BIAS-A Computer Aided Test System for Brass Instruments

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SUMMARY

BIAS (Brass wind Instrument Analyzing System) was developed to test brass instruments without the influence of the player. "High level players" are sometimes able to judge the musical quality of a trumpet, horn, trombone, etc. within a few minutes. But usually musicians get completely confused, if they have to test a sequence of several instruments. In addition the judgement of the individual player depends on his individual embouchure, the mouthpiece used and so on. There are some methods to assess the objective quality of a brass instrument. These methods however test the acoustic qualities under laboratory conditions.

0 INTRODUCTION

Musician and instrument (especially in the case of brass wind instruments) have to be seen as a physical unit. Intonation, response and accuracy of the played tone are, apart from design and mechanics, the most important characteristics of an instrument for the player. Besides this characteristic acoustical behaviour of the instrument ("objective quality"), an instrument may have many different "subjective qualities", because of the individual interaction between the player and the instrument. The sound of the instrument will not be considered isolated in this work: it is a consequence of that interaction. The graphic and numeric interpretation of the stored data of the measured input impedance versus frequency allows to judge these characteristics.

1 PHYSICS OF A BRASS INSTRUMENT

From the point of an engineer, a brass instrument is a tube with oscillating air (including a regime of standing waves) inside. Whereas a semiclosed (one end open, one closed) cylindrical tube has its resonances at odd multiples of the frequency of the first resonance, a conical one shows, depending on the opening angle, more integer relations [1].

The frequencies for which appear standing waves in the air column depend on the combination of cylindrical and conical parts of the tube, they do not differ much from integer multiples of the first resonance frequency. A player can blow these frequencies without changing the length of the tube, therefore they are called natural tones (Fig. 1).

For using the whole musical notes-reservoire between this series of natural tones (chromatic scale), the tube has to be extended in length. A valve inserts an additional air column, the first resonance and the whole series of natural tones now is placed one more semi-tones lower. Trumpets, horns and cornets have three valves:

1. valve	two semitones lower
2. valve	one semitone lower
3. valve	three semitones lower

These valves can be used together with an additional result. As the length of the inserted air column relates to the length of the instrument without additional tube, there is difference between the combination of the first plus second valve to the third one. This property can be used to correct little intonation errors. The use of all valves allows playing of a chromatical scale starting at the second natural tone.

2 MEASUREMENT OF ACOUSTIC IMPEDANCE

2.1 Definition

The input impedance (Z) of an acoustic system is defined as the complex ratio of sound pressure and acoustic volume velocity. With the analogy of

voltage	=	sound pressure (p)
current	=	volume velocity (u)

the two Kirchhoff theorems can be transformed. Fig. 2 shows the equivalent circuit of the unit player - instrument.

2.2 Problems with acoustical measurements

The geometric dimensions inside the mouthpiece in the plane of the lips do not allow the use of a microphone for measuring the volume velocity without disturbing, therefore it seems to be better to substitute the measurement of impedance by the measurement of sound pressure using a volume velocity within the steady state.

Based on the theory of AC circuit the impedance, measured versus frequency, offers informations about resonance condition. At the frequencies of impedance extremas the phase plot crosses the zero line and changes his sign [2],[3]. Therefore the measurement of the phase can be neglected for the frequencies between 20 and 5000 Hz.

2.3 Measurement arrangement

The sinusoidal steady state signal for the measurement is produced by the artificial voice B&K 4219. Using an ohmic acoustic serial impedance $Z_s >> Z_i$ we consider the volume velocity to be constant over the whole frequency range. This impedance consists of a tube (length: 60 mm , diameter: 6 mm) filled with steel wires of different diameters [4]. These small channels do not represent an additional volume which could influence the position of minima and maxima of the impedance plot. The position of microphone and tube compensates the volume of the lips inside the mouthpiece.

The sound pressure at the orifice of the artificial voice can be kept constant with the aid of the built-in condensor microphone/preamplifier and the compressor circuit of the B&K 1023. With a special adapter the instrument is connected to the end of the wire-filled tube. The output voltage of the microphone B&K 4136 is amplified by the Sound Level Meter B&K 2209 and another DC amplifier (INA 101) to get the full range of our I/0-board used for storage of data (Fig. 3).

2.4 Computer aided measurement

The judgement of quality of a brass wind instrument based on interpretation of input impedance needs a large quantity of data: The impedance has to be measured and stored within a frequency range from 20 Hz to 5000 Hz and steps of 1 Hz. The step by step measurement procedure can be automatized by using sweeped sinusoidal test signal. The speed of frequency variation is limited by settling time of the instrument [5]. The plot of the impedance magnitude requires, depending on the "Q" - factor of the internal acoustical resonance circuit, a relatively high resolution in the frequency domain. The linear steps are chosen because of the fact that the resonance frequencies are situated approximately at integer multiples of the first resonance frequency. Impedance measurement at 1 Hz-steps (a F-horn with the first resonance at about 44 Hz needs this density of data) causes the use of a computer aided system which allows an automatical sequence of test signal and storage of measured data for minimizing time needed for measurement and interpretation. Drawing a plot, successive points of the plot are connected by linear interpolation.

