Bryant Hichwa/David Rachor

Calculated Success or Accident? An In-Depth Study of the Musical Acoustics of Baroque Bassoons, Comparing Originals and Reproductions, by Maker, Region and Temperament[1]

1 Abstract Hichwa and Rachor developed a physical acoustical modeling procedure to characterise Baroque bassoons.[2] In the previous work the researchers developed techniques to precisely determine the physical size of all aspects of the bassoons. From these data they mathematically deduced 1) natural pitch; 2) playing pitch; 3) equivalent volume[3] of the reed, and 4) acoustic length corrections.

In the current work, the study expanded to include 44 original bassoons and 12 reproductions. Original makers include Scherer, Poerschman, Eichentopf, Prudent, August Grenser and Heinrich Grenser. The researchers' analysis demonstrates major quantitative differences among period and contemporary bassoon makers.

To verify the historical origin of an instrument, an exhaustive study of temperaments was explored. The researchers considered 47 temperaments in a blind mathematical modeling procedure which included several accidentals E♭ and B♭, enhancing the sensitivity to specific temperaments. They chose German, French, English and Italian temperaments originating in the 18th and early 19th centuries. Results for each bassoon indicate a grouping of 5–7 preferred temperaments, typically mean-tone. The preferred temperaments exhibit a correlation between the country of origin and the bassoon maker. Significantly, there was clear distinction of temperaments that were not compatible, including equal temperament.

The model indicates that there were a number of excellent bassoon makers in the Baroque era. In addition, the model is predictive and shows where improvements can be

1 This article is a revised version of a paper submitted at the Acoustics 2012 conference in Nantes: Bryant Hichwa/David Rachor: *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* (Société Française d'Acoustique. Acoustics 2012), https://hal.archives-ouvertes.fr/hal-00810841 (18. 11. 2016). We want to thank the following private collectors: Benjamin Coelho, Mathew Dart, Cindy Fix, Ken Hammel, Jean Jeltsch, Bruno Kampmann, Ricardo Rapoport, Jean-Michel Renard, Marianne van Rijn, Marlowe Sigal, Marc Vallon and Denis Watel. In addition, the following museums contributed to this work: Historisches Museum Basel – Museum für Musik, Museum für Musikinstrumente der Universität Leipzig, Münchner Stadtmuseum, Metropolitan Museum of Art (New York), Germanisches Nationalmuseum (Nürnberg), Musikinstrumentenmuseum Fruchtkasten (Stuttgart)

2 Bryant Hichwa/David Rachor: *Musical Acoustical Modeling of Various Baroque Bassoons*, Presentation at the CIMCIM conference, Rome, September 2009.

3 James B. Kopp: Physical Forces at Work in Bassoon Reeds, in: *The Double Reed* 26/2 (2003), pp. 69–81.

made. In about 25% of the bassoons the model shows that through minor changes, a significantly improved "designer" wing joint can be created. The model is also consistent with the makers' knowledge of the instrument which led to the major changes in bassoon construction in the mid-19th century.

2 Introduction The primary goal of the current study is to characterise the acoustical performance of Baroque bassoons. We have developed an analytical modelling procedure to compare the experimental and theoretical acoustic lengths. Physical measurements (106/bassoon) of tonehole positions, diameters and lengths, conical bore radii and the 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 minimise simultaneously the difference between the experimental (measured) acoustic lengths and the theoretical lengths for each of the 13 primary notes on the lower register of the Baroque bassoon. These differences between the measured and theoretical lengths in turn were converted to frequency differences or "frequency residuals" expressed in musical cents (one semitone = 100 cent). The overall acoustical performance can be characterised by the standard deviation (STD DEV) of frequency residuals or the equivalent χ^2 value. Results from the optimised 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, which would typically lie beyond the maker's capabilities. To overcome this deficiency, makers usually design the natural pitch about a semitone above the desired playing pitch (thus a factor of 1.059). 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 modelling procedure. For each possible natural pitch, the acoustical model is optimised for minimum standard deviation (STD DEV) of the frequency residuals. This procedure is repeated in 0.25 Hz steps from 350 to 500 Hz. The resulting minimum of the inverted parabola is the "best fit" acoustical performance solution. Low χ^2 or frequency residuals indicate good acoustical performance.

