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Netherlands in the sixteenth and seventeenth centuries.[42] Further, there is at least some Dutch keyboard music of the period (many of the works of J. P. Sweelinck) suited to a compass starting on F. This repertoire might well, upon occasion, have been played an octave lower in order to make full use of keyboards starting on FF. If so, these harpsichords could be regarded as related to the sixteenth-century 16′ transposing double now in the Brussels collection.[43] Although this argument that the Ruckers family made chromatic-bass transposing doubles for Dutch organists is pure speculation on the part of the reviewer, that an alternative explanation for their existence can be proposed suggests that it is unfortunate that O'Brien has, perhaps indelibly, marked these doubles as "French."

The reviewer should stress to his readers the peripheral nature of the few reservations that he has expressed. This is *the* book about the Ruckers family, and it is difficult to imagine that it will ever be surpassed. The dust cover blurb that this "book will be essential for all harpsichord builders and indispensible for players, collectors and scholars"—and, for that matter, for all music libraries—is, for once, no exaggeration. Especially if the author's urgent plea for the conservation (not restoration) of Ruckers *clavecimbels* is observed by those to whose care they are entrusted, there will remain, as he writes (p. 234), "doubtless much more information still to be recovered from Ruckers instruments." Nevertheless, it is unlikely that whatever will be found in the future will be anything more than a footnote to Grant O'Brien's great work.

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***Five Lectures on the Acoustics of the Piano*, ed. by Anders Askenfelt. Stockholm: Kungl. Musikalska Akadamien; Long Island City, N. Y.: Steinway and Sons, 1990. 105 pp.; 19 line drawings, 37 black-and-white photographs, 71 charts and tables, 14 musical examples; compact disk. ISBN: 91-85428-62-0. $23.00**

In 1988, from the 25th to the 27th of May, a group of engineers and scientists from both academe and piano manufacturing met at the Royal

42. See Maarten A. Vente, *Die Brabanter Orgel* (Amsterdam: H. J. Paris, 1963).
43. See note 37, above.

Institute of Technology in Stockholm, Sweden, to discuss the past, present, and future of the piano. On the last day five public lectures were presented by six of the attending specialists. The texts of their talks constitute this slender volume, and are arranged in a sequence roughly corresponding to the order of events that produce piano tone: the action, string vibration, and the behavior of the soundboard. Also on the last day a concert was presented illustrating the development of the piano from the harpsichord to the modern concert grand. A compact disk with excerpts from this concert, along with sound examples used by the lecturers during the course of their papers, is included with the book.

Harold A. Conklin Jr. writes on "Piano Design Factors: Their Influence on Tone and Acoustical Performance," in which design problems for hammers, striking points, soundboard, case, iron plate, strings, and tuning pins are discussed. Conklin explains that hammers are graduated in size and weight in order to effect the best balance between tone, volume, and playability. The hardness of hammers is also important: too soft produces a tone lacking brightness; too hard, a tone overly harsh. Although for over a century conventional wisdom has held that the best position for striking points is at $1/7$ or $1/9$ of the string's sounding length, Conklin points out that in the modern piano striking points range from between $1/8$ to $1/17$.[1]

Conklin goes on to describe the modal behavior of the soundboard—the way in which it vibrates in response to frequencies transmitted to it from the strings via the bridge. He demonstrates a method for showing the soundboard's modes (Chladni patterns), and illustrates the discussion with pictures of the first, second, third, and eighth modes. He also describes modal analysis, a newer technique of identifying soundboard modes. Throughout, he notes that compromise is the order of the day: for example, a thicker soundboard produces a louder tone, but one of shorter duration.

The piano has a cast iron plate whose purpose is to maintain the integrity of the shape of the instrument, thereby allowing the use of heavy strings. Conklin recalls the astounding fact that the string tension

1. See Robert S. Winter, "Striking it Rich: The Significance of Striking Points in the Evolution of the Romantic Piano," *The Journal of Musicology* 6:3 (Summer, 1988): 267–292. Winter shows that right from the beginning pianos never conformed to this abstract ideal.

on Cristofori's piano was about 190 pounds per foot, while on the modern piano it is about 47,000 pounds per foot. He points out that in order that it not vibrate easily the plate needs to be rather massive. It is. A cast iron plate weighs between 350 and 400 pounds.

