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The Scaling of Flemish Virginals and Harpsichords

WILSON BARRY

THE YEAR 1990 saw the publication of Grant O'Brien's long-awaited book on the Ruckers family and their instruments.[1] The review of this book belongs elsewhere, and by another author; suffice it to say that it is a classic, and a generation in advance of the classic works of Boalch, Russell, and Hubbard. Nevertheless, answering questions and solving problems in the field of keyboard organology can only lead to more questions and the recognition of further problems. Undoubtedly, there are investigations in progress by a number of scholars, which, when concluded and published, will yet alter and advance our understanding of the history of musical instruments.

Modern investigators have sometimes resorted to higher mathematics —the use of semi-logarithmic graph paper,[2] calculus,[3] or logarithms[4]— to study and analyze early keyboard instruments. Useful as these tools can be, they are outside the ken of the makers of these instruments. If we want to understand the instruments, we ought to view them, finally, in the context of the science of their makers; some idea of the history of science can be useful to investigators in organology. Similarly, if we want to understand the dimensions of these instruments, we ought not to measure them in English inches, as Russell and Hubbard did. Instead, we ought to measure them first in millimeters, as modern investigators are doing.[5] And then, we ought to try to convert them to the standard of measurement prevailing when and where these early instruments were

1. See the Bibliography.
2. O'Brien (1977), 53; 56.
3. Barry, 29.
4. Barry, 30; 32.
5. The use of millimeters has two advantages: first, since only in the United States is the English inch still in current use, metric measurements are more accessible to our colleagues worldwide; second, it is not always clear how accurately an investigator has measured in inches. Russell (e.g., Plate 7) sometimes goes down to eighths of an inch, and Hubbard (e.g., Plate l) to sixteenths, but one doubts that all of Russell's measurements were accurate to ±1/16″ (1.6 mm), or Hubbard's to ±1/32″ (0.8 mm). In the metric system, 75 mm implies ±0.5 mm, and 75.0 mm implies ±0.1 mm. The dimension 0.1 mm is a little less than the thickness of this page.

built, as future investigators will probably be doing. The fundamental question is: What was in the mind of the maker as he began his work?

W.R. Thomas and J.J.K. Rhodes pointed out in 1973 that some of the dimensions of the Ruckers harpsichords are commensurable with an Antwerp *voet* of 283.8 mm, divided into 11 *duimen* of 25.8 mm.[6] I reported in 1990 that some of the dimensions of the Theewes harpsichord seem to be commensurable with the same standard, including the scaling.[7]

Grant O'Brien has discovered that a second Antwerp measurement, which he calls the "short *duim*,"[8] amounting to 25.48 mm, seems to have been used in Ruckers instruments for small measurements of less than one *voet*.[9] There is evidence that the string lengths of Flemish virginals and harpsichords may also be commensurable with this short *duim*. The purpose of this paper is to present this evidence.

One might reasonably expect to discover that the dimensions chosen by the original designers of Flemish virginals and harpsichords, in the absence of any reason to the contrary, were commensurable with the prevailing standard of measurement. More than ten years ago, I tried to reconcile the string lengths of the Ruckers instruments, as reported by O'Brien,[10] with the "large *duim*," then estimated at 25.8 mm, with less than satisfactory results; using the small *duim* seems to produce better results.

The scaling of a Ruckers virginal[11] at unison pitch,[12] as measured by O'Brien,[13] is shown in Figure 1.[14] It seems that the lengths of the upper strings, #21–45, with Pythagorean scaling, resonate to the number 7. It seems that the lengths of the lower strings, #1–20, with non-Pythagorean scaling, resonate to the number 9. The length of *c* exhibits an ambivalence where $5 \times 9 = 45$, minus 1, equals $4 \times 11 = 44$, which

6. See Thomas and Rhodes, 112–21, esp. 114.

7. Barry, 16–17.

8. O'Brien (1990), 69–70; Appendix 1 (284–85); Appendix 5 (291–92).

9. O'Brien (ibid.) has corrected the estimated size of the large *duim* to 25.88 mm.

10. O'Brien (1977), 51; 54.

11. In Castello Sforzesco, Milan; No. 595. See O'Brien (1990), 241. The identification of the particular Ruckers instruments in the following Notes and Figures is according to the system devised by O'Brien, described on his page xix.

