Early Development Process of the Steinway & Sons Grand Piano Duplex Scale

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Abstract:

This article presents an attempt at retracing the early development process of the grand piano's duplex scale mechanism by combining an evaluation of contemporary written sources with acoustical measurements on extant grand pianos. For Steinway & Sons, 1870-1890 was an extremely innovative period, mainly driven by the work of C. F. Theodore Steinway. For the invention of the duplex schematic, which was patented in 1872, he claimed to have been inspired by Hermann von Helmholtz's research on the perception of higher order harmonics. In appreciation of the impact of his work, Steinway & Sons consecutively presented three grand pianos to Helmholtz. Design parameters and acoustical measurements on several historical Steinway grand pianos—among them the earliest of Helmholtz's pianos—are compared to investigate if the intended effect instantly emerged, or if it was firstly a theoretical concept, which was later refined to enhance a certain tonal character.

1. Introduction

The grand pianos of Steinway & Sons (hereafter referred to as S&S) experienced one of their most inventive periods under the technical direction of C. F. Theodore Steinway (1825-1889). For him and other piano makers, the research and knowledge in acoustics had become an increasingly important foundation in piano making. Hermann von Helmholtz's *On the Sensations of Tone* [1] was an especially useful resource due to its many practical experiments on musical instruments and new approaches to the theory of timbre perception [2]. The most prominent result of these endeavours may well be the duplex scale (patented in 1872), which has become an integral part of S&S's grand pianos [3]. Despite its scientific basis, this invention caused some controversy: several competitors criticized it, and others copied it.

Until now, there have been few attempts to verify how such constructions worked in their early years and how they changed. As an example, Henry Steinway, Jr. stated in his 1859 patent, that "grand piano overstringing" was advantageous in two ways: longer bass strings could be accommodated, and it would be possible to position the bridge closer to the centre of the soundboard. When Paul Poletti tested these statements by measuring the respective parameters before and after the implementation, he found that the differences were not significant [4]. Nevertheless, cross-stringing has become a standard feature of grand pianos.

A few surveys on the functionality and effect of the duplex scale have been published focusing on the modern grand piano (as will be outlined in section 3). This article adds a historical perspective on the motivation behind the invention, its development within the first two decades, and the perceivable effects of these early versions. By evaluating relevant historical documents, some of which have not been taken into account before, and by comparing these results with measurements of the scale and vibrational behaviour of selected historical S&S grand pianos, some central issues will be addressed: Did the duplex scale work as intended from the beginning? How is its theory related to the practice in the pianos? Why were modifications made? To what extent did Hermann von Helmholtz contribute to its invention?

2. C. F. Theodore Steinway and His Relation to Hermann von Helmholtz

C. F. Theodore Steinway, the first son of the company's founder, was the most innovative piano maker in the history of S&S in terms of the number of patents obtained, a total of 45 between 1868 and 1885 [5] (see **Fig.1**).

These inventions are manifestations of Theodore's knowledge about acoustics. As Alfred Dolge summarized in 1911: "He demonstrated to what extent science can aid in the development of the piano by his own productions, and thus broke the path for the enormous development of the past 30 years [c.1880-1910]. This is more than all the empirics have ever done" [6].

When consulting contemporary reports about Theodore's biography it is important to note that almost all of this information originated directly from the family members themselves or people around them. Fanny Morris Smith for instance was trained in the S&S factory [7] and her book *A Noble Art. Three Lectures on the Evolution and Construction of the Piano* [8] was published by Charles Tretbar, William Steinway's advisor. The Steinway family compiled an undated pamphlet "On the Founding and Development of Steinway", which presents an insider point of the family's history [9]. According to the latter source, Theodore's varied talents became apparent at an early age and so he received special tuition in acoustics whilst at school, at the Jacobson Institute in Seesen. The then director, Dr. Benjamin Ginsberg, gave Theodore access to the "Jacobsohn library and lecture-room, the latter containing all the acoustic and scientific apparatus known at that period. In return Theodore assisted the teachers and professors of acoustics and mathematics in their lectures and experiments" [9]. Ginsberg seems to have played a key role in Theodore's career: "This intimate relation to the scientist in his youth prevented Theodore from ever becoming a mere empiric. It was the cause of the restless search he later so forcibly demonstrated for the scientific laws underlying the construction of the pianoforte" [6].

Another particularity about Theodore's biography is that he spent most of his life in Germany and thus remained in exchange with the cultural and scientific communities there. Only between 1865 and 1880, when he was indispensable in the factory due to the death of two of his brothers, did he relocate to New York, but repeatedly made extended

Fig.1

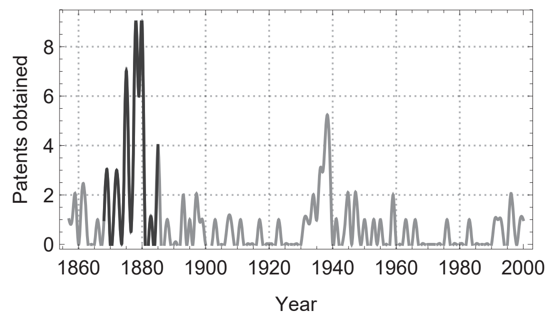


Fig.1 Number of patents per year granted to Steinway & Sons. The period of Theodore's activity is emphasized.

journeys back to Braunschweig [10]. During one such stay from summer 1869 to fall 1870, Theodore and Hermann von Helmholtz likely met for the first time. In a letter to Helmholtz, Theodore sent his best regards and stated that he remembered their "stimulating conversations" in 1870 with pleasure [10]. According to Fanny Morris Smith, they had already become acquainted several years before: "Helmholtz, [Theodore's] friend and companion, the greatest and most ingenious of all acousticians, was his most stimulating influence. In many of the researches of 'Die Lehre von Tonempfindungen' [sic] did the great pianomaker lend a hand" [8]. When Helmholtz published this book in 1863, Theodore still lived in Germany, but there is no evidence of any contact between them at that time. Altogether only a few letters and meetings are documented, none dating before 1870 [10].