The article by Anders Askenfelt and Erik Jansson, "From Touch to String Vibrations," is perhaps the one most useful to pianists. The authors present a detailed account of the action, the mechanism that transforms the motion of the pianist's finger to a blow of the hammer. They stress the importance of proper regulation, going so far as to give the proper distance between the resting hammer and the string (45–47 mm) and the "let-off," the distance between the hammer at its highest point and the string (1–3 mm, depending on the string diameter and the preferences of the pianist). To help understand the relationship between all the parts they present a diagram giving the time history of each element of the action plus the vibrating string for the production of a staccato note, middle C, played forte. The duration of the tone is about 1⁄10 of a second, but the contact between hammer and string is only about 1⁄5 of this, or 1⁄500 of a second!

The authors explain that the relationship between dynamic level, the onset of the tone, and the bottoming of the key provides important feedback to the performer. They note that when the key is struck from some distance above—a staccato touch—the force of the blow creates a resonance in the hammer head which is transferred back to the key via the flexible hammer shank. But in legato playing, with the finger close to the key, this "hammer mode" is either suppressed or absent, and the key motion is smooth. Hence, the feel of the key motion varies with the touch, a sensation easily perceived by the pianist.

Hammer motion is complex. For years, particularly since the publication of Otto Ortmann's book, *The Physical Basis of Piano Touch and Tone,*[2] scientists have held that piano tone is dependent solely on the velocity imparted to the hammer head. But Askenfelt and Jansson present data indicating that even with a note of the same dynamic level, different tone qualities can be produced by the type of touch used. They attribute this to admixtures of two of the vibrational modes developed by the hammer. Interestingly, they found that performers were much more aware of these tonal distinctions than listeners. The authors caution that

2. New York: Dutton, 1925; Dutton paperback, 1962.

these data must be interpreted with the utmost care. Undoubtedly, this phenomenon will prove to be a rich field of investigation.

A struck string exhibits a rather intricate motion. The striking hammer puts a "hump" into the string which then travels down the string as a pulse in both directions. String vibration is transferred to the soundboard by the impact of this pulse with the bridge. The situation becomes complicated when things such as hammer mass, string length, and string stiffness are taken into account. For example, the spectra of bass notes are dramatically different from those of treble notes, in part because of the properties of the hammers in these registers. Askenfelt and Jansson show that simply striking middle C with a bass hammer and a less massive treble hammer can produce drastically different spectra. The stiffness of the hammer is also important to the spectral content of the string; the authors report that softening a hard hammer with needles (a process of voicing, carried on regularly by technicians) reduces the higher limits of the string spectrum from 8,000 Hz (8,000 cycles per second) to 4,000 Hz.

Because a hammer consists of a wooden core covered by a layer of hard, then soft felt, the *relative* hardness of any given hammer depends on the velocity with which it strikes the string. In quiet playing only the soft outer layer of felt is utilized, producing a spectrum in which higher partials are absent. Loud playing, on the other hand, feels "hard" to the string, since the inertia of the hammer blow forces the string to bury itself in the soft outer layer of felt and, in effect, to contact the compressed inner layer. The resulting spectrum fairly crackles with the energy of higher partials. Accordingly, a large part of what we call piano tone is the performer's ability to manipulate the partial content of the tone through touch.

A naive image of the relationship between the hammer and string would expect the striking hammer to bounce off the string before the resulting pulse returns from its trip to the bridge. Just how unsophisticated this view would be is the subject of Donald E. Hall's essay, "The Hammer and the String." As Hall puts it (p. 61),

> . . . we can only come to a correct understanding [of the relationship between hammer and string] by admitting that the hammer remains in contact with the string for a finite time, during which the force exerted by the hammer upon the string may change in a complex way.