12. O'Brien estimates the unison pitch of Ruckers instruments to have been between A413 Hz and A419 Hz; see O'Brien (1990), 27; 62.

13. O'Brien (1977), 51; O'Brien (1990), 58.

14. Since the compass of Ruckers instruments begins with *C/E*, the length of F, which is merely the string next to *C/E*, is empirically determined as 55 - 1–1/2 = 53–1/2 *duimen*.

is 4 *voeten*. Remarkably, in the organ world, this note on the keyboard, and the corresponding unison pipe, are called "4' C" to this day. Also, at *C/E*, 6 × 9 = 54, plus 1, equals 5 × 11 = 55, which is 5 *voeten*.

To say that the scaling of the upper strings of this virginal is Pythagorean is equivalent to saying that the length of every string from c^1 (#21) to c^3 (#45) is given by the formula:

$$L_n = 28 \cdot (2)^{(21-n)/12}$$

The scaling of a Ruckers harpsichord[15] at unison pitch, as measured by O'Brien,[16] is shown in Figure 2.[17] The resonances to the numbers 7 and 9 are the same as in the virginal, except that the Pythagorean scaling applies only to the top twenty strings. At the crossover point, c^1, an ambivalence occurs where 4 × 7 = 28 (virginal), minus 1, equals 3 × 9 = 27 (harpsichord). It is notable that *C/E* is exactly twice as long as c^1, two octaves higher in pitch.[18] It seems that, where the scaling of the harpsichord differs from that of the virginal, it is the harpsichord string that is shorter.

The difference between the calculated and the measured dimensions in Figures 1 and 2 is usually quite small, and the plus and minus signs balance each other in a satisfying way. According to O'Brien:

> . . . like the virginal bridges, harpsichord bridges were positioned as accurately as possible to give the correct scaling, but . . . the primary concern was with spacing the strings accurately relative to the jacks and quills to ensure the correct mechanical operation of the instrument.[19]

It seems that the designer of these instruments avoided mixed numbers (except for the necessary dimension 10–1/2 *duimen,* 1/2 of 21 *duimen*). Any adjustments, also, are in whole *duimen*. The principles of design exhibited by these instruments seem to be:

1. There is one simple numerical scaling formula for the upper portion of the string band, and another for the lower portion.
2. Mixed numbers are completely avoided, except where they are generated by proportionality.

15. In the Vleeshuis Museum, Antwerp, No. VH 2137; see O'Brien (1990), 267–68.
16. O'Brien (1977), 54; O'Brien (1990), 59.
17. The length of *F* is empirically determined as 54 − 1–1/3 = 52–2/3 *duimen*. See note 14.
18. A scaling halving on the double octave has sometimes been used for the width of organ pipes, even to the present day. See Barry, 28. See also Mahrenholz, 39–41.
19. O'Brien (1990), 106; see also O'Brien (1977), 42.

Ruckers Virginal Scaling: (ca. 1600) HR

Note Formula Pythagorean:		**Adjustment**	**Calculated 1/1**		**Difference (Δ)**	**Measured 1/1**
c^3	1 × 7 =		7 *duimen* =	178 mm	+ 5 =	183 mm
f^2	3/2 × 7 =		10-1/2	268	+ 1 =	269
c^2	2 × 7 =		14	357	+ 10 =	367
f^1	3 × 7 =		21	535	− 8 =	527
c^1	4 × 7 =		28	713	− 5 =	708
Non-Pythagorean:						
f	4 × 9 = 36	+ 1 =	37	943	− 7 =	936
c	5 × 9 = 45	− 1 =	44 (4 *voeten*)	1121	+ 10 =	1131
F			53-1/2	1363	+ 3 =	1366
C/E	6 × 9 = 54	+ 1 =	55 (5 *voeten*)	1401	− 4 =	1397

FIGURE 1. The Scaling of a Ruckers Virginal in Short *Duimen*.