The notion of a close collaboration between Helmholtz and the Steinways still recurs frequently based on these contemporary reports. The piano material supplier Alfred Dolge claimed that Theodore even "returned to Germany to be near Helmholtz and benefit by that great savant's epoch-making discoveries." [6] One of Helmholtz's motivations to exchange ideas with skilful instrument makers was to put his musical findings—mainly regarding just intonation on keyboard instruments—into practice. In 1871 he also encouraged the Steinways to try this in their pianos, "perhaps with a similar system to a pedal harp but without a far too complicated mechanism" [11]. Above all, Helmholtz was a passionate piano player. In appreciation of the scientist's impact on their pianos but also for promotional purposes, the Steinways sent a grand piano to him in 1871 (today located at Deutsches Museum Munich, see section 5), and two more in 1885 and 1893, respectively. In return, S&S printed his endorsements regarding the quality of their pianos and most notably the positive effects of the duplex scale in their catalogues.

3. Functional Principle of the Duplex Scale

As described in the patent, the basic idea of the duplex scale is to bring "the vibrations of that portion of the string which is situated between the agraffe and the tuning pin [further denoted as front duplex], in proportion to those of the main portion of the string". For the section of string between the bridge and hitch pin (further denoted as rear duplex) he proposes to bring "[…] the longitudinal vibrations of that portion of the string […] in proportion to the vibrations of the main section of the string, so that the sounds due to these longitudinal vibrations are brought in harmony with the tone of the main section of the string, and the purity and fullness of the tone of the instrument is improved" [3] (see **Fig.2**).

Fig.2

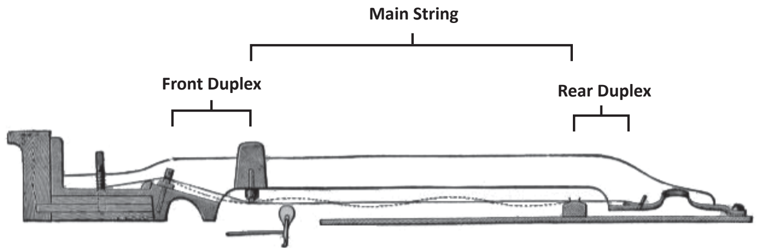


Fig.2 Illustration of the string parts in piano treble range. After Fanny Morris Smith, [8, p. 59].

Although Theodore extensively describes the audible effects achieved by the duplex scale, the actual physical process is covered rather superficially. In his understanding: "The main agraffe, which supports the string only at one point, allows the transverse vibrations to extend to that part of the string between the said agraffe and the tuning-pin, the vibration of this part being in a direction opposite to that of the main section of the string" [3]. Due to the precisely proportioned length of the duplex string, the string's termination at the agraffe is said to act as a "theoretical nodal point" for the corresponding partial. The patent does not give any explanation for the alleged process of the coupling of longitudinal duplex string vibrations into the main string. Currently, longitudinal string vibrations are considered to play an important role for tone production in the bass and midrange but have no perceivable effect in the treble [12]. However, the contribution of the non-mensurated rear string end to the string-bridge-soundboard coupling is comprehensively discussed [13-15].

An encompassing study of the duplex scales on a modern grand piano is presented by Öberg [16] and summarized by Öberg and Askenfelt [17]. Important findings on the rear duplex are among others: damping the rear duplex string increases the corresponding partial of the bridge vibration by 3 dB while the rest of the spectrum remains unaffected. Crosstalk through the bridge to rear duplex strings of other notes exists, and the effect of rear duplex strings on the bridge motion seems to decrease with "more complex" harmonic relations (unison – octave – double octave – twelfth) [17]. As the main effect of the front duplex Öberg and Askenfelt state that "dampening not only removes the front duplex tone in the bridge motion, but also makes the main string fundamental and partials weaker and shorter in duration." [17] This contribution is also observable in the radiated sound (see **Fig.3**) and is audible even to non-experts. In the front duplex string motion, the fundamental frequency of the main string (further denoted as $f0_{main}$)

is 3 dB stronger than the fundamental frequency of the duplex string (further denoted as $f0_{duplex}$). When plucking the front duplex string, $f0_{main}$ is reduced but still observable in the duplex string motion.