The settling time of a brass wind instrument causes a low speed of frequency variation of the sweeped sinusiodal signal. This cannot be generated within a satisfying accuracy in analog way. Therefore we used the programmable clock signal of the data acquisition board as a clock signal for a digital 16 Bit-counter with an additional D/A-Converter to generate a stepwise changed sinusoidal test signal. (It could be generated also by a signal processor.)

3 INTERPRETATION OF INTERNAL INTONATION

3.1 Definition of cent

The cent-unit was established to enable comparisons of frequency relations in a musical sense. The octave is subdivided in 12 half-tones, therefore the relationship between the frequencies of two successive semitones is

$$\frac{f_2}{f_1} = 2^{1/12} = 1.0594 \qquad (1)$$

1 cent is defined as $2^{1/1200} = 1.0005778$ (2)

The frequency relation of an interval can be calculated as

$$d\,[\text{cent}] = 1200\,\frac{\log f_2 / f_1}{\log 2} \qquad (3)$$

3.2. Judgement of intonation

Whereas a string instrument does not physically limit the range of correcting the pitch, the situation with brass instruments seems to be more complicated because of the "interaction of player and instrument". A brass instrument "offers" a special intonation equal to the frequencies of its impedance peaks. The player is able to change these playable frequencies in a small range according to his physiological condition.

Musicians call it "to lip up" or "to lip down". Variation of lip tension, breath-support and the support of the whole mouth-region allow to change the tuning. Due to the fact that adaption is no more optimal, the player has to supply more energy, the result is "different" sound, moreover the note becomes "instable". Therefore the frequencies with resonances can be seen as a very important component of quality of a brass instrument.

3.3 Intonation error of natural tones

If we consider that an instrument has its resonance peaks exactly at the integer multiples of the fundamental we cannot expect that the frequencies of these peaks correspond with the frequencies of the tempered tonal system. Fig. 4 shows the intonation errors of the natural tones. The frequency relation of nearly all natural tones (with exception of numbers 7, 11, 13) to the fundamental harmonizes exactly, or with small errors, with musical intervals.

This is the basis of using brass wind instruments in our tone system. We see on the other hand that the tonal system claims resonance frequencies differing from those of an "ideal" conical tube for the used natural tones.

3.4 Reference pitch

Orchestral playing always requires adjustments of intonation to the melody instruments (e.g. first violins or woodwinds) and to the harmony the played tone is belonging to. These corrections take place in a range which is greater than the frequency differences between different temperatures of keyboard stringed instruments. This is the reason why we took the tempered tonal system for reference.

3.5 Tuning: Interpretation of measured resonance frequencies

The length of the tube of a brass instrument can be adjusted by the tuning slide to find the best adaption to the other players intonation. The measurement of the input impedance takes place with a certain position of the tuning slide. If we want to get information about intonation behaviour of a instrument, we have to find a reciprocal method to get the tuning (the frequency of the a_1) which would have caused the player to choose this position of the tuning slide. The procedure of tuning the instruments from the chamber pitch is quite complex, requiring considerable experience and "feeling".

3.6 The algorithm

The first step of interpreting an impedance plot is to get the frequencies with resonance peaks. Having got them, we have to look for the special chamber pitch (which determines the frequencies of all natural tones) with the minimal sum of relative quadratic deviation [6]. The solution of this minimum problem is the wanted "ideal" frequency of the fundamental. Now we have only to decide, which natural tones should be included in this calculation to have an good accordance to musical practice.

a) The player often uses one tone on his instrument for "pitch-reference". This need not be the written a_1: On the F-horn (a transposing instrument) the written a_1 is played by the 10^{th} natural tone. Fig. 4 indicates, that especially this natural tone is too low (this fact is also valid for trumpets, cornets, ...). Having the correct intonation of this tone would cause any others being too high.

b) Often you can observe a player who uses more than one tone to find his optimal intonation. His chosen position of the tuning slide will be a compromise (according to the minimum problem).

After calculating the frequencies of the tempered tonal system, the intonation error [cent] can be printed in a different way to give information about the acoustical behaviour of the instrument (Fig. 5 and 6).

4 THE SUM FUNCTION

4.1 Definition

Measuring the input impedance of the instrument, a sinusoidal signal is used for excitation. As the excitation signal of the real musician contains many harmonics, not only the value of the input impedance at e.g. 220 Hz (if he plays an "a") is important, but the sum of the values at 220 Hz, 440 Hz, 660 Hz, 880 Hz, ... ,because the frequency of the played note is directly related to that frequency of the impedance plot, at which the sum of the values of all harmonics of the input spectrum has its maximum. Therefore we considered a "Sum-Function". The sum-function is defined as

$$S_n = \frac{\Sigma\ (P_{n \cdot i})}{\Sigma\ i} \tag{4}$$

i . . . number of harmonic taken in account
S_n . . . magnitude of the sum-function at frequency n
$P_{n \cdot i}$ . . . input impedance at frequency $n \cdot i$
(P = primary data)

In Fig. 7 we see such a sum function for a horn (F-horn) which corresponds for some aspects with the "playing feeling" of the musician (the realisation of notes of the low register is "easier", than such of the high register). Looking more close to this sum function, one can see that all harmonics of the input spectrum of the player have the same amplitude (Fig. 8). In addition to this, experiments showed that the calculation of the internal intonation using formula (4) produced discrepancies to the frequency values of real played notes (Fig. 9, 10).