Ruckers Harpsichord Scaling: 1644a AR

Note Formula		Adjustment	Calculated		Difference	Measured
Pythagorean:			**1/1**		**(Δ)**	**1/1**
c^3	$1 \times 7 =$		*7 duimen* =	178 mm	− 1 =	177 mm
f^2	$3/2 \times 7 =$		10-1/2	268	+ 2 =	270
c^2	$2 \times 7 =$		14	357	+ 1 =	358
f^1	$3 \times 7 =$		21	535	− 7 =	528
Non-Pythagorean:						
c^1	$3 \times 9 =$		27	688	− 5 =	683
f	$4 \times 9 = 36$	+ 1 =	37	943	− 3 =	940
c	$5 \times 9 = 45$	− 1 =	44 (4 *voeten*)	1121	+ 4 =	1125
F			52-2/3	1342	+ 4 =	1346
C/E	$6 \times 9 =$		54	1376	− 11 =	1365

FIGURE 2. The Scaling of a Ruckers Harpsichord in Short *Duimen*.

3. Some adjustments are made to the dimensions in the lower portion of the string band; these must be improvements, specific to the particular model, probably to fine-tune the acoustical results of the location of the bridge on the soundboard.

* * *

According to O'Brien:

> It is important to note that the scalings of the various sizes of virginal are in proportion to the instrument's pitch, not only in the treble part of the compass . . . but also in the tenor and bass . . .[20]

In Figure 3 are shown the nominal string lengths of the six sizes of Ruckers virginals.[21] The lengths of some bass and tenor strings are adjusted by adding or subtracting one or two *duimen*. In Figure 4 are shown the nominal string lengths of three Ruckers harpsichords, 1 × 8′, 1 × 4′, at three different pitches.[22] The unison strings of the 4/3 harpsichord were drastically foreshortened in the bass and tenor, allowing the length of the instrument to be 6 *duimen* shorter than it would otherwise have needed to be. The octave strings were allowed to be 2 or 3 *duimen* longer in the bass and tenor than they needed to be, since the space was available.[23] The agreement between the calculated and the measured dimensions is quite good in Figures 3 and 4;[24] it appears that, in studying the differences, we are really studying how carefully the Ruckers craftsmen seem to have worked.

20. O'Brien (1990), 58.
21. The particular virginals are listed as follows:
 * (ca. 1600) HR: *moeder* and *kind*; see note 11.
 * 1604 HR: Musée Instrumental du Conservatoire Royal de Bruxelles, No. 2927; see O'Brien (1990), 241. Also see Mahillon for all the Brussels instruments.
 * 1629 IR: Musée Instrumental du Conservatoire Royal de Bruxelles, No. 2511; see O'Brien (1990), 250–51.
 * 1613b AR: Musée Instrumental du Conservatoire Royal de Bruxelles, No. 2928; see O'Brien (1990), 257.
 * (ca. 1610)a AR: private ownership, Australia; see O'Brien (1990), 256.
22. The particular harpsichords are listed as follows:
 * 1638b IR: Russell Collection, Edinburgh. No. 6. See O'Brien (1990), 252–53.
 * 1644a AR: see note 15.
 * 1627 AR: Haags Gemeentemuseum, The Hague, No. EC 545–1933; see O'Brien (1990), 261–62.
23. For these reasons, normalizing and averaging these harpsichord string lengths, as O'Brien did in 1977, seems to have been a procedural error. See O'Brien (1977), 55; Table Three (p. 54).
24. See the Appendix.

O'Brien has published several determinations of the scaling of iron wire in the Ruckers instruments.[25] It is hard to believe that these dimensions do not simply amount to:

Iron wire: 14 *duimen* = 357 mm at c^2.

Since the designer of these instruments avoided mixed numbers, all one can say for the scaling of iron wire in Ruckers instruments is that 14 *duimen* (357 mm) seems to have been safe, but 15 *duimen* (382 mm) was probably not.[26]

For the scaling of the three red brass strings (*C, D,* and *E*) and the seven yellow brass strings (*F* to *c*♯), it seems that Ruckers knew from experience that the second tautest yellow brass string, and the slackest red brass string ought to be:

Yellow brass wire: 4 *voeten,* or 44 *duimen* (1121 mm) at *c*[27];

Red brass wire: 5 *voeten,* or 55 *duimen* (1401 mm) at *C*[28].