Fig.3

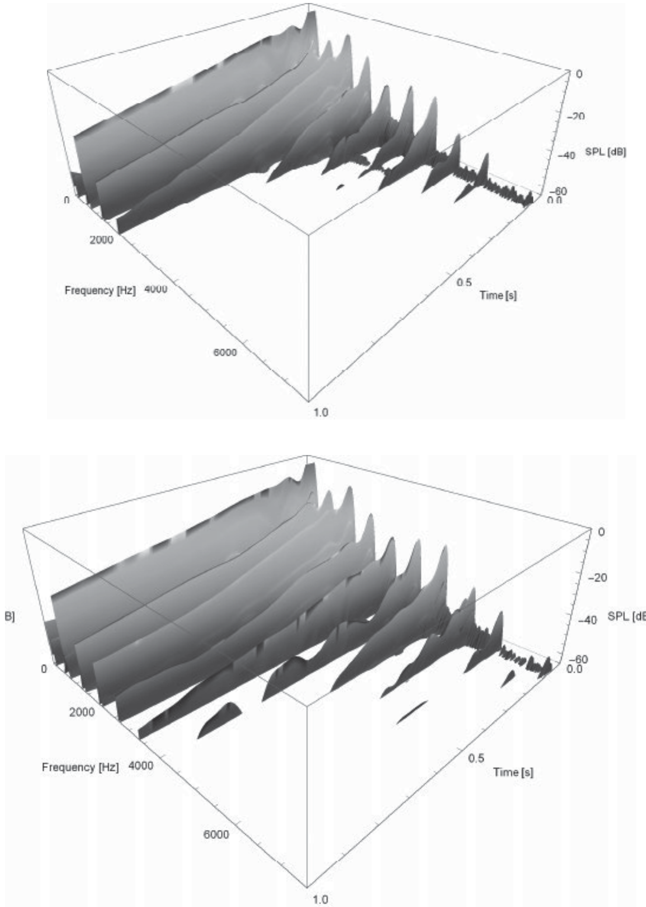


Fig.3 Spectrogram of radiated sound of forte played E5 note on a modern concert grand with (top) damped and (bottom) undamped front duplex. $f0_{duplex}$ at 5.3 kHz. Reference sound pressure $p_0 = 0.063$ Pa.

Regarding the coupling between the main string and the front duplex, Öberg and Askenfelt do not give a detailed explanation, but assume the string termination under the capo d'astro bar to be "not well defined". Further, "due to stiffness the string may exhibit a vertical rocking motion under the capo bar which transmits the motions of the main and duplex string rather effectively across the termination" [17]. Recent measurements give insight into the front duplex string coupling: due to the capo d'astro bar the main string faces different impedances for (at least) both transverse polarizations (parallel and perpendicular to the soundboard) which increase if the duplex string is undamped [18]. The existence of more high partial energy on the main string if it is coupled to a second string can be thus explained, despite being counter-intuitive at first glance. The effect does not depend on precise mensuration (consistent with the current realization), but on the angle of the front duplex string to the main string (a greater angle should increase the difference of impedances between polarizations), and type of coupling (agraffe/capo d'astro). The effect is, therefore, a result of complex boundary conditions instead of partial amplification by "sympathetic" co-vibration. In a metaphorical sense, the front duplex string can be understood more as working "against" the main string, contrary to Theodore's concept of working "in harmony".

4. Documentary Evidence about the Development

In the case of the duplex scale, the preliminary considerations probably started a long time before the patent application. Besides the duplex scale, Theodore registered two other new constructions in May 1872, both of them regarding plate improvements (U.S. patents No. 127,383: Monitor grand cupola plate and No. 127,384: Small upright cupola plate) [5]. Their preparations date back to Theodore's visit to Germany in 1869-70, where he "carefully studied the latest achievements of the steel and iron industry" [9]. Some of the ideas had already transformed into physical models as early as March 1871, according to one of William Steinway's diary entries: "In aft. Theo. shows me the new Plate of the Grand Piano, also wooden pattern of the new small Upright, which is nearly ready" [19, entry on March 25, 1871].

Likewise, Theodore's meeting with Helmholtz in 1870 might have already been the starting point to refine the sound qualities of the piano. In his studies Helmholtz dealt with the impact of several sound shaping factors, such as "the properties of the hammer, nature of the blow, striking place of the hammer, characteristics of the string, radiation of the soundboard [...] and the length, breadth, and dip of the keys" [2]. For the invention of the duplex scale, Theodore profited especially from the new knowledge about timbre and the theory of resonance phenomena, but also from new tools for sound analysis. Helmholtz's resonators, a series of brass or glass spheres of various diameters, filter particular overtones out of a complex sound. In Theodore's own words, it was this fundament that "prompted us to study by means of these instruments [the resonators], if what science has proven to be the richest tone, could come to reality in the Steinway piano" [20]. These efforts resulted in the duplex scale. Theodore was finally granted the U.S. patent "Improvement in Duplex Agraffe Scales for Piano-Fortes" on May 14, 1872. The accompanying drawing in the patent shows both front and rear duplex sections and specifies that the only resulting intervals are octaves, ranging from one to six octaves above the respective fundamental note.

Six weeks earlier, on March 30, the invention is mentioned for the first time in William's diary, yet apparently a proper designation was still missing: "In afternoon with Theo & Albt [Albert Steinway] uptown looking over points of the new Upr & grand patents, cupola Iron frame & increasing length of strings on the vibrating nodes" [19]. An entry three days later states a little more precisely: "…at Theodors house, looking over his new three scale Patent with Mr. Hauff" [19].

On April 26, 1871, the first grand piano to include the duplex scale (ser. no. 25.000) was already present in the warerooms [19], even before the patent was registered. This implies that the invention had either been completed and applied before the piano plate's casting or that it was attached as a separate piece at a later point. This latter method is documented on a few pianos built prior to 1875, some even before 1872, and will be discussed with examples in section 5. Their common characteristic is that the front duplex section produces only octaves as described in the patent, but the rear section is missing. This is because the hitch pins were positioned very close to the edge of the plate, so that duplex bridges could not be mounted on the plate at a suitable position. In 1873, the German musicologist Oskar Paul had the chance to study the duplex scale on a new S&S grand piano in Vienna. Consistently, he mentioned only the front part and only octaves as resulting intervals [20]. In contrast to the patent, even S&S's 1872 catalogue indicates that the earliest duplex scale specimen consisted only of the front part on the wrestplank which added octaves to the fundamental notes [21]. The advantages of this solution were that no modification to the plate production was required and the mounting of the front duplex at any time to any grand piano was made possible. After all there is no evidence that the duplex scale was ever manufactured exactly as indicated in the patent, with long resonating sections even in the lower range.

The first major occasion to present the duplex scale to an international audience would have been the Viennese world fair in 1873, but

S&S did not officially participate. Theodore nevertheless presented S&S pianos to members of the jury in order to make them write an approval in the world fair's official report [7].