Taking in account the importance of the different amplitudes of the harmonics of the human input spectrum, the amplitude values are simulated by "weighting" the various harmonics during the summation-procedure. The weighted sum-function is defined as

$$S_n = \frac{\Sigma\ (P_{n \cdot i}) \cdot W_i}{\Sigma\ (W_i)} \tag{5}$$

S_n . . . magnitude of the weighted sum-function at frequency n
W_i . . . weight of the i^{th} harmonic

The "weight" of a harmonic is given by the linearized difference to the amplitude of the fundamental frequency of the individual input spectrum of a player. To get values close to the real playing practice of the musicians, variation of the weights depending on playing range (high or low notes) and dynamic (piano, mezzoforte, fortissimo) is necessary. Fig. 11 shows a weighted sum-function in contrast to a sum-function where all weights are equal one.

4.2 The input spectrum

The realistic use of this principle requires the knowledge of the input spectrum.The input signal cannot be recorded directy without destroying the mouthpiece. The use of a prepared reference mouthpiece does not seem to be convenient as information of measurement is not representative if the player cannot use the mouthpiece he is accustomed to (musicians usually spend years looking for "their" optimal mouthpiece). The influence of the mouthpiece to the unit player-instrument must not be neglected. Therefore we chose a indirect method to get the spectrum of the input signal. The transfer function of an instrument can be calculated with the help of an artificial player. This allows to get the input spectrum of the instrument.

4.3 The artificial player

This machine has been constructed by G. Widholm, H. Pichler and H. Dum at Institut für Wiener Klangstil in cooperation with the Institut für Allgemeine Elektrotechnik, Technical University of Vienna under the permission of K. Wogram, who developed this mechanical playing device in the early seventies. The function is based on the "principle of a hole-sirene" [2], the artificial player makes it possible to play a brass wind instrument like a human player but in a reproducible way.

Fig. 12 shows the mechanical construction which enables a nearly sinusoidal variation of opening area in accordance to the function of the human lips [7]. A DC-motor drives a half-opened cylinder ("rotor") with 16 quadratical slits. The rotor is surrounded by a box with air supply. Different masks can be put on the slit of the box for varying the input spectrum [8].

The frequency can be selected

a) by a keyboard (frequency range 65.4-987.8 Hz) with additional precision tuning (+/- 100 cent).

b) manually by internal ramp voltage.

c) external in connection with the XY-Recorder B&K 2308 or a PC.

The wow and flutter is situated within +/- 0.75 Hz (lowest octave) and +/- 0.05 Hz (4th octave). The range of static atmospheric pressure, selected by thyristor control, is situated between 20 and 1800 (+/- 2) mm water column. Air temperature is measured inside the rotor and controlled digitally.

Measurement takes place in an anechoic room. The microphone B&K 4165 is positioned at a distance of 1m from the bell. The output signal of the amplifier B&K 2609 is the input signal of the audio processor Sony PCM-F1, digital data is stored at a video cassette Sony SL-F1E. Using the correct calibration it is possible to calculate the original sound intensity level. The spectrum calculated by Signal Analyzer B&K 2033 is transferred to the PC by a IEEE-Interface and processed.

4.4 Measurement of the input spectrum

At first PCM - records are made of the artificial player alone (spectrum 1). Then the artificial player with the instrument (spectrum 2) and finally the musician with the instrument (spectrum 3) at different dynamics are recorded (Fig. 13). The sound-spectrum of a played note depends on the musical dynamic and the imagination of the "ideal sound" by the player. Therefore it is necessary to extract the spectrum of various tones and dynamics to obtain representative input spectra for different playing situations.

The difference between the amplitude values of the harmonics of spectrum 2 and spectrum 1 represents discrete points of the transfer function of the instrument, these are subtracted from the output spectrum (spectrum 3) to get the input spectrum. The first harmonic of this new input spectrum is set equal 1, the difference of the others to the first is calculated by linearization of the dB-differences. Fig. 14 shows the input spectrum and the extracted weigths for three dynamics of a horn player.

The influence of the input spectrum on the shape of the impedance plot shows Fig. 15.

5 INTERPRETATION

The way of interpretation does not change if a weighted sum-function is considered instead of a pure impedance plot. The program BIAS allows to plot each frequency range which is desired to look at. Three plots can be put together. All numeric data of intonation judgement can be printed in a table (Fig. 16) which allows to compare the measured resonance frequencies, the interpolated tempered frequencies, the impedance differences and the "Q"-factors (Fig. 9). The "Q"-factor is calculated as ratio of frequency with maximum and the frequency range above the 3 dB-line.

