In-depth acoustic modeling and temperament studies of 18th and early 19th century baroque bassoons comparing originals and reproductions by maker, time period, and region

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The researchers developed a non-linear least squares acoustical modeling procedure and precision measurement techniques of physical dimensions to characterize Baroque bassoons. They deduced 1) Natural and playing pitch; 2) Reed equivalent volume; 3) Acoustic length corrections for the tone holes and boot joint double miter bend.

The initial study expanded to 44 original bassoons and 14 reproductions. Original makers included Scherer, Poerschmann and Eichentopf. Multiple bassoons by five makers were compared and measureable differences between period and contemporary makers were noted.

Unique to woodwinds, dimensional measurements determining pitch allowed an exhaustive study comparing 47 temperaments selected from English, French, German and Italian temperaments of the 18th and early 19th centuries. Sensitivity was enhanced by including forked fingerings, E-flat and B-flat. For each instrument results indicated a grouping of 5-7 preferred temperaments, typically mean-tone. Preferred temperaments exhibited a correlation with region and maker.

Pitch differences by note for every temperament were evaluated for each bassoon. The model demonstrated the proficiency of 18th century bassoon makers. It is also predictive. In about 25% of the instruments, minor changes to the wing joint result in a significantly improved “designer” bassoon. The model also illustrates bassoon evolution leading to changes in mid-19th century bassoons.

1 Introduction

The primary goals of the current study are to characterize the acoustical performance of Baroque bassoons. We developed an analytical modeling procedure to compare the experimental and theoretical acoustic lengths. Physical measurements (106/bassoon) of tone hole positions, diameters and lengths, conical bore radii and overall dimensions of the bassoon were incorporated into the model. A temperament (scale) was chosen, from which the theoretical acoustic lengths associated with the bassoon notes were calculated. A non-linear least squares procedure was developed to simultaneously minimize the difference between the experimental and theoretical acoustic lengths for each of the 13 primary notes on the Baroque bassoon. These in turn were converted to frequency differences or “frequency residuals” expressed in musical cents (semi-tone = 100¢). The overall acoustical performance can be characterized by the standard deviation (STD DEV) of frequency residuals or equivalent χ^2 value. Results from the optimized acoustical model include 1) the natural pitch of the bassoon, 2) the length of the bocal + bocal extension (the distance from the end of the wing joint or beginning of the bocal to the tip of the conical bore), 3) the tone hole corrections, 4) the acoustical length of the boot joint turn-around and 5) the bore angles.

The natural pitch is defined as the pitch the bassoon would have if the tone holes’ lengths included the bocal and bocal extension. Note that the conical bore is truncated at the end of the bocal and a double reed inserted to create a playable instrument. If the natural and playing pitches are equal, the volume of the conical bocal extension is equal to the reed volume. To actually build such an instrument would require extraordinary precision and accuracy typically beyond the maker’s capability. To overcome this deficiency, makers usually design the natural pitch about a semi-tone (a factor of 1.059) above the desired playing pitch. Since the acoustical model directly predicts the natural pitch and the bocal extension values, it also predicts the reed volume required to meet the chosen playing pitch.

A wide range of natural pitches was feasibility tested via the non-linear least squares modeling procedure. For each possible natural pitch, the acoustical model is optimized for minimum STD DEV of the frequency residuals. This procedure is repeated in 0.25 Hz steps from 350-500 Hz. The resulting minimum of the inverted parabola is the “best fit” acoustical performance solution. Low χ^2 or frequency residuals, “freq res”, indicate good acoustical performance.