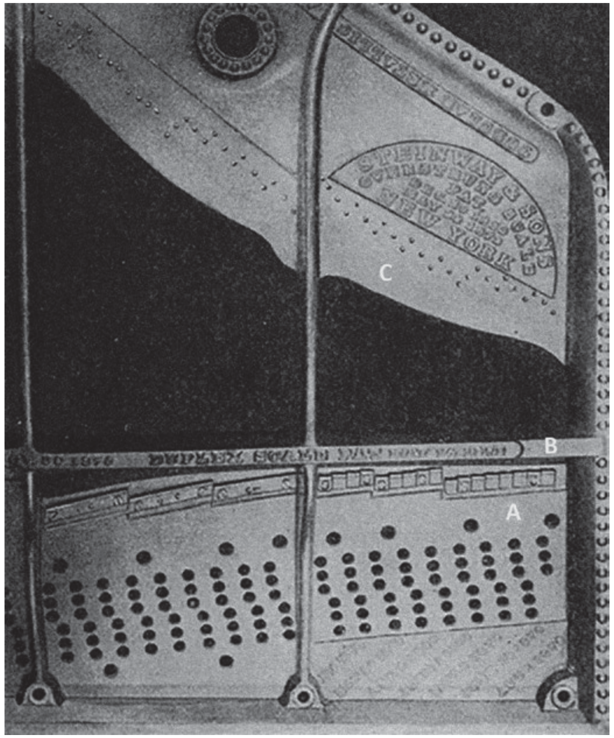
In December 1874 Ludwig Bösendorfer published a pamphlet in which he criticized Theodore Steinway's invention [20]. He recounted that during the Viennese world fair he received an order to copy the duplex scale according to drawings. It is doubtful whether he had seen one of S&S's grand pianos at all. Curiously he only knew of the rear part as rendered ineffective by weaving felt through the strings. Bösendorfer was sure that a duplex scale would have an audible effect, but in an undesired way, making the piano sound like the damping did not work properly.

Theodore defended himself against Bösendorfer's allegations by publishing a response in which he explained the motivation behind the duplex scale, the way it was supposed to work and its advantages in detail [20]. In this description, the duplex string lengths produce octaves, fifths or thirds. Here, for the first time, a diversification of intervals takes place, yet they are still partial tones to the fundamental.

The passionate debate between Bösendorfer and Theodore caught the Hungarian piano maker Lajos Beregszászy's interest. He reacted to the two articles in his own short pamphlet. As this source is hardly available today, it seems necessary to outline its purpose briefly [22]. Just like Bösendorfer, Beregszászy does not seem to have actually seen an S&S grand piano. He is only commenting on the statements made by Theodore and Bösendorfer and on that basis tries to point out why the duplex scale cannot work as intended, even though "there is hardly anything to criticize about the invention of the double scale, as long as we stay in the field of theory" [22]. Firstly, he continues, a fundamental tone can be enhanced "only by connecting the fundamental directly to a resonator. If this is supposed to work with an object separated from the fundamental, then the resulting resonance would disturb the fundamental" [22]. Beregeszászy further claimed that both parts of the duplex scale were insufficient due to the additional string section on the wrestplank being too short. As a result, the frequencies they produce lie outside the perceivable spectrum, whereas the rear section was dampened by felt and thus did not sound at all.

In summary, only from 1875 onwards is the practice of a full front and rear duplex scale documented. In this year, preparations for the so-called centennial grand began, which S&S presented at the Philadelphia world fair in 1876. For this updated flagship model the plate was equipped with some modifications. As part of these activities, a next step in the development of the duplex scale came with the introduction of the capo d'astro bar in 1875 (U.S. patent No. 170,646). This transverse bar replaces the agraffes in the treble range and terminates the

Fig.4



sounding string lengths. An undated contemporary photo (**Fig.4**, taken before 1892) shows the treble portion of the new iron frame with its typical ornamental rosettes on the outer edge [8].

In **Fig.4** letter *B* marks the new capo d'astro bar. On the hitch pin plate *C*, the pin holes have been moved away from the outer edge at various distances. The rear duplex bridges are missing in the photo, because they are not cast into the plate. They need to be positioned in front of the hitch pins and by moving them, tuning becomes possible. The wrestplank plate *A* is equipped with two different types of bearing surfaces for the front duplex: the left plate section contains three diagonal pads, whereas the supports on the right section are individually mensurated for each course. In both versions, the strings run over a metal edge in order to form a clear termination point.

Between 1880 and 1886, when Theodore was back in Braunschweig, he kept on instructing his nephew Henry Ziegler on technical

Fig.4 "Treble Portion of the Iron Frame", after Fanny Morris Smith, [8, p. 149].

matters. A series of 26 letters entirely written in German documents these efforts [23]. Several passages in the letters deal with defects of the duplex scale and suggestions for improvement. In 1883, for example, Theodore told his nephew Henry Ziegler: "I have decided on a longer duplex [...] and that works very well. Behind the bridge I take only two sections of the duplex scale; but in the front on the wrestplank three sections" [24]. The most detailed statements date from 1884:

> As far as the loud singing of the duplex [scale] is concerned, there is a very simple remedy for those who feel disturbed by it: that is, to weave a ribbon through the duplex. However, the sharp and high tones in the lowest position of the duplex are not caused by the duplex itself. [...] The duplex's length should maintain 2 ¾ inches to 1 ⅓ inches as the shortest dimensions, but that is only possible if you use a lot of fourths and then it will hardly last. Right now we have 3 ¼ inches to 1 ½, but as I said I know that pianos completely without duplex screech like the devil, for instance Blüthner most of all, then Chickering, then Bechstein. So it's not the duplex's fault, especially when there's leather on the bearing surface. [...] Similarly the long duplex scale, that chatter ["schnattern"] should just have a steeper slope and thereby all the small flaws would disappear. So just put wedges under those duplexes [sic] which stick out the most and thus modify the flexibility. If you deal with this issue carefully, it won't be necessary to partition the duplex scale differently and shorter [25].