5.1 Comparison between a good and a bad horn

The bad instrument of Fig. 17 (dashed line) has following defects: Some of the natural tones with odd numbers (5th, 7th, 9th and 11th) have a lower magnitude at the maximum: even for professional players it is nearly impossible to blow these tones.

5.2. Putting the hand into the bell

It is traditional that a horn player puts his right hand into the bell. Apart from the necessity to hold the instrument this has the effect of improvement of the acoustical behaviour in the upper octave: In this frequency range (from the 12th to the 16th natural tone) more energy is reflected from the bell to the mouthpiece instead of being radiated to the surrounding air: The musicians hand causes a smaller diameter of the bell. The peaks of the impedance plot (Fig. 18) become higher, the tones can be played with greater security. The effictive length of the instrument played with the hand inside (dashed line) increases, the peaks are situated at a lower frequency.

5.3. Applications

A computer aided system that analizes brasswind instruments can be used in the stage of development of a new instrument (objective quality) as well as to detect the reason(s) for troubles musicians often have to deal with (subjective quality): If a musician tests an instrument he will not be able to judge objectively: Each instrument has his special qualities and the player gets used to it if he is practicing with this instrument. That means that he corrects tones with intonation errors and blows unconsciously with more energy if this tone has bad resonse. He gets confused if another instrument does not claim these corrections. For example he will play a tone with correct intonation too high because he is used to lip him up. In these cases an objective judgement of instrument quality can be helpful.

An example for graphic representation of a special problem of playing technique (related to the subjective quality) shows Fig. 19:

The solohorn player of a Viennese Orchestra always had problems playing the written "g"; it was too high. To solve the problem he lowered the playing frequency with the tuning-slide. After doing that the intonation was correct, but the response of the instrument so weak, that he generally produced a "crack" playing that note during a solo-part which requires a musical dynamic of "piano".

6 CONCLUSION

The presented hard- and software system **BIAS** seems to be a suitable tool for the use in musical instrument production as well as a tool for the individual player for diagnosis of individual problems concerning the interaction between player and instrument.

Several experiments with professional players and their instruments pointed out a good correspondence between calculated values and reality. Testing the objective quality of the different elements of an instrument (e.g. the mouthpiece, mouthpipe, F-crook,...), BIAS allows predictions for optimal configurations for a given brass instrument and the diagnosis of results after mechanical changes by craftsmen.

To ensure and improve the representativ quality of the results we obtained up to now, a lot of measurements will have to be carried out in the future.

7 REFERENCES

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Fig. 1: Scale of natural tones.

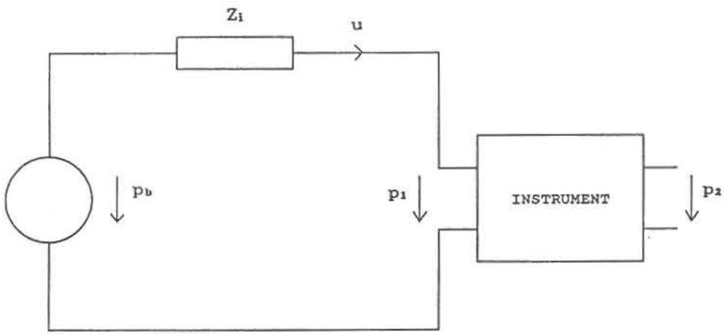


Fig. 2: Equivalent circuit of the unit player - instrument.

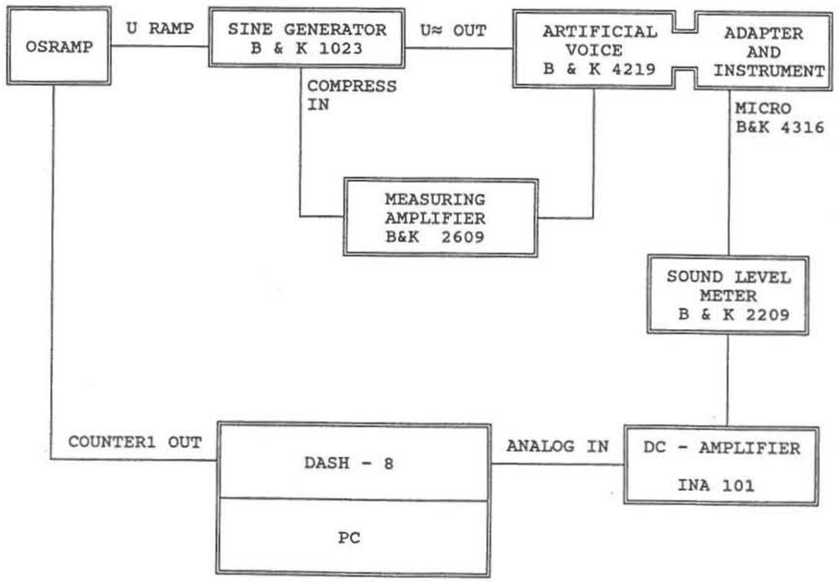


Fig. 3: Block diagram of impedance measurement.