Just how long this contact lasts depends on the relationship of the mass of the string to the mass of the hammer, the relative hardness of the hammer, and the striking point on the string. It is also dependent on the length of the string (or, putting it another way, the amount of time it takes for the pulse of the fundamental to make its trip to the bridge). But the inertia of the hammer assures that it will remain in contact with the string for more than one round trip of the pulse. Traveling in both directions, the wave propagated by the hump is reflected from the string terminations (the agraffe and the bridge) back toward the hammer. The interaction between wave and hammer generates a new wave. This new wave is reflected and, passing the hammer, generates yet another new wave (Hall calls these children and grandchildren). The shape these generations of waves take depends on the hardness of the hammer. A soft hammer exerts a rather steady force on the string; a hard hammer gives the string a series of sharp pulses. It is this complex restoring force of the string, acting like a bow to the hammer's arrow, that finally forces the hammer off the string. Complicating all this is the nonlinearity of the event—any given hammer is relatively soft on the outside, under soft playing, and harder on the inside, with louder playing.

Hall attempts to present what we know about the theory of the interaction between hammer and string, and to modify it with practical information gained through experimentation. He hopes to set up a mathematical model that will enable us to predict string and hammer behavior with far greater accuracy than we now possess. His article is an important one, although the information it contains may be of less interest to the non-scientist. Nevertheless, for a detailed account of the fascinating *pas de deux* danced by hammer and string, Hall's article should be read with care.

In "The Coupled Motion of Strings," Gabriel Weinreich describes the nonlinear element of piano tone as "miraculous." He begins by supposing that an engineer inventing the piano would quickly have to decide how to deal with the energy of the vibrating string. If transferred to the soundboard with great efficiency the result would be a loud sound, but one that decayed quickly. On the other hand, a less efficient coupling would produce a sound with longer decay but less volume. But, says the author, a phenomenon of hearing provides the means for getting around that limitation, because sounds that start loud are perceived as loud, even if that volume decays quickly; and sounds can be perceived as sustained even if part of that sound is rather weak. This, says Weinreich, is "the miracle of the piano tone." The rest of the article clarifies these statements.

Weinreich explains that for every mode the string has two possible directions of vibration, vertical and horizontal. The vertical component is the first to be excited, so it vibrates with an amplitude much in excess of the horizontal, although with rapid decay. The horizontal mode is also vibrating, but with less rapid decay, and transmitting less sound to the board. After a while the horizontal component becomes the dominant one, and the overall effect is one of a tone that starts loud with a rapid decay, but soon changes to a more sustained sound. Thus the tone of a single piano string decays in two portions. The first is the exponential decay to be expected from the linear system of string and soundboard. But soon the first part of the tone (called "prompt sound"), a loud sound with rapid decay, is superseded by a second part ("after sound"), at less that one-fourth the rate of the first.

Weinreich next explains that this effect is intensified when a note is double or triple strung. No piano tuner is so good that two, no less three strings can be set absolutely dead on. That the strings of a triplet are slightly mistuned means that they cannot vibrate in an absolutely united fashion. That these "mistuned" strings do not beat is explained in terms of the effect each string has on the impedance of the bridge, or the rate at which the bridge admits vibration from the string to the soundboard. The relationship is a complex one, with each string affecting the impedance with which the bridge meets the other strings. The change in the rate of the decay here is due to the slightly different rates at which the disturbances in the strings impact the bridge. The closer together they are (and at the outset of the tone they are practically in unison), the quicker the decay and the louder the tone; but the farther apart they become, the more the decay slows down.

In the final article, "The Strings and the Soundboard," Klaus Wogram describes how the blow of the hammer sets up a spectrum of string vibrations whose energy is transferred to the soundboard via the bridge. The paper then deals with the behavior of the soundboard, whose function is to change string vibrations into radiated sound. At low frequencies the soundboard acts somewhat like a diaphragm, but at higher frequencies it tends to vibrate in discrete areas, which become smaller as the frequency rises. There are limits, as Wogram points out. At low frequencies acoustic short-circuiting occurs, as air flows between the top and bottom of the soundboard. At high frequencies adjacent areas will be out of phase with each other and will thus spill air back and forth, rather than radiate sound. Hence, the frequency band at which piano sound is most efficiently radiated is between 100 Hz and 2,000 Hz.