Since we have little knowledge of what temperament (scale) the bassoon maker targeted, we repeated the above process for 47 known temperaments from the 15th C. – 20th C. with a focus on 18th and early 19th C. temperaments. Included in these calculations are two chromatic notes, E-flat 3 and B-flat 2. There are no separate tone holes on the Baroque bassoon for these notes, rather they are obtained by ”forked” fingering (blocking the adjacent downstream tone hole) which forces the use of the 2nd and 3rd adjacent tone holes to create the chromatic acoustic lengths. The surprising result is that the acoustical model exhibits no anomalies and acts as if there were separate tone holes for the chromatics. This is a stringent test of the non-linear least squares procedure. The use of chromatics also enhances temperament sensitivity allowing for discrimination among temperaments that would otherwise produce identical results with other temperaments.

2 Bassoon Analysis

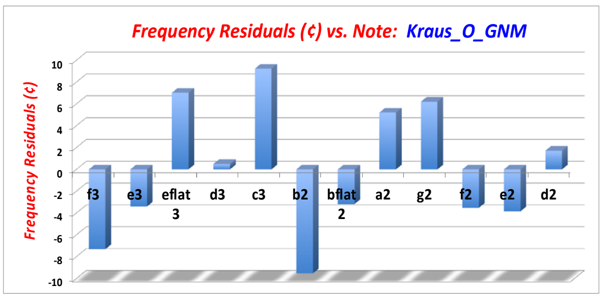

Figure 1: Frequency Residuals (¢) vs. Note for the original Kraus bassoon in the collection of the German National Museum (Kraus_O_GNM)

The current study included 44 original, 14 fine copies and 18 "redesign" bassoons. Figure 1 shows the distribution of frequency residuals by note for an original Kraus bassoon. Positive residuals (E-flat 3, C3, and G2) indicate the note is sharp, while negative residuals (F3 and B2) are flat. The residuals for the remaining notes are small and beyond the level of our perception.

The nomenclature we adopted to identify bassoons included the name of the maker, an O or a C (original or copy), owner name and additional information if needed, e.g. Kraus_O_GNM. We have chosen a representative sample of bassoons to present in this paper. The entire study results are extensive and available to other researchers.

We studied five groupings of original bassoons by makers (Porthaux, Prudent, Eichentopf, A Grenser and H Grenser) in an effort to observe similarities/differences in acoustical performance. Included in the study were modern copies to assess their performance. In Figure 2 we compared six Porthaux originals. The STD DEV of frequency residuals varied from 5 to 11¢, a very good rating for acoustical performance. Also note that we measured short and long wing joint versions of the Basel and MET instruments.

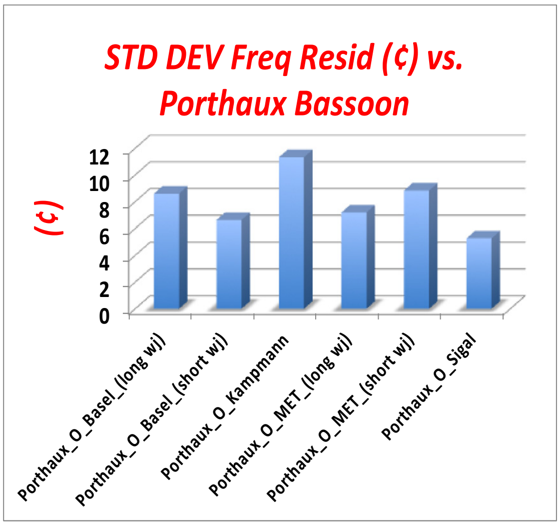

Figure 2: STD DEV Frequency Residuals (¢) vs. Porthaux bassoons

In Figure 3 we compared the average frequency residuals of the Porthaux bassoons by note. Several notes, E-flat 3, D3 and A2, exhibited larger than average frequency residuals indicating possible areas where improvement might be achieved (see section 4).