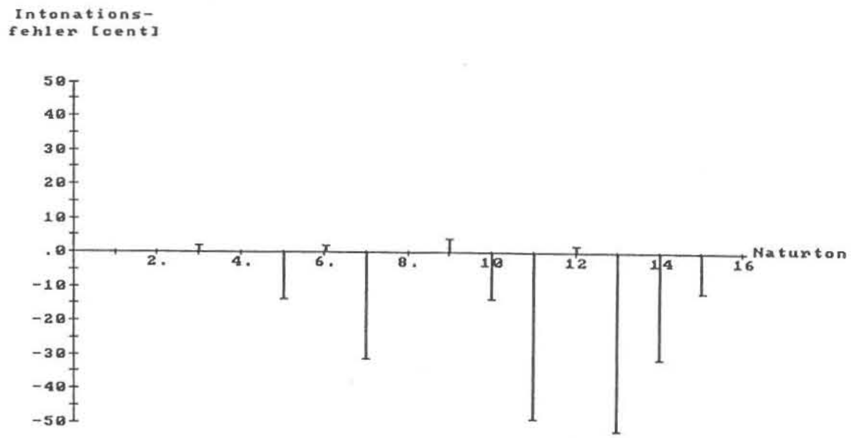


Fig. 4: Calculated intonation error for natural tones with frequencies at integer multiples of the fundamental due to the equal tempered scale.

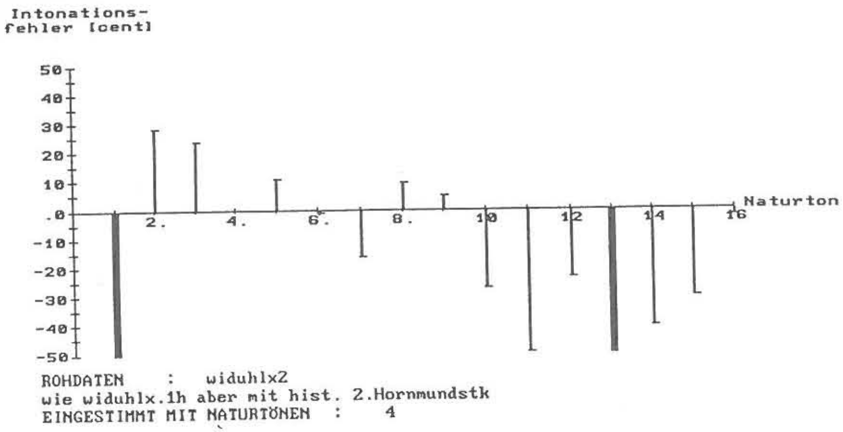


Fig. 5: Calculated intonation error for a horn.

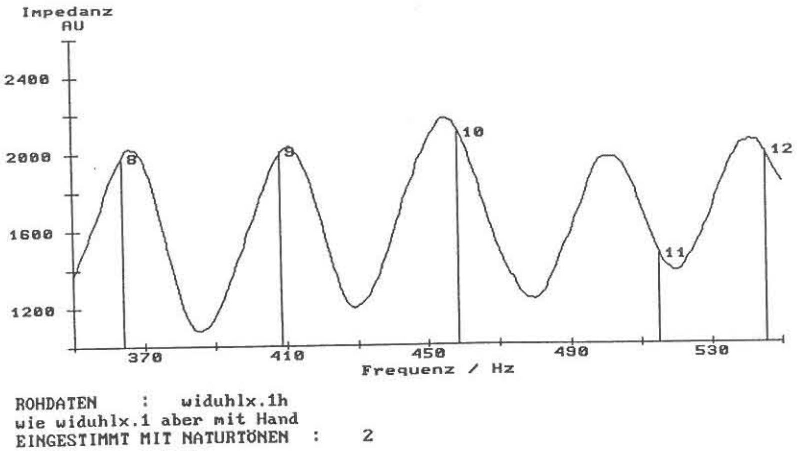


Fig. 6: Detail of in figure 5 shown data. The bars mark the frequencies corresponding to the equal tempered scale.

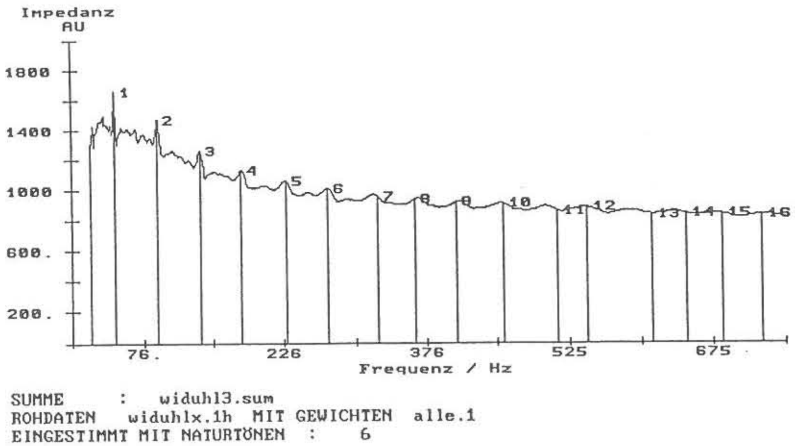


Fig. 7: Sum function of a horn according to (4).