Since we have little knowledge of what temperament the bassoon maker targeted, we repeated the above process for 47 known temperaments from the 15th to the 20th centuries with a focus on temperaments of the 18th and early 19th centuries. Two chromatic notes were included in these calculations: E♭3 and B♭2. There are no separate tone holes on the Baroque bassoon for these notes. These 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 chromatic notes. 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.

3 Bassoon analysis The current study included 44 original bassoons, 14 fine copies and 18 "redesigned" instruments. Figure 1 (page 106) shows the distribution of frequency residuals by note for an original Kraus bassoon. Positive residuals (E♭3, C3, and G2) indicate that 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 chose 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 maker (Porthaux, Prudent, Eichentopf, August Grenser and Heinrich Grenser) in an effort to observe similarities and differences in acoustical performance. To assess their performance, the study also included modern copies. In Figure 2 (page 106) we compared six Porthaux originals. The STD DEV of frequency residuals varied from 5 to 11 cent, which was a very good rating for acoustical performance. Also note that we measured short and long wing joint versions of the Basel and MET instruments.

In Figure 3 we compare the average frequency residuals of the Porthaux bassoons by note. Several notes, E♭3, D3 and A2, exhibited larger-than-average frequency residuals, indicating possible areas where improvement might be achieved (see section 5).

4 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.

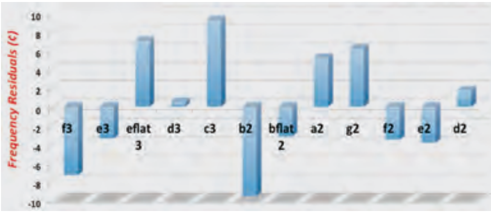

Figure 1 Frequency residuals (cent) versus note for the original Kraus bassoon in the collection of the German National Museum (Kraus_o_GNM)

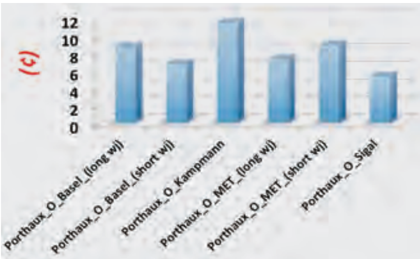

Figure 2 STD DEV frequency residuals (cent) versus Porthaux bassoons

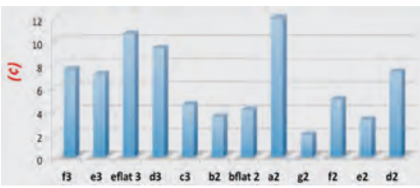

Figure 3 STD DEV Frequency Residuals (cent) versus note for Porthaux Bassoons

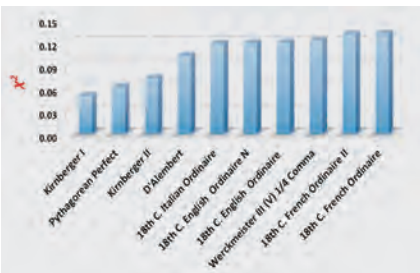

Figure 4 Porthaux_O_Sigal: χ^2 versus probable temperaments

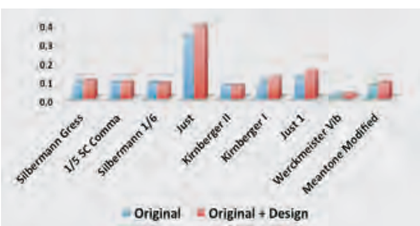

Figure 5 1/Average temperament rank for August Grenser bassoons

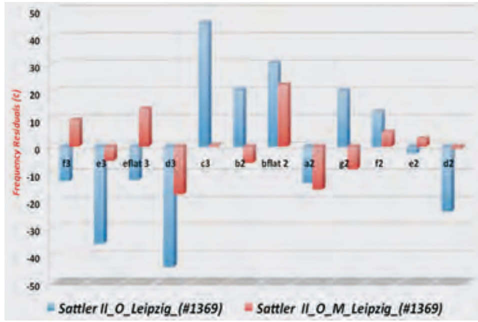

Figure 6 Comparison of frequency residuals (cent) versus note for "redesign" results of the Sattler II_O_Leipzig (# 1369). The raw or unmodified results are in blue, while the modified wing joint results are in red.