This, no more and no less, seems to have been Ruckers's secret scaling formula for yellow brass: to make 4′ C 4 *voeten* long.

In Figures 3 and 4, it seems that Ruckers did not round his dimensions to integers, even for differences as small as ⅛ or ⅑ *duim.* Yet, the designer avoided mixed numbers completely. The explanation of this

25. O'Brien's determinations of the average scaling of iron strings at c^2 at unison pitch are:

Year	Virginal	Harpsichord	References
1977	356.3 mm	355.3 mm	pp. 53; 56
1990	354.8	355.2	pp. 59; 60

26. The Flemish builders seem to have been more concerned with safe "rules of thumb" than with extracting the most beautiful tone from "critically stressed strings." (See O'Brien [1990], 18- 20.)

27. O'Brien's determinations of the average scaling of yellow brass strings at *c*♯, converted to c^2 at unison pitch, are:

Year	Virginal	Harpsichord	References
1977	288.4 mm	290.6 mm	pp. 53; 56
1990	288.4	290.6	pp. 59; 60

To convert the length of *c*♯ to c^2 via Pythagorean tuning, multiply the length of *c*♯ by 2187/8192.

28. O'Brien's determinations of the average scaling of red brass strings at *E,* converted to c^2 at unison pitch, are:

Year	Virginal	Harpsichord	References
1977	210.2 mm	211.6 mm	pp. 53; 56
1990	210.8	211.6	pp. 59; 60

To convert the length of *E* to c^2 via Pythagorean tuning, multiply the length of *E* by 81/512.

Virginals		(ca. 1600) HR *moeder*	1604 HR	1629 IR	1613b AR	(ca. 1600) HR *kind*	(ca. 1610)a AR
Note	**Formula**						
Pythagorean:		**1/1**	**8/9**	**3/4**	**2/3**	**1/2**	**4/9**
c^3	1 × 7 =	7 *duimen*	6-2/9 *duimen*	5-1/4 *duimen*	4-2/3 *duimen*	3-1/2 *duimen*	3-1/9 *duimen*
f^2	3/2 × 7 =	10-1/2	9-1/3	7-7/8	7	5-1/4	4-2/3
c^2	2 × 7 =	14	12-4/9	10-1/2	9-1/3	7	6-2/9
f^1	3 × 7 =	21	18-2/3	15-3/4	14	10-1/2	9-1/3
c^1	4 × 7 =	28	24-8/9	21	18-2/3	14	12-4/9
Non-Pythagorean:							
f	4 × 9 =	36	32	27	24	18	16
	Adjustment	+1		+1			
		37		28			
c	5 × 9 =	45	40	33-3/4	30	22-1/2	20
	Adjustment	−1	−2		−1		
		44 (4 *voeten*)	38		29		
F		53-1/2	45-2/3	40-3/8	35	26-1/4	23-1/3
C/E	6 × 9 =	54	48	40-1/2	36	27	24
	Adjustment	+1	−1	+1			
		55 (5 *voeten*)	47	41-1/2			

FIGURE 3. Ruckers Nominal Virginal Scaling Calculated in Short *Duimen*.

Harpsichords		1638b IR 8′	1644a AR 8′	1627 AR 8′	1638b IR 4′	1644a AR 4′	1627 AR 4′
Note	**Formula**						
Pythagorean:		**4/3**	**1/1**	**2/3**	**2/3**	**1/2**	**1/3**
c^3	1 × 7 =	9-1/3 *duimen*	7 *duimen*	4-2/3 *duimen*	4-2/3 *duimen*	3-1/2 *duimen*	2-1/3 *duimen*
f^2	3/2 × 7 =	14	10-1/2	7	7	5-1/4	3-1/2
c^2	2 × 7 =	18-2/3	14	9-1/3	9-1/3	7	4-2/3
f^1	3 × 7 =	28	21	14	14	10-1/2	7
Non-Pythagorean:							
c^1	3 × 9 =	36	27	18	18	13-1/2	9
	Adjustment	−1					
		35					
f	4 × 9 =	48	36	24	24	18	12
	Adjustment	−1	+1	+1		+1	+1
		47	37	25		19	13
c	5 × 9 =	60	45	30	30	22-1/2	15
	Adjustment	−5	−1	−1			+1
		55 (5 *voeten*)	44 (4 *voeten*)	29			16
F		64-1/2	52-2/3	33-7/8	37	28-1/4	20-1/3
C/E	6 × 9 =	72	54	36	36	27	18
	Adjustment	−6		−1	+2	+2	+3
		66 (6 *voeten*)		35	38	29	21