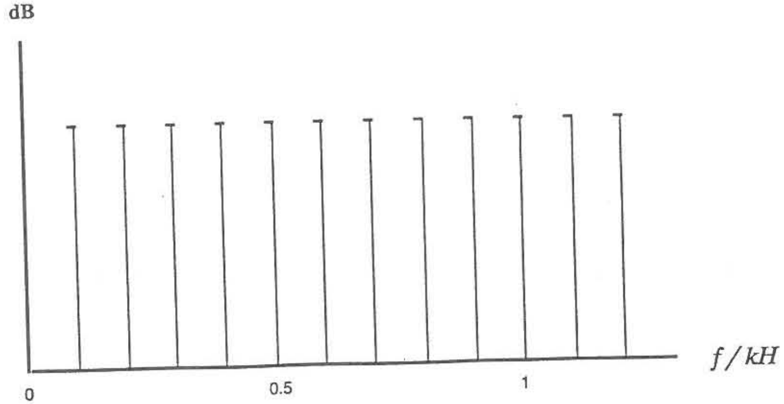
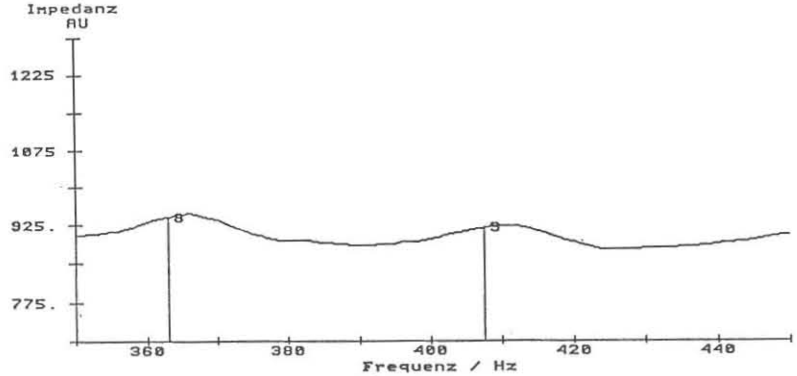
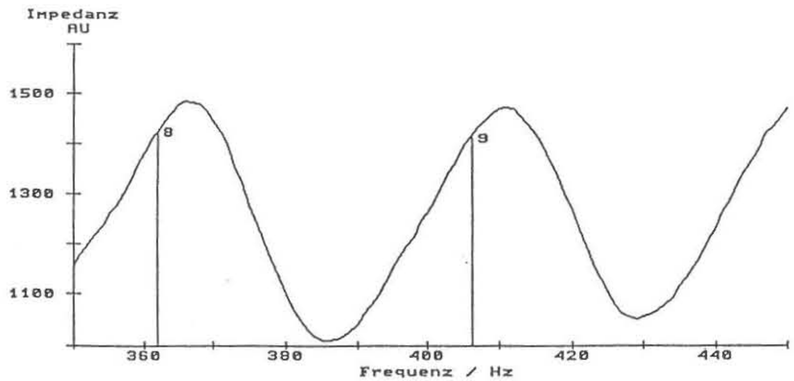


Fig. 8: Theoretical input spectrum of formula (4).



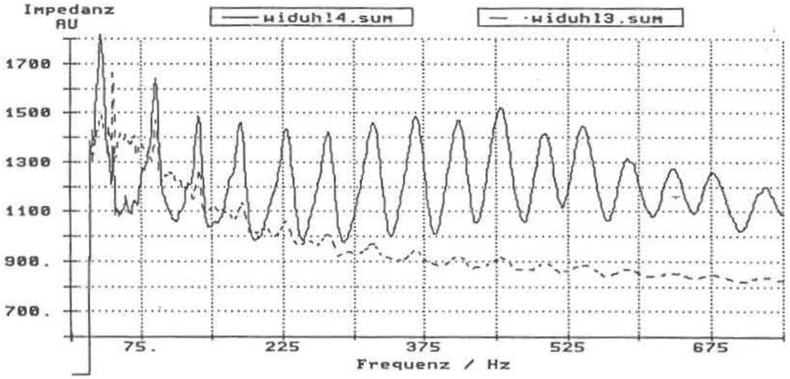
SUMME : widuhl3.sum
ROHDATEN widuhlx.1h MIT GEWICHTEN alle.1
EINGESTIMMT MIT NATURTÖNEN : 3

Fig. 9: Calculated intonation error for the 8th and 9th natural tone according to the input spectrum of Fig. 8.



SUMME : widuhl4.sum
ROHDATEN widuhlx.1h MIT GEWICHTEN ff350.wid
EINGESTIMMT MIT NATURTÖNEN : 5

Fig. 10: Calculation of the intonation error using extracted weights and the sum-function (5).



widuhl4.sum : ROHDATEN widuhlx.1h MIT GEWICHTEN ff350.wid
widuhl3.sum : ROHDATEN widuhlx.1h MIT GEWICHTEN alle.1

Fig. 11: Comparison between calculated sum function plots with extracted weights (solid) and theoretical weights (all equal one).