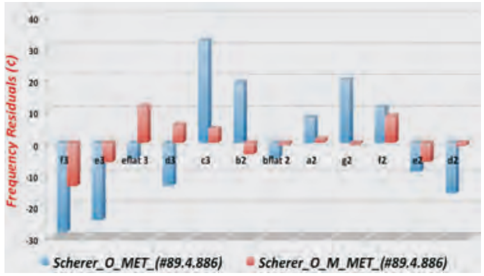

Figure 7 Comparison of frequency residuals (cent) versus note for "redesign" results of the Scherer_o_MET. The raw or unmodified results are in blue, while the modified wing joint results are in red.

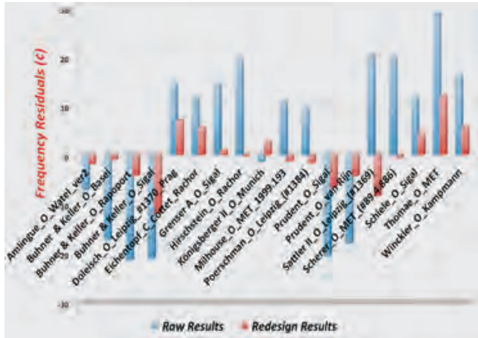

Figure 8 Comparison of frequency residuals (cent) versus bassoon for raw and "redesign" data for the note G2. The raw or unmodified results are in blue, while the modified wing joint results are in red.

Figure 4 shows 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 according to maker. Unlike August Grenser instruments (see Section 4.1), no temperament correlation was observed in the bassoons of Heinrich Grenser.

4.1 August Grenser examples We selected nine probable temperaments and found the average temperament rank position over two categories of August Grenser bassoons: original, and original + redesign. The "redesign" category will be dealt with in Section 5. In Figure 5 we plotted 1/average temperament rank. Note that just temperament is four times more probable than any other temperament.

	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 9 Rank-ordered temperaments for the most probable temperaments versus August Grenser bassoons

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

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

4.2 Prudent examples Results of the analysis of the original Prudent bassoons (1/average temperament rank) show that Werckmeister III (v) ¼ Comma is 20 times more probable than other temperaments. Furthermore, in Figure 10 the average temperament rank of all Prudent bassoons was 8.75. Note the de Koningh Prudent copy ranks 41st for Werckmeister III. 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.

FIGURE 10 Rank-ordered Werckmeister III (V) ¼ Comma temperament grading table for Prudent bassoons

	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

4.3 Eichentopf examples We measured two original Eichentopf bassoons, one each from the German National Museum (Nürnberg) and Linz, and four copies by Cottet, de Koningh and Ross.

FIGURE 11 Rank-ordered grading table for Eichentopf bassoons

	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

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

4.4 Porthaux examples We analysed 6 Porthaux bassoons, all originals. As shown in Figure 12, the Ordinaire # 298 temperament had an average rank order of 4.5, about 50 % lower than the next most probable temperaments, 18th century French Ordinaire II, Ordinaire # 297 and D'Alembert. The Sigal original was ranked 19th. Eliminating it from the average lowers the average rank order value for Ordinaire # 298 to 1.6, strongly suggesting that the Porthaux bassoons best match the French temperament Ordinaire # 298.

FIGURE 12 Rank-ordered grading table for Porthaux bassoons

	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	7
O_Sigal	19	3	25	23	20	8
Average	4.500	9.667	10.000	10.167	9.333	9.167

5 Bassoon "redesign" study The acoustical performance of the 58 bassoons, as measured by the 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 the STD DEV of frequency residuals ranged from 3.17 to 26.4 cent. For the "redesign" study we chose 18 bassoons (17 originals and one copy) with the poorest acoustic performance results.

We posed the following question: Is the poor acoustical performance due to having the wing joint replaced or altered? Since the wing joint is vulnerable to the corrosive effects of saliva it 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 wing joint by either modifying its length, by altering the tonehole positions of the F3, E3 and/or D3, or by a combination of these two options. We imposed one ground rule: the resulting bassoon had to be playable, i. e. the tone holes had to be in locations that allowed 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 by 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 cent. This was a 57 % decrease in the STD DEV of frequency residuals. Note that "redesigned" bassoons are given the designation M, or modified, following the O or C nomenclature. Figure 6 (see page 106) is a comparison of the results of the raw (unmodified wing joint) data in blue and the modified wing joint data in red, versus note. There were significant reductions in the frequency residuals in 8 of the 12 notes.