FIGURE 4. Ruckers Nominal Harpsichord Scaling Calculated in Short *Duimen*.

paradox is that Ruckers did not need to engage in number play, as we do; his purpose was to produce a series of scale sticks recording the intended string lengths of the various instruments.[29] In Figure 5 is shown a way of generating the basic lengths of all the C's and F's of all six virginal models, using only three fundamental dimensions: 7, 8, and 9 *duimen*. The original designer of these instruments probably laid out such a diagram on his workbench, full scale, producing scale sticks that could be copied and carried from one workshop to another. The use of geometrical diagrams to produce linear dimensions was common in those days; Henri Arnaut de Zwolle (Dijon, ca. 1440), for example, used a diagram to show both the string lengths of his *clavicordium* and all the dimensions of his organ pipes.[30] Marin Mersenne (Paris, 1588–1648) and Athanasius Kircher (Rome, 1601–80), among many others, produced similar diagrams showing the dimensions of organ pipes.[31] Hans Ruckers the Elder himself, like quite a few members of the Guild of St. Luke, was an *orgelmaker* as well as a *clavesingelmaker*.[32]

* * *

In Figure 6 are shown the scalings of two virginals by Ioes Karest, also of Antwerp.[33] The compass of the 1548 virginal is *C/E* to c^3, as in the Ruckers instruments, but the compass of the 1550 virginal is, quite exceptionally, *C, D,* to f^3 (no *C♯*), 53 notes.[34] The lengths of the upper strings, with Pythagorean scaling, of the 1550 virginal, seem to resonate to the number 7, as in the Ruckers instruments, and the pitch clearly seems to be 1/1. The little curl that belongs at the extreme treble end of the bridge seems to have straightened out after it was formed and before it was glued to the soundboard.[35] As a consequence, the f^3 is foreshortened by nearly a *duim* (22 mm). It seems that the lengths of the lower strings, with non-Pythagorean scaling, resonate to the number 8.

29. Our method has been digital; his was analog.
30. See Le Cerf and Labande, 13–16; Plate IX (Fol. 129 r°).
31. See Mahrenholz, *passim*, esp. 29–30.
32. O'Brien (1990), 6.
33. The particular virginals are listed as follows:
    * 1550 Karest: Raccolta Statale degli Antichi Strumenti Musicale, Rome (Inv. No. 812); see O'Brien (1990), 23–26.
    * 1548 Karest: Musée Instrumental du Conservatoire Royal de Bruxelles, No. 1587; see O'Brien (1990), ibid.
34. In this instrument, the length of *F* is pertinent.
35. See O'Brien (1990), Plate 2.2 (p. 24).