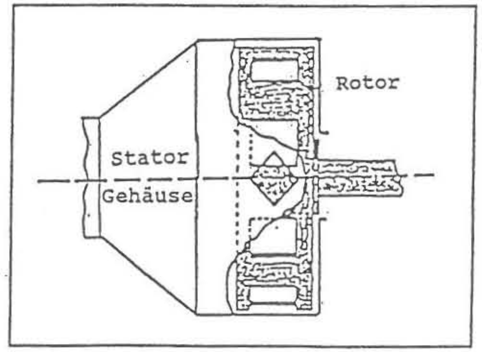


Fig. 12: Mechanical blowing device of the artificial player.

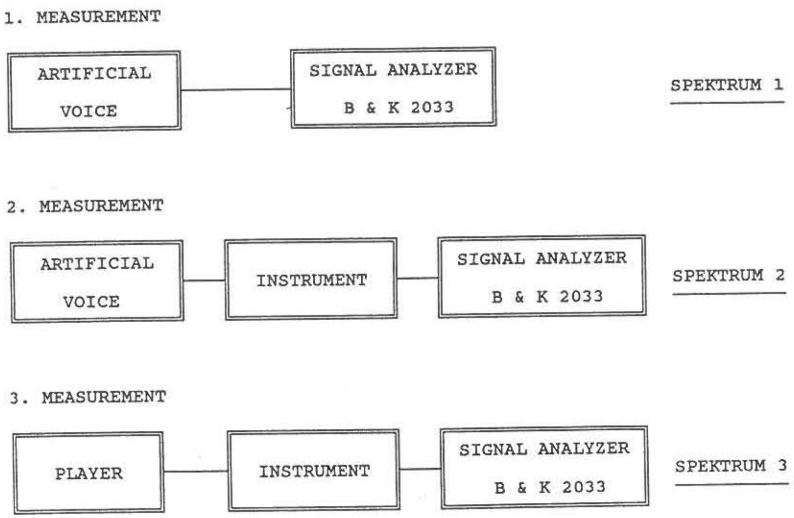


Fig. 13: Diagram of the process for obtaining source spectras for extraction.

	Harmonic sound pressure level [dB]			weight		
	p	mf	ff	p	mf	ff
1	59.6	66.4	71.3	1	1	1
2	30.5	39.2	46.5	0.035	0.043	0.057
3	31.1	43.3	54.4	0.038	0.069	0.142
4	14.2	35.9	48.8	0.005	0.029	0.075
5	3.0	24.4	39.3	0.001	0.008	0.011
6	-	18.6	34.2	-	0.004	0.020
7	-	17.2	40.8	-	0.003	0.029

Fig. 14: Table of extracted weights for three dynamic levels.

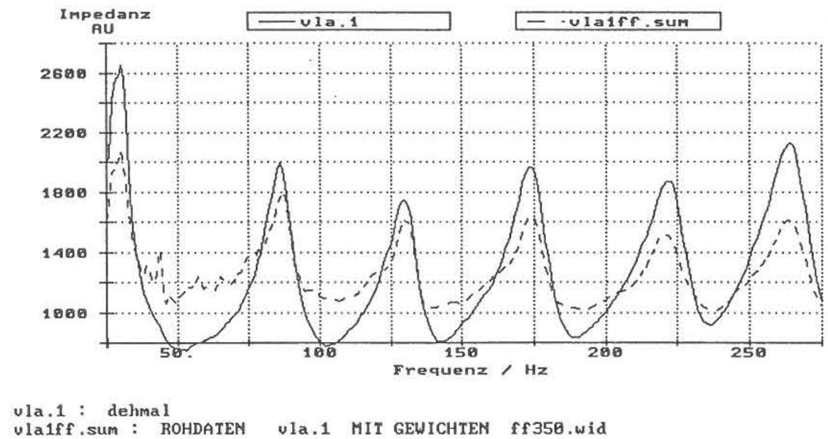


Fig. 15: Comparison between primary data (solid) and weighted sum.

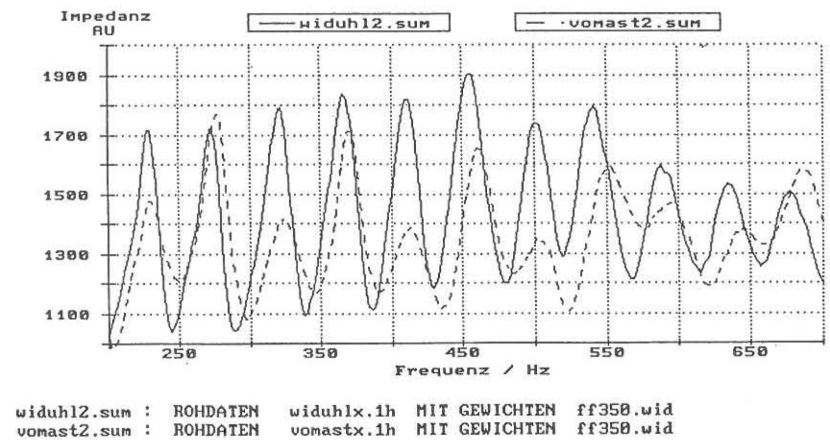


Fig. 16: Weighted sum function for a good (solid) and bad quality horn.