A few months later Theodore came back to this subject, probably reacting to Henry's response:

> Your idea to set the duplex entirely on metal is not bad, but that means you have to exceed the audible frequency range, otherwise the resonating tone would be too disturbing. [...] There is nothing disturbing, viz. between the 36^{th} and 53^{rd} tone, but from this point on the duplex could be shorter. [...] The tone in this area has a virtually tender charm and a special elegance, which unfortunately disappears from the 54^{th} onwards. On the contrary, here the overtone reaches the ear as an individual and that should not be. Only a very short scale on metal would prevent this and the impulse of the string's division would increase, provided that the length is above the audible range [26].

The outer audible limit of approximately 16 kHz is only two octaves above the fundamental frequency of the piano's top note C8 (f0 for A4 = 440 Hz), but in the patent all the resulting duplex intervals stay clearly below that limit. The use of fourths shows a further diversification of intervals.

These constant changes in the intervals and lengths of the duplex scale illustrate that the company did not strictly reproduce what had been defined in a patent at some point, but that it was common to make adjustments throughout the years.

5. Case Study: "Helmholtz Grand", New York 1871 (ser. no. 21460)

On April 22, 1871, William Steinway departed by steamer for a trip to several European cities, which included a stay in Berlin for a few days. He intended to meet Helmholtz there, but did not succeed (compare [11] or [19, entry on May 25, 1871]). The reason for this visit probably was the new grand piano Helmholtz had just received. Since 2009, this piano is located at Deutsches Museum Munich (ser. no. 21460, hereafter referred to as the "Helmholtz grand"). An entry in S&S's sales book of 1871 verifies its identity [27]. The piano was sent by steamer from New York to Hamburg on April 17, 1871 and was then transported to Berlin, where Carl Bechstein attended to the tax formalities. On June 23, William noted in his diary: "…call on Bechstein, receive about 5 Thlrs from him after deducting about 20 Thlrs duty for Helmholtz Grand" [19].

After the piano had arrived safely at his home, Helmholtz expressed his gratitude in a letter to Theodore, in which he praised this piano's "organ-like" duration of tone, the light touch, the precise damping of the split damper pedal and the long bass strings, which made the bass notes more articulate [11]. He further claimed to frequently hear combination tones there and even added a paragraph about his acoustical experiments on this piano in the fourth edition of *On the Sensations of Tone* [1]. No. 21460 is a large concert grand piano with an extended range of 88 keys and a length of 8'5" (260 cm). The rosewood veneer and the carved cabriole legs and lyre contributed to the distinctive appearance of S&S's grand pianos at that time (see **Fig.5**).

According to the plate inscriptions, this piano is equipped with cross stringing, agraffes and the iron frame resonator, but there is no mention of the duplex scale. This is due to the fact that the piano was built one year before the duplex scale's regular implementation. Yet surely the Steinways wanted to show Helmholtz the invention that was connected to his work and hear his opinion. For this purpose, they decided to retrofit the piano "at least as far as possible" [28], so they inserted only the front part on the wrestplank. Theodore himself and a foreman came to Helmholtz's house in Berlin in July 1873. It took them 6 days to finish their work. Helmholtz documented this procedure in a letter to his wife [28].

This particular front duplex scale in the upper two plate sections has a zig-zag shaped bearing surface (see **Fig.5**), probably made of hardwood. Despite the overall diagonal outline, each course of three strings runs over an individually mensurated support. Today it is fully covered with roughly cut felt. The strings, hammers and felt pieces in this piano have not been replaced in the recent past.

The results of the new duplex scale were very effective according to Helmholtz: "The highest tones of our piano have really improved; you can still make the difference audible by dampening the cleared string portions. By the way, it is unbelievable what degree of studies and precision work is put into such a grand piano. Mr Steinway showed me a lot of details in the interior; but I will still propose some changes" [28]. These suggestions might have been included in a letter to the Steinways of August 13, 1873 in which Helmholtz thanked them for the new duplex scale "just applied to my Steinway Grand Piano" [20]. Only a few sentences of this letter were printed in the S&S catalogues and unfortunately the autograph is not extant [10] so that Helmholtz's ideas about what to improve remain unknown.

The detailed source material regarding the "Helmholtz grand" indicates that S&S themselves used to retrofit the duplex scale even if a piano predated its invention. So far, it is not clear how often that happened. Moreover, this instrument's duplex scale belongs to the earliest type. This makes it especially valuable for the following measurements.

Fig.5

Fig.5 Left: Steinway grand piano (ser. no. 21.460), New York 1871, since 2009 at Deutsches Museum, inv. no. 2009-0477 (Deutsches Museum, München, Archive, CD_L6383-01, reproduced with permission). Right: close-up view of front duplex section in the treble range.