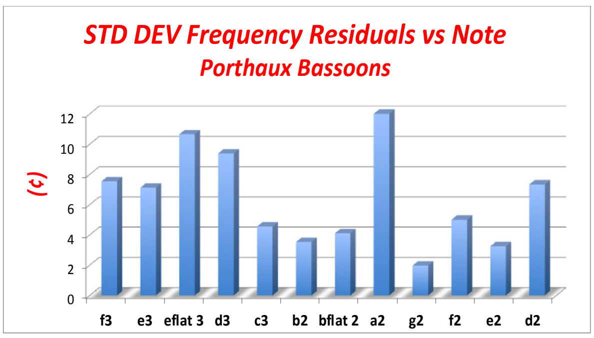

Figure 3: STD DEV Frequency Residuals (¢) vs. Note for Porthaux Bassoons

3 Temperaments

We developed a procedure to evaluate the most probable temperament match to individual bassoons. A set of theoretical acoustic lengths was generated, one for each of the forty-seven temperaments. The non-linear least squares fitting procedure was applied and the results were rank ordered from 0 to 46. Ranks 0-3 represent the most probable temperaments. Typically the first 4-7 temperaments are statistically equivalent.

Shown in Figure 4 are the results of the first ten temperaments for the Porthaux_O_Sigal in rank order. Note that the χ^2 value has doubled indicating a strong preference for the initial temperaments.

In the following subsections we discuss several examples of the temperament analysis grouped by maker.

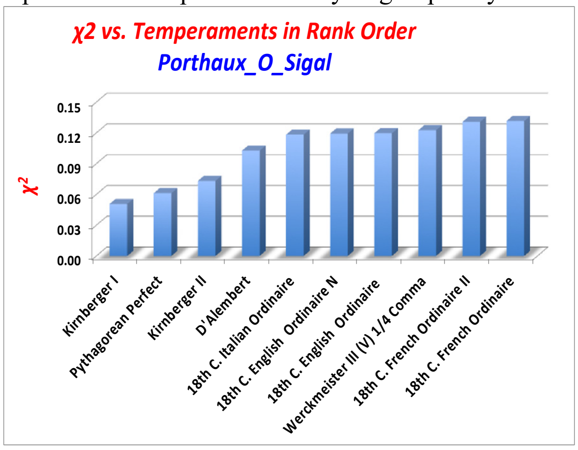

Figure 4: Porthaux_O_Sigal: $\chi 2$ vs. Probable Temperaments

3.1 Grenser A Examples

We selected nine probable temperaments and found the average temperament rank position over two categories of Grenser A bassoons, Original and Original + Redesign. The Redesign category will be dealt with in Section 4. In Figure 5 we plotted 1/Average Temperament rank. Note that the Just temperament is 4x more probable than any other temperament.

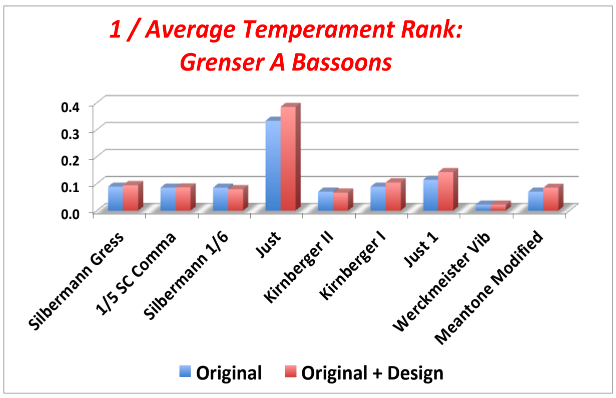

Figure 5: 1/Average Temperament Rank for Grenser A bassoons

We created a grading table of temperament rank order for the most probable temperaments vs. bassoons (in this case Grenser A). The average rank order for each temperament is noted at the bottom of the table (in blue).