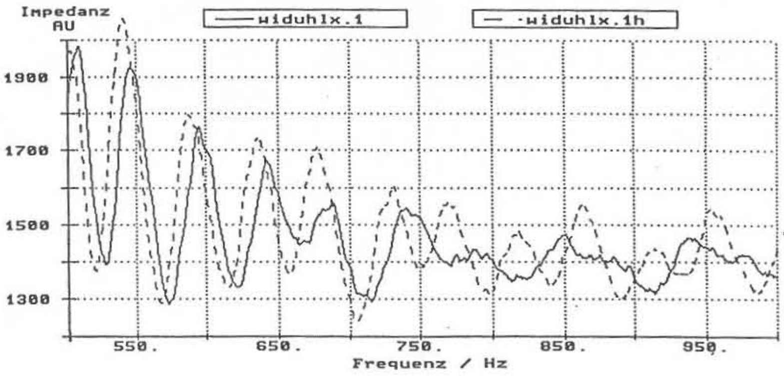
ROHDATEN : F-HORN widuhl.2a

KOMMENTAR : Widuhl.1 plus Hand

EINGESTIMMT NACH NATURTÖNEN : 6

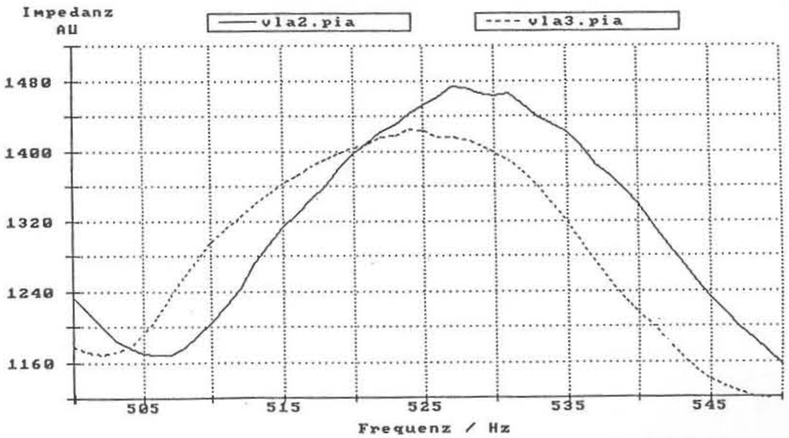
NATUR TON	TEMPERIERT FREQUENZ Hz	TEMPERIERT IMPEDANZ AU	MAXIMUM FREQUENZ Hz	MAXIMUM IMPEDANZ AU	INTONATIONS FEHLER cent	IMPEDANZ DIFFERENZ AU	GÜTE
(1 C	46.6	806.4	42.9	812.4	-137.4	-6.6	-)
2 C	93.1	840.2	99.0	849.0	123.7	-13.8	5.40
3 G	139.5	875.5	141.1	875.9	-6.2	-.5	8.85
4 c	186.2	927.6	186.8	926.4	16.6	-1.4	10.89
5 e	234.6	976.3	234.8	977.8	2.9	-2.7	12.71
6 g	279.0	1022.0	278.6	1020.1	.0	.0	14.05
(7	331.8	1060.3	328.4	1076.4	-14.6	-16.7	14.04)
8 c	372.4	1141.0	374.8	1155.8	11.9	-17.0	16.45
9 d	418.0	1190.3	418.4	1193.5	4.0	-8.7	17.56
10 e	469.2	1283.5	465.6	1311.8	-11.9	-30.5	16.32
(11	526.7	1137.8	509.1	1328.5	-55.7	-195.2	19.97)
12 g	558.0	1466.0	553.3	1514.7	-12.5	-50.0	19.54
(13	626.3	1297.4	597.9	1494.7	-80.1	-197.6	21.69)
14 b	663.6	1291.7	642.5	1575.0	-57.2	-283.3	22.44
15 h	703.0	1299.0	687.7	1655.0	-40.0	-358.0	22.61
16 c	744.8	1474.7	736.0	1605.8	-20.7	-131.3	-

Fig. 17: Table of internal intonation for a horn due to the equal tempered scale.



widuhlx.1 : Uhl Wid Zischek +Satzl E71
widuhlx.1h : wie widuhlx.1 aber mit Hand

Fig. 18: Influence of the players hand (dashed line) positioned inside the bell.



vla2.pia : ROHDATEN vla.2 MIT GEWICHTEN piano.1
vla3.pia : ROHDATEN vla.3 MIT GEWICHTEN piano.1

Fig. 19: Graphic representation of the response for the 12th order natural tone (written g2) for different positions of the tuning slide. (Solid: normal position, good response, but too high. Dashed: correct intonation, but bad response).