6. Measurements

6.1. Comparison of Historic Grand Pianos Manufactured Between 1871 and 1884

As an attempt to find alterations which led to the current design, the "Helmholtz grand" is compared to several instruments built after 1871 and before 1885. Instruments of that period are notably difficult to find: they are too young to be exhibited, too old to be treated for general restoration at the factory (which becomes necessary after roughly 100 years) and they are quite unpopular on the second-hand market due to the fact that they mostly have only 85 keys. For the study at hand,

Table 1

Year	Ser. No.	Model	Keys	Front Duplex Keys	Front Duplex Coupling	Rear Duplex Keys	Condition	Ownership
1871	21.460	Style 3	88	52-88	Agraffe	none	unrestored, playable	Deutsches Museum, Munich
1877	35.855	Monitor	85	52-85	Agraffe	46-85	restored, playable	Klangmanufaktur, Hamburg
1877	35.983	C hist.	85	36-85	Agraffe	36-85	unrestored, most keys playable	Klangmanufaktur, Hamburg
1879	42.411	C hist.	85	52-85	Capo D'astro	52-85	unrestored, some keys playable	Klangmanufaktur, Hamburg
1884	51.611	B-211	85	52-85	Capo D'astro	40-85	unrestored, not playable	Klangmanufaktur, Hamburg
1977	454.791	B-211	88	52-88	Capo D'astro	52-88	playable	LMU, Munich

four additional pianos could be examined. Most of them are considered "unrestored", which only means that no signs of restoration (and/or modification) are visible or known. The state of preservation varied widely: for some notes on the unrestored instruments, the pressed key just about produced a tone or the knock by the key bed contact completely dominated the sound. Some strings lost their tuning with the first played note due to loose tuning pins. On the other hand, one piano from 1877 is restored to the state of a brand new instrument (new action, new strings, and new sanded height profile for the soundboard).

Herein lies a common dilemma in the investigation of historic instruments: their appearance is distorted, either by time or restoration. In this regard, general statements about the vibroacoustic behaviour of the instrument in its past based on current measurements are problematic. Furthermore, the replacement of smaller construction parts complicates an organological evaluation of the development of the duplex construction (e.g., string sections damped with pieces of felt). Nevertheless, careful consideration of measurements and informed correlation of these measurements with available historic data represents the most promising approach to making meaningful assumptions about construction decisions made over a century ago.

Table 1 Overview for the examined pianos, including the "Helmholtz grand" and a modern model B.

A modern S&S model B is examined to compare obtained historic data to the present norm. See **Table 1** for a detailed classification of the instruments under study.

6.2. Scale Measurements

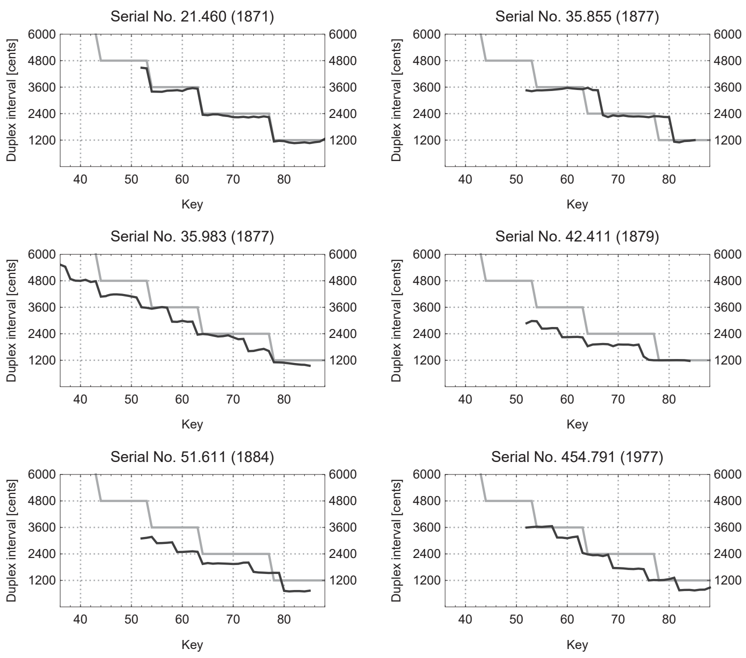
For the modern rear duplex scale, large deviations from the nominal harmonic relations are found (50 cent average) as well as within trichords (25 cent average) [13, 16]. Öberg and Askenfelt assume, "that the authors of the Steinway patent were aware of that accurate tuning to the nominal frequency relations is not of critical importance for the perception" [16]. This is in contrast to Theodore's reasoning about the need for precise mensuration of the harmonic relations between main and duplex string to obtain the desired effect [3, 20].

For the modern front duplex, trichords are largely mistuned (70 cent average) due to the pressure bar running at an angle with the capo d'astro bar and nominal relations to the main strings vary widely [16]. The modern implementation also does not allow the tuner to adjust the string length relations. Again, this contradicts statements by Theodore who praises the duplex mechanism as to give the tuner control over this part of the string [20].

For all examined instruments the following parameters are measured: the lengths of all string parts (using steel rulers) and the angle from the main string to the front duplex string (using a digital goniometer). Since for all historic pianos the front duplex plate is realized in a staircase shape (from key to key), all trichord strings have the same length. The front duplex string lengths per trichord for the modern grand are measured separately. For specification of the nominal front duplex intervals, the average length per trichord is used.

Fig.6 depicts the measured nominal front duplex intervals per piano and key. The light lines illustrate the intervals proposed by the patent. The "Helmholtz grand" is the only piano to precisely follow the patented intervals. The front duplex is realized down to C5. The Monitor, built six years later, still follows the specification of using only single and multiple octaves but later jumps to lower intervals. The serial number of the second piano from 1877 indicates that it was built shortly after the first, but it is a different model (C hist.). It is the only instrument to have the front duplex realized down to G3 and does not follow the patent over most of the course. Instead, intervals between the octaves are utilized. Built two years later, another historic C utilizes intervals between octaves for most of the keys down to C5. Built five years later, a B-211 manufactured in Hamburg only matches the double octave for a few keys between G5 and B5 and otherwise uses fifths, twelfths and higher intervals between the integral multiples

Fig.6



of octaves. For the modern B-211, nominal intervals (apart from the large deviations due to the duplex plate design) go up to the triple octave and it uses one interval between each two integral multiples of the octaves.