	Silbermann Gress [1]	1/5 SC Comma Meantone	Silbermann 1/6 Comma	Just	Just 1	Werckmeister Vib
C_Cottet_Rachor	17	10	2	43	45	0
O_Leipzig (#1376)	4	5	11	0	18	46
O_Leipzig (#1377)	34	33	23	2	4	46
O_Leipzig (#1378)	0	1	2	9	13	43
O_Sigal	7	8	11	1	0	44
O_M_Sigal	8	11	16	1	0	44
AVERAGE	11.7	11.3	10.8	9.3	13.3	37.2

Figure 6: Rank Ordered Temperaments for the Most Probable Temperaments vs. Grenser A Bassoons

The Just temperament has the most probable average rank order value (9.3) Note that Cottet_Rachor copy has a rank order of 43, "most unlikely" category. If this instrument is removed, the average rank order for the Just temperament decreases to 2.6, a strong case that the original Grenser A bassoons were most probably made in accord with Just temperament. The Cottet copy fits both the Silbermann 1/6 Comma and the Werkmeister Vib temperaments, ranking 2 and 0, respectively. The original bassoons are definitely not Werkmeister Vib since their rankings are 43-46, the "most unlikely" category.

3.2 Prudent Examples

Results of the analysis of the original Prudent bassoons (1/Average Temperament Rank) show that the Werkmeister III(V) ¼ Comma are 20 times more probable than other temperaments. Further in Figure 7, the average temperament rank of all Prudent bassoons was 8.75. Note the de Koningh Prudent copy ranks 41st for the Werkmeister III choice. If this bassoon is removed from the average, the rank order decreases to 4.1. The de Koningh copy best matches either of the Silbermann temperaments.

	Werckmeister III (V) 1/4 Comma	Werckmeister III (V) 1/4 Comma
C_Cottet_Rachor	16	16
C_Cottet_Rapoport	1	1
C_de Koningh_Coelho	41	
O_Jeltsch	0	0
O_Sigal	0	0
O_M_Sigal	0	0
O_van Rijm	1	1
O_M_van Rijn	11	11
AVERAGE	8.75	4.14

Figure 7: Rank Ordered Werkmeister III(V) ¼ Comma Temperament Grading Table for Prudent Bassoons

3.3 Eichentopf Examples

We measured 2 original Eichentopf bassoons, GNM (Nurnberg) and Linz and 4 copies by Cottet, de Koningh and Ross.

	Kirnberger I	Pythagorean Perfect	Werckmeister II (IV) 1/3 Comma	D'Alembert	Kirnberger II	18th Century French Ordinaire II
C_Cottet_Rachor	2	0	1	3	20	4
C_M_Cottet_Rachor	0	19	1	6	11	7
C_de Konigh_Vallon	0	1	3	12	22	10
C_Ross_Fix	4	40	32	18	1	11
O_GNM (Nurnberg)	0	1	5	6	2	11
O_Linz (Dart)	3	1	22	2	0	8
AVERAGE	1.50	10.33	10.67	7.83	9.33	8.50

Figure 8: Rank Ordered Grading Table for Eichentopf Bassoons

The average rank order results for the temperament Kirnberger I was 1.5. All others were >7.8. Other possible temperaments include Pythagorean Perfect, Werkmeister II and Kirnberger II, but the most probable temperament choice is Kirnberger I.

3.4 Porthaux Examples

We analyzed 6 Porthaux bassoons, all originals. As shown in Figure 9, temperament Ordinaire #298 had an average rank order of 4.5, about 50% lower than the next most probable temperaments, 18th C. French Ordinaire II, Ordinaire #297 and D'Alembert. The Sigal original was ranked 19th. Eliminating it from the average drops the average rank order value for Ordinaire #298 to 1.6, strongly suggesting that the Porthaux bassoons best match the French temperament Ordinaire #298

	Ordinaire #298	D'Alembert	18th C. French Ordinaire I	18th C. French Ordinaire	Ordinaire #297	18th C. French Ordinaire II
O_Basel (long wj)	1	19	0	3	2	21
O_Basel (short wj)	1	7	2	4	3	17
O_Kampmann	4	22	16	14	17	6
O_MET (long wj)	2	6	13	12	8	1
O_MET (short wj)	0	1	4	5	6	2
O_Sigal	19	3	25	23	20	8
Average	4.500	9.667	10.000	10.167	9.333	9.167