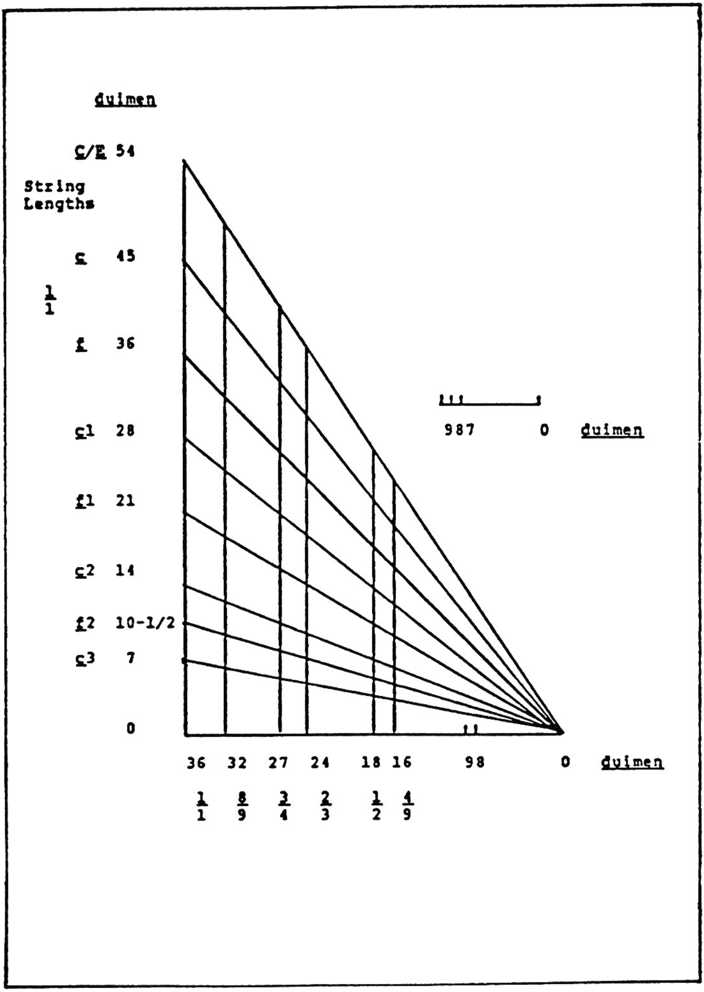

FIGURE 5. The Basic Scaling of Ruckers Virginals in Short *Duimen*. Scale: 1:15.

Note	Formula	Adjustment	1550 Karest 1/1	Formula	Adjustment	1548 Karest 3/4
Pythagorean:						
f^3	3/4 × 7 =		5-1/4 *duimen*	—		—
c^3	1 × 7 =		7	1/2 × 11 =		5-1/2 *duimen*
f^2	3/2 × 7 =		10-1/2	3/4 × 11 =		8-1/4
c^2	2 × 7 =		14	1 × 11 =		11 (1 *voet*)
Non-Pythagorean:						
f^1	5/2 × 8 = 20	− 1 =	19	2 × 8 =		16
c^1	3 × 8 =		24	5/2 × 8 =		20
f	4 × 8 =		32	7/2 × 8 = 28	− 1 =	27
c	5 × 8 =		40	9/2 × 8 = 36	− 2 =	34
F	6 × 8 = 48	− 1 =	47	—	—	44-2/3*
C	7 × 8 = 56	− 2 =	54	(*C*/*E*) 6 × 8 = 48	− 3 =	45

FIGURE 6A. The Scaling of Two Karest Virginals in Short *Duimen*, compared.
*empirically determined.

	1550 Karest 1/1 Calculated	Δ	Measured		1548 Karest 3/4 Calculated	Δ	Measured
f^3	134 mm	− 22 mm	= 112 mm		—	—	—
c^3	178	− 8	= 170		140 mm	− 4 mm	= 136 mm
f^2	268	− 1	= 267		210	+ 6	= 216**
c^2	357	− 4	= 353		280	+ 0	= 280
f^1	484	− 6	= 478		408	− 12	= 396
c^1	612	− 8	= 604		510	− 9	= 501
f	815	+ 4	= 819		688	+ 5	+ 693
c	1019	− 9	= 1010		866	+ 1	= 867
F	1198	+ 6	= 1204		1138	+ 0	= 1138
C	1387	− 1	= 1375	(*C/E*)	1147	− 7	= 1140

FIGURE 6B. The Scaling of Two Karest Virginals: Calculated versus Measured Dimensions in Millimeters. **216 mm × 16/9 = 384 mm, or 15.07 *duimen*. This seems to be Karest's tautest measured iron string.

In the 1548 virginal, the lengths of the treble strings seem to resonate to the number 11. The string c^2 seems to be exactly 1 *voet* in length. Remarkably, in the organ world, this note on the keyboard, and the corresponding unison pipe, are called "1′ C" to this day. Comparing the string lengths of the two instruments at c^2, 11/14 (0.786) is not far from 3/4 (0.750), and the pitch of the smaller instrument would seem to be 3/4, a fourth above 1/1. This would produce a nominal scaling for the iron wire in this virginal of 44/3, or 14–2/3 *duimen* (374 mm). Probably, using the smallest, and therefore strongest, gauges of wire, it was just possible to tune the top 13 strings of the 1548 Karest virginal to 3/4 pitch.[36] The lengths of the lower strings of this virginal also seem to resonate to the number 8. Comparing the string lengths at c^1 and *C/E,* 20/24 and 45/54 both amount to 5/6 (0.833); the bass and tenor strings of the smaller virginal are proportionately longer than those of the larger.