Fig.7 illustrates the nominal rear duplex intervals per piano and key. The light lines depict the intervals proposed by the patent. As discussed in section 5, the “Helmholtz grand” does not have a realized rear duplex mechanism. In general, no examined instrument follows the design proposed by the patent. For the Monitor from 1877, the rear duplex is realized down to C5 utilizing octaves, twelfths and double octaves. The model C from the same year has a rear duplex down to G3, very roughly following octaves and double octaves. The model C two years later has a rear duplex down to C5, again forming the same intervals but having more keys in higher relations. The B-211 from 1884 has a rear duplex down to C4 and is the only instrument with rear duplex intervals higher than the double octave. For the modern grand, rear duplex intervals of octave, approximate thirteenth and double octave are realized.

Fig.6 Nominal front duplex intervals as implemented (dark) compared to what is specified in the patent (light).

Fig.7

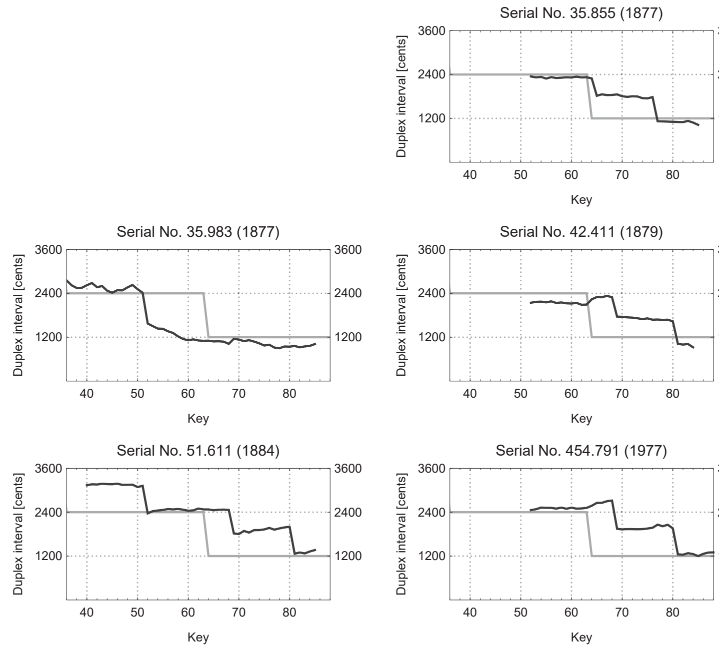
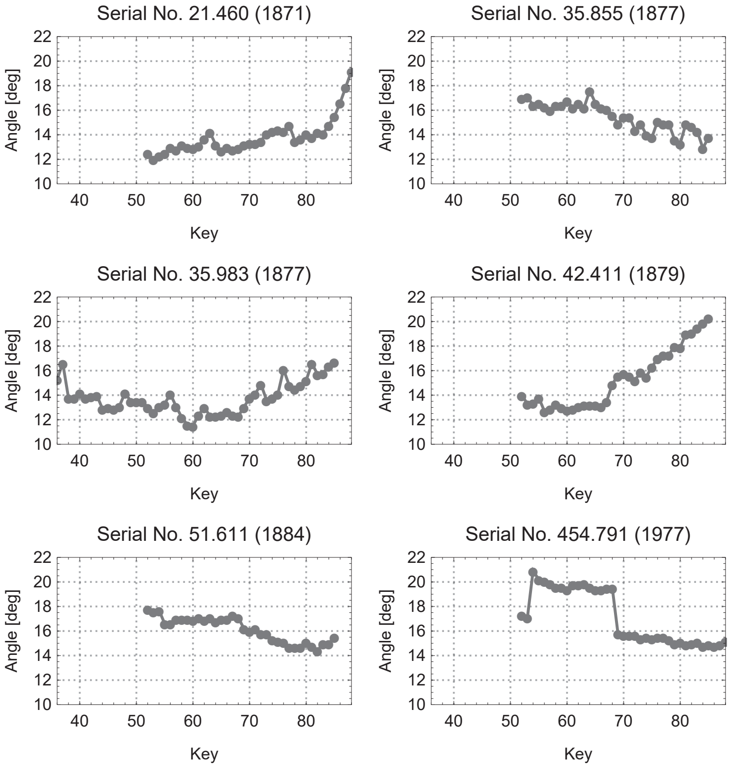


Fig.8 illustrates the angles between the main string and the front duplex string per piano and key. In general, earlier instruments seem to have a sharp increase of angle in the high treble range (with the highest gradient for the “Helmholtz grand”). The Monitor from 1877 as an outlier has been restored and thereby brought to a design comparable with current manufacturing.

For all pianos before implementation of the capo d’astro bar, the front duplex plate is covered with felt. As a consequence, the front duplex strings do not end point-like but run into a bed of felt. For the two historic pianos with capo d’astro bar, the front duplex string terminates on a small metal block with indentations for each string, thus yield to a point-like fixed boundary condition (as implemented in the current design). Note that the two instruments from 1877 (ser. no. 35.855 and ser. no. 35.983) have little separate metal blocks defining the string termination on the frame. These can be shifted to tune the rear duplex trichord by trichord.

Fig.7 Nominal rear duplex intervals as implemented (dark) compared to that specified in the patent (light).

Fig.8



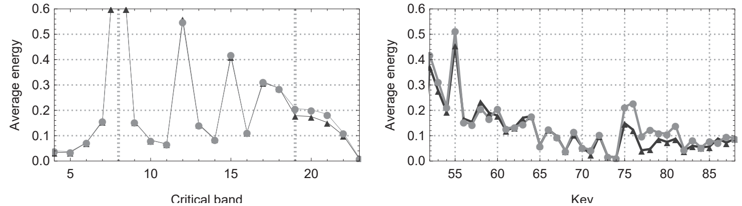
6.3. Vibroacoustic Measurements

Due to the fact that the pianos were situated in very differently shaped rooms with, in part, high reverberation times, the obtained radiation measurements are not considered for the analysis. The presented data, therefore, is solely based on acceleration measurements at the string/bridge termination points perpendicular to the soundboard (piezoelectric transducer model: PCB 352C23). The rear duplex strings are damped for all measurements. For all playable instruments, the keys with a front duplex are played by hand in forte range (finger stays on key before strike). If playable, the instruments were tuned before the measurements. Ten takes for each key are recorded. All recordings are performed with 48 kHz and 16 bit resolution.