Figure 9: Rank Ordered Grading Table for Porthaux Bassoons

4 Bassoon "Redesign" Study

The acoustical performance of the 58 bassoons, as measured by χ^2 value and STD DEV of frequency residuals, ranged from excellent to poor. The χ^2 value varied by a factor of 50 from 0.05 to 2.64, while STD DEV of frequency residuals ranged from 3.17¢ to 26.4¢. For the "Redesign" study we chose 18 bassoons (17 originals and 1 copy) with the poorest acoustic performance results.

We posed the following question: Is the poor acoustical performance due to having the wing joint (WJ) replaced or altered? Since the WJ is vulnerable from the corrosive effects of saliva, the WJ might have needed to be replaced. If so, replication errors in measurement or design could result in poor acoustical performance. To test this hypothesis, we "redesigned" the WJ by either 1) modifying its length or 2) altering the tone hole positions of the F3, E3 and/or D3 or 3) Some combination of 1 and 2. We imposed one ground rule: The resulting bassoon had to be playable, i.e. the tone holes must be in locations that allow the musician to play the instrument.

The results proved quite startling. The acoustical performance of 15 of the 18 bassoons improved dramatically. χ^2 values decreased 40-90%, while the STD DEV of frequency residuals also decreased (25-63%). The frequency residuals of the Sattler_O_M_Leipzig_(#1369), the bassoon with the poorest acoustical performance, improved from 26.4¢ to 11.3¢, a 57% decrease in STD DEV of frequency residuals. Note "redesigned" bassoons are given the designation M, or modified, following the O or C nomenclature. Figure 10 is a comparison of the results of the raw (unmodified WJ) data in blue and the modified

WJ data in red vs. note. There were significant reductions in the frequency residuals in 8 of the 12 notes.

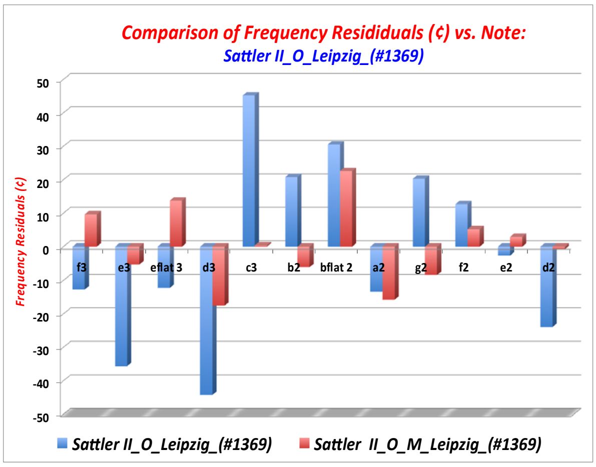

Figure 10: Comparison of Frequency Residuals (¢) vs. Note for "Redesign Results of the Sattler II_O_Leipzig_(#1369). The raw or unmodified results are in blue, while the modified wing joint results are in red.

Figure 11 demonstrates similar "redesign" results for the Scherer original from the MET. Significant frequency residuals decreases are observed for 9 of the 12 notes. Examples include E3 from -35¢ to -5¢, D3 from -45¢ to -19¢, C3 from +45¢ to +1¢ and D2 from -23¢ to -1¢. Overall the STD DEV of frequency residuals decreased 63% from 18.2¢ to 6.7¢.

These reductions occur for minor alterations of the WJ. Note that the length is altered on the boot joint side of the WJ. In addition small changes are also incorporated in the locations of the tone hole positions.

