and frequency change due to the perturbation.

The yellow Startpoint also equals to be a positive borestep from Dia 10mm to 11mm at 2% tube length, the blue Endpoint also satisfies to be a negative borestep from Dia 11mm to 10mm at 98% tube length, so these 2 points are of further interest, concerning the effects of boresteps compared to local perturbations, which can be also considered as boresteps, but followed by invers boresteps back to boresize.



same as above, Mode #3, but now with a moving enlargement „Gap",
with cross sectional area ratio being invers prop. to the constrictions, q0=1,1

This sideletter is submitted to INRIA / Openwind to get hopefully more usefull input and will be extended in the future!