The author describes some interesting experiments on the ribs of a soundboard. Ribs serve to carry the vibrations *across* the grain of the board at a speed approximating the velocity of sound *with* the grain (with no ribs or bridges the difference between the stiffness of the wood with and across the grain is about twenty to one). But they also increase the general stiffness of the board. Without this effect the transfer of energy from string to board would be too efficient, with the concomitant loud but quickly decaying sound. Wogram found that as the ribs were reduced in height about 50% the resonance frequencies of the board were shifted downward, the resonance peaks became narrower, and sound radiation was reduced. It was also discovered that reducing the number of ribs by 50% was equivalent to reducing the height of the ribs by 25%. What this all boils down to, of course, is a confirmation of the design of the modern piano, arrived at by *a priori* methods rather than by laboratory experiments.

In another experiment Wogram mounted a single string on an assembly consisting of frame, soundboard, and plate. Impedance matching was tested by tuning the string to a variety of frequencies at and near a resonance peak on the soundboard. The string was then plucked and decay times noted. As predicted, the decay time was longest when the frequency of the string was furthest from the frequency of the soundboard resonance. This means that in a good soundboard there will be a consistently high impedance between strings and board, assuring good reflection of the energy from the vibrating string at the bridge, and providing the comparatively long decay times deemed desirable in the piano.

The final section of Wogram's paper deals with a modal analysis of the soundboard, a computer-dependent technique that gives information on the frequency, amplitude, phase, and damping of each of the board's modes.[3] The data are digitized and can be displayed in any form. In his article Wogram presents "snapshots" of the first eight modes, but in his verbal presentation he showed a video tape of the actual movement of the soundboard.

3. This technique has also been applied to the harpsichord and is described in an article entitled, "Air and Structural Modes of a Harpsichord," by William Savage, Edward Kottick, Thomas Hendrickson, and Kenneth Marshall, and accepted for publication in *The Journal of the Acoustical Society of America*.

The five articles are preceded by a well-written ten-page introduction to the acoustics of the piano. The book contains solid information on the acoustics of the piano, and there is nothing else quite like it. All the articles are written in an interesting fashion and should be comprehensible to any educated musician, although some readers may well need to go through the material several times before comprehension takes hold. The book should be on the shelf of every mature and thoughtful pianist, and required reading for anyone interested in musical acoustics.

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Martha Maas and Jane McIntosh Snyder. *Stringed Instruments of Ancient Greece*. New Haven, Conn.: Yale University Press, 1989. xx, 261 pp.; 165 black-and-white illustrations. ISBN 0-300-03686-8. $45.00.

A 1991 winner of the American Musical Instrument Society's prestigious Nicolas Bessaraboff Prize for the most distinguished book-length work which best furthers the Society's goal "to promote study of the history, design, and use of musical instruments in all cultures and from all periods," *Stringed Instruments of Ancient Greece* is a monumental scholarly study, the comprehensiveness of which is approached by no other published work in its field. An amalgam of the highest quality of musicological, iconographical, and literary research, this outstanding book provides the best-informed insight currently available into the musical life and the musical instruments of the ancient Greeks.

Authors Maas and Snyder, both distinguished scholars in their fields, are on the faculty of Ohio State University, in the departments of music and the classics, respectively. In the preparation for this, their first collaborative effort, they studied nearly 2,000 artistic representations (vase paintings and sculpture) and the more than 700 literary references (in surviving epic and lyric poetry and drama) to plucked stringed instruments in ancient Greece, dating from about 2700 B.C. to the deaths of Alexander the Great and Aristotle in 323–322 B.C. The dependence upon iconographic and literary source material was necessitated by the scarcity of archaeological evidence for the existence and use of the three types of stringed instruments popular in Greece during that time period—the lyre, the harp, and the lute.

As in all studies based primarily upon iconographical and literary sources, the authors had to deal with a myriad of potential problems and