The scaling of the Karest virginals seems to show that the general principles of design exhibited by the Flemish instruments were well in place some thirty years before Hans Ruckers the Elder joined the Guild of St. Luke in 1579.[37] Perhaps the Ruckers version shows more refinement than Karest's, in that the Pythagorean scaling is carried farther down the keyboard. But who will say that it is better for the lengths of non-Pythagorean bass and tenor strings to resonate to the number 9 than to the number 8?

* * *

Contemporary with these Northern instruments with Pythagorean treble scaling were other instruments with non-Pythagorean scaling throughout. The so-called "Duke of Cleves" virginal[38] of 1568 is an example; the Lodewyk Theewes harpsichord[39] of 1579 is another. The

36. The smaller the wire gauge, the stronger is the wire. The literature on this subject is still not entirely satisfactory, and I hope to write about this later. In the meantime, there are the following accounts: 1965, Hubbard, 281, note 113; 1977, Gug, 125–28; 1979, Thomas and Rhodes, 130–31; 1980, Koster, esp. 54; 1981, O'Brien, esp. 161; 1987, Goodway and Odell, Chapter 5 (51–84).

37. This conclusion is contrary to the notion I expressed a year ago (page 18). Then I was relying upon previous writers, who have tended to imply that a degree of chaos reigned in the scaling of keyboard chordphones until Hans Ruckers the Elder arrived on the scene. See, e.g., O'Brien (1990), 16; Koster, 66. The expression "pre-Ruckers" means "before 1579;" it should not necessarily be taken to imply "primitive" or "transitional."

38. In the Victoria and Albert Museum, London, Mus. No. 447–1896. See Schott, 26–28; O'Brien (1990), 26.

39. Also in the Victoria and Albert Museum, Mus. No. 125–1890. See Schott, 40–42; Barry, 5–41.

earliest examples we know much about were described and illustrated in ca. 1440 by Henri Arnaut de Zwolle, whose *clavicordium* was strictly Pythagorean, but whose *clavisimbalum* was strongly non-Pythagorean.

The mathematical techniques available to us today, such as logarithms, were not available to the Flemish builders. It would be a mistake for us to assume, on that account, that we are in any way superior to them. They produced superb instruments using various practical "rules of thumb" (or, *duim*) together with their own science, which, after all, goes back to the ancient Greeks. Those who study early instruments would do well to study their principles of design, finally, in the context of this early science and technology.

Brentwood, New Hampshire

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Appendix

Virginals	(ca. 1600) HR *moeder*		1604 HR		1629 IR		1613b AR		(ca. 1600) HR *kind*		(ca. 1610)a AR	
Note: Pythagorean:	Δ	1/1	Δ	8/9	Δ	3/4	Δ	2/3	Δ	1/2	Δ	4/9
c^3		178		159		134		119		89		79
	+ 5	183	+ 4	163	+ 5	139	+ 3	122	+ 0	89	− 4	75
f^2		268		238		201		178		134		119
	+ 1	269	+ 5	243	− 3	198	− 3	175	+ 2	136	− 5	114
c^2		357		317		268		238		178		159
	+10	367	+13	330*	+ 6	274	+ 5	243	+ 0	178	−12	147**
f^1		535		476		401		357		268		238
	− 8	527	−12	464	+ 1	402	− 9	348	− 7	261	−12	226
c^1		713		634		535		476		357		317
	− 5	708	−13	621	+14	549	− 3	473	− 3	354	+ 3	320

FIGURE 7A. Ruckers Virginals: Calculated/Measured Dimensions in Millimeters (Pythagorean).

*330 mm × 9/8 = 371 mm, or 14.57 *duimen*. This seems to be the tautest string in this sample of seventy-two measured Ruckers iron strings.

** 147 mm × 9/4 = 331 mm, or 12.98 *duimen*. This seems to be the slackest string in this sample of fifty-four measured Ruckers iron strings with Pythagorean scaling.