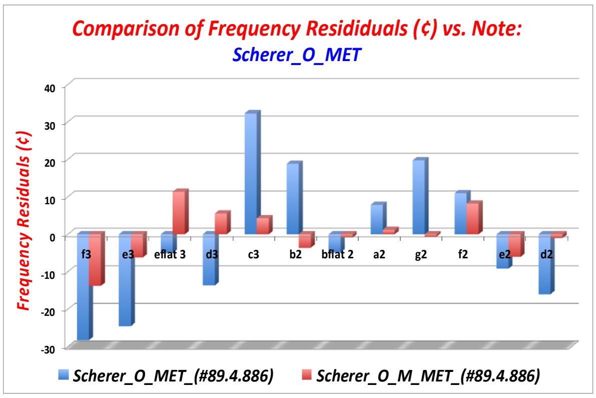

Figure 11: Comparison of Frequency Residuals (¢) vs. Note for "Redesign" Results of the Scherer_O_MET. The raw or unmodified results are in blue, while the modified wing joint results are in red.

In order to demonstrate the effectiveness of the WJ modifications for specific notes we plotted the raw vs. "redesigned" results for each of the "redesigned" bassoons. In Figure 12 we compare the change in frequency residuals for the note G2 vs. bassoon. Eleven of 12 notes exhibited marked reductions of frequency residuals. Recall that G2 is the first note on the bell side of the boot joint, approximately 75cm from the position of the WJ length modification. The magnitude of the change in the frequency residuals is surprising, especially with the relatively small dimensional changes in the length of the WJ and/or position of the WJ tone holes.

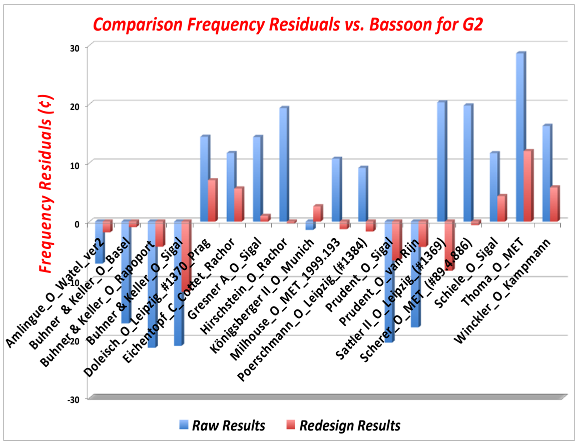

Figure 12: Comparison of Frequency Residuals (¢) vs. Bassoon for Raw and "Redesign" Data for Note G2. The raw or unmodified results are in blue, while the modified wing joint results are in red.

5 Conclusions

We have developed a non-linear least squares modeling tool to assess the acoustical performance of the Baroque bassoon. Inclusion of E-flat 3 and B-flat 2 into the analysis procedure is a stringent test of the acoustical model. We have demonstrated a successful methodology to assess the various possible temperaments and make an informed choice for various families of Baroque bassoons, e.g. Kirnberger I for Eichentopf bassoons. The addition of the chromatics E-flat 3 and B-flat 2 increases the model sensitivity to specific temperaments. If the chromatics were not part of the procedure, many temperaments would give equivalent results.

Our results to date overwhelmingly favor Meantone temperaments and reject other temperaments including equal temperament. Our results demonstrate that the natural pitch of the bassoon is typically a semi-tone higher than the playing pitch. In addition, we have found that the majority of 18th C. bassoons were built with two bore angles, which affects instrument timbre. The model directly calculates the "Phantom" bocal volume or bocal extension. This allows us to predict the vibrational reed volume.

In the "redesign" study we demonstrated that a simple modification of the wing joint could significantly improve acoustical performance of 18th C. bassoons. A combination of small changes in downstream side of the WJ length and/or changes in the WJ tone hole positions will affect the frequency residuals of most of the downstream notes.

We invite museums and collectors to join our collaboration to locate and study original bassoons. In particular we seek pre-1750 bassoons, but any bassoon made before 1830 would prove useful to the study. We have presented only a representative sample of the results from our bassoon database. We hope to share our extensive results with other researchers.

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