Figure 7 (page 106) demonstrates similar "redesign" results for the Scherer original from the MET. Significant frequency residual decreases are observed for nine of the 12 notes. Examples include E3 from -35 to -5 cent, D3 from -45 to -19 cent, C3 from +45 to +1 cent and D2 from -23 to -1 cent. Overall, the STD DEV of frequency residuals decreased 63 % from 18.2 to 6.7 cent.

These reductions occurred in minor alterations of the wing joint. Note that the length was altered on the boot joint side of the wing joint. In addition, small changes were also incorporated in the locations of the tonehole positions.

In order to demonstrate the effectiveness of the wing joint modifications for specific notes, we plotted the raw versus "redesigned" results for each of the "redesigned" bassoons. In Figure 8 (page 106) we compare the change in frequency residuals for the note G2 versus bassoon. Eleven of 12 notes exhibited marked reductions of frequency residuals. We should remember that G2 is the first note on the bell side of the boot joint, approximately 75 cm from the position of the wing joint 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 wing joint and/or the position of the wing joint tone holes.

6 Conclusions We developed a non-linear least squares modelling tool to assess the acoustical performance of the Baroque bassoon. The inclusion of E♭3 and B♭2 in the analysis procedure was a stringent test of the acoustical model. We demonstrated a successful methodology to assess the various possible temperaments and make an informed choice for various families of Baroque bassoons, e. g. Kirnberger 1 for Eichentopf bassoons. The addition of the chromatics E♭3 and B♭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 favour meantone temperaments and reject others, including equal temperament. This finding is significant, considering that the woodwind instruments are the only family of orchestral instruments for which a temperament calculation can be obtained. This also offers us insights into the temperaments used in the 18th-century orchestra. Our results demonstrate that the natural pitch of the bassoon is typically a semitone higher than the playing pitch. In addition, we have found that the majority of 18th-century bassoons were built with two bore angles, which affects the timbre of the instrument. Our model directly calculates the "phantom" bore or bocal extension (the missing bore from the end of the bocal to the apex of a cone formed by the angle of the bore). 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 the acoustical performance of 18th-century bassoons. A combination of small changes to the downstream side of the wing joint length and/or changes in the wing joint tonehole positions will affect the frequency residuals of most of the downstream notes.

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Bericht des Symposiums »Exakte Kopie« in Bern 2012 • Herausgegeben von Sebastian Werr und Lyndon Watts unter redaktioneller Mitarbeit von Daniel Allenbach

Musikforschung der
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Herausgegeben von Martin Skamletz
und Thomas Gartmann
Band 8

Dieses Buch ist im September 2017 in erster Auflage in der Edition Argus in Schliengen/Markgräflerland erschienen. Gestaltet und gesetzt wurde es im Verlag aus der *Seria* und der *SeriaSans*, die von Martin Majoor im Jahre 2000 gezeichnet wurden. Gedruckt wurde es auf *Alster*, einem holzfreien, säurefreien, chlorfreien und alterungsbeständigen Werkdruckpapier der Firma Geese in Hamburg. Ebenfalls aus Hamburg, von Igepa, stammt das Vorsatzpapier *Caribic cherry*. *Rives Tradition*, ein Recyclingpapier mit leichter Filznarbung, das für den Bezug des Umschlags verwendet wurde, stellt die Papierfabrik Arjo Wiggins in Issy-les-Moulineaux bei Paris her. Das Kapitalband mit rot-schwarzer Raupe lieferte die Firma Dr. Günther Kast aus Sonthofen im Oberallgäu, die auf technische Gewebe und Spezialfasererzeugnisse spezialisiert ist. Gedruckt und gebunden wurde das Buch von der Firma Bookstation im bayerischen Anzing. Im Internet finden Sie Informationen über das gesamte Verlagsprogramm unter www.editionargus.de. Zum Forschungsschwerpunkt Interpretation der Hochschule der Künste Bern finden Sie Informationen unter www.hkb.bfh.ch/interpretation und www.hkb-interpretation.ch. Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über www.dnb.de abrufbar.
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