Therefore, the Ruckers nominal scaling of 14.00 *duimen* is observed to vary in practice from +4.1% to −7.3%. By comparison, Karest's tautest iron string (Figure 6) is 14.00 *duimen* plus 7.6%.

Virginals		(ca. 1600) HR *moeder*		1604 HR		1629 IR		1613b AR		(ca. 1600) HR *kind*		(ca. 1610)a AR
Note: Non-Pythagorean:	**Δ**	**1/1**	**Δ**	**8/9**	**Δ**	**3/4**	**Δ**	**2/3**	**Δ**	**1/2**	**Δ**	**4/9**
f		943		815		713		612		459		408
	− 7	936	−12	803	+ 3	716	− 4	608	+ 6	465	+10	418
c		1121		968		860		739		573		510
	+10	1131	+ 1	969	− 2	858	+ 3	742	−11	562	− 3	507
F		1363		1164		1029		892		669		595
	+ 3	1366	− 8	1156	−12	1017	−11	881	+ 4	673	+ 4	599
C/E		1401		1198		1057		917		688		612
	− 4	1397	+ 6	1204	− 2	1055	− 1	916	+ 1	689	− 6	606

FIGURE 7B. Ruckers Virginals: Calculated / Measured Dimensions in Millimeters (Non-Pythagorean).

Harpsichords		**1638b IR 8′**		**1644a AR 8′**		**1627 AR 8′**		**1638b IR 4′**		**1644a AR 4′**		**1627 AR 4′**
Note:												
Pythagorean:	**Δ**	**4/3**	**Δ**	**1/1**	**Δ**	**2/3**	**Δ**	**2/3**	**Δ**	**1/2**	**Δ**	**1/3**
c^3		238		178		119		119		89		59
	− 3	235	− 1	177	+ 2	121	− 6	113	− 1	88	+ 1	60
f^2		357		268		178		178		134		89
	− 3	354	+ 2	270	+ 0	178	− 3	175	+ 1	135	+ 0	89
c^2		476		357		238		238		178		119
	+ 1	477	+ 1	358	+ 0	238	− 3	235	+ 1	179	− 2	117
f^1		713		535		357		357		268		178
	− 9	704	− 7	528	− 1	356	− 9	348	+10	278	− 3	175

FIGURE 8A. Ruckers Harpsichords: Calculated/Measured Dimensions in Millimeters (Pythagorean).

Harpsichords		1638b IR 8′		1644a AR 8′		1627 AR 8′		1638b IR 4′		1644a AR 4′		1627 AR 4′
Note: Non-Pythagorean:	Δ	4/3	Δ	1/1	Δ	2/3	Δ	2/3	Δ	1/2	Δ	1/3
c[1]		892		688		459		459		344		229
	− 1	891	− 5	683	+ 2	461	− 7	452	− 1	343	+ 8	237
f		1198		943		637		612		484		331
	− 2	1196	− 3	940	− 9	628	+ 9	621	− 9	475	+ 8	339
c		1401		1121		739		764		573		408
	+12	1413	+ 4	1125	+10	749	−10	754	+ 2	575	+11	419*
F		1643		1342		863		943		720		518
	+ 1	1644	+ 4	1346	+13	876	−12	931	+ 0	720	+11	529
C/E		1682		1376		892		968		739		535
	+11	1693	−11	1365	− 6	886	−10	958	+ 6	745	+ 8	543**

FIGURE 8B. Ruckers Harpsichords: Calculated / Measured Dimensions in Millimeters (Non-Pythagorean).

*419 mm × 3/4 = 314 mm, or 12.33 *duimen,* versus a nominal 44/4 = 11.00 *daumen,* or 280 mm. This seems to be the tautest string in this sample of twenty-four measured Ruckers yellow brass *c* strings. The unmeasured *c*♯'s, of course, would be somewhat tauter than their *c*'s.

** 543 mm × 3/8 = 204 mm, or 7.99 *duimen,* versus a nominal 55/8 = 6.87 *daumen,* or 175 mm. This seems to be the tautest string in this sample of twelve measured Ruckers red brass *C* strings. The unmeasured *D*'s and *E*'s, of course, would be considerably tauter than their *C*'s.