Since the spectral content of a piano tone is highly dependent on the acceleration of the key, a mechanical finger would have been

Fig.8 Angle from main string to front duplex string per key and piano.

Fig.9



preferable to ensure a constant key-pressing force in all measurements. Unfortunately, such a device could not be used for the study at hand. Therefore, the 10 x 10 takes are filtered regarding the combination with minimum difference of amplitudes of the first string displacement approaching at the bridge. Since no interaction with the front string termination has happened for the first pulse, it should be unaffected by the duplex mechanism. This process reduces data to 1 x 1 per key but thereby diminishes the error effected by variance of played dynamics. Even though the pitch of a piano tone is considered to change over the span of the decay, for FFT-based analysis a fixed 1s-window with Hamming window function is used starting after the initial transient phase. For the main strings f_0 is estimated by a peak detection. The corresponding frequency band is derived based on the measured chamber pitch and following the Railsback curve [29]. The inharmonicity coefficient (B) is estimated for each string by iterating a peak detection for increasing partial numbers and adjusting B consecutively [30].

For all notes the average energy per critical band is calculated [31]. As described in section 3, application of the duplex schematic firstly enhances higher partials of the produced tone and secondly prolongs their decay. To detect enhanced higher partials in the bridge motion, the average energy in the frequency band containing $f_{0duplex}$ is compared to the band containing f_{0main}. $f_{0duplex}$ is not measured but estimated, assuming the same tension for the duplex part as for the main string part. **Fig.9** exemplarily illustrates the effect of the front duplex scale for a modern grand. Average energy in the bands around $f_{0duplex}$ is slightly increased.

The Monitor from 1877 shows the greatest average increase in critical band energy when undamped. This can be explained by the fact that this instrument had just been restored a few weeks before measurements with the focus of enhancing the duplex effect (the felt was removed from the duplex plate and the front duplex plate was sharpened

Fig.9 Left, Average bridge acceleration per critical band for damped (triangle) and undamped (circle) front duplex. Key 60 (G5/A5) on a modern model B, forte played. Vertical dashed lines denote bands containing f_{0main} and $f_{0duplex}$; Right, Average energy ratio for the same piano for all keys.

to form a point-like string termination). The modern model B shows the second greatest average increase of band energy. The historic C from 1879 has the third greatest increase of average energy, which happens to be the first one with a capo d'astro bar. The "Helmholtz grand" and the historic C from 1877 show no significant increase in duplex band energy when undamped.

7. Conclusions

Even though an active contribution of Helmholtz to the invention or even a close collaboration with Theodore Steinway could not be observed, the duplex scale seems to be highly influenced by his findings. The construction was patented in May 1872 and is regularly realized for grand pianos from ser. no. 25.000 on. The case study of the "Helmholtz grand" showed that it was possible to retrofit older pianos with the duplex mechanism.

In the earliest phase up to 1875, the grand pianos follow the nominal front duplex intervals proposed by the patent, which is never the case on later instruments known to the authors. In these instruments, only octaves appear as resulting intervals. Over time, a gradual diversification of intervals takes place: at first they correspond to the harmonic series (octaves, fifths and thirds), and later, indefinite intervals are realized. Thus, the theory and practice of the duplex scale diverged increasingly.

Little variation is observable over the selection of instruments in regard to the range of the compass, to which the duplex scales have been applied. As an outlier, the historic model C from 1877 has the greatest range. Again, no instrument follows the range proposed in the patent, where the rear duplex scale covers most of the compass.

The issue of the duplex scale's tunability was subject to criticism from the beginning, as the possibility to control the duplex string length was an important part of Theodore's reasoning for the value of the invention. Two of the instruments studied (and a frame depicted in **Fig.4**, dating from before 1892) have little, separate metal blocks for the rear duplex string termination. By shifting these blocks, the tuner could adjust the length ratio from rear duplex string to main string. However, in later instruments, the separate blocks are replaced by a single metal band fixated on the frame.

In summary, precisely mensurated intervals turn out not to be decisive factors in the functionality of the duplex scale. Instead, several other factors could have an impact on the working mechanism: up to the implementation of the capo d'astro bar, all considered historic pianos have their front duplex plate fully covered with felt. This is mentioned neither in the patent nor in other known historic sources. The instruments with capo d'astro bar have a point-like front duplex string termination. Earlier instruments seem to have a sharp increase of angle in the high treble range (with the highest gradient for the "Helmholtz grand") in contrast to a more homogenous progression of angles for the current model. All considered historic instruments have a staircase-shaped front duplex plate which ensures the single strings in a trichord to be of the same length. This is consistent with statements by Theodore, but contrary to the front duplex design currently applied by S&S.

As a result of the vibroacoustic measurements, the duplex effect in the bridge motion is most pronounced for the Monitor grand from 1877. This could be explained by the fact that it has been recently restored. The influence of the duplex mechanism is lower for the modern B-211 and for the historic C from 1879. No significant effect is measurable for either the "Helmholtz grand" or the historic C from 1877.

The previous observations can only sketch certain tendencies; nevertheless, the extent of constructional modifications over the first twenty years indicates that the duplex mechanism did not work as intended from the beginning. In this regard, the development could be understood as the implementation of a highly theoretical concept which was then refined through a trial-and-error approach.

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