Hammers and Strings

All-Day Seminar
Del Fandrich
4/19/1014

How Hammers Work

1. The basic musical concept of the piano-forte is that it creates musical dynamics – a voice that is both soft and loud, or soft and bright – not just less loud, louder and loudest.
2. Volume and timbre are two different concepts
    a. Volume (or sound power)
        i. Real sound power and perceived sound power are not he same thing
        ii. Sound power can be measured & quantified
        iii. Perceived sound is objective; our interpretation of a piano's "voice"
    b. Timbre: the harmonic mix in the wave envelope
        i. Are more lower partials excited or more higher partials?
        ii. The timbral change resulting from volume changes give the piano its dynamics – pianissimo and forte
        iii. Volume can change with or without a timbre change
3. More than any other single component it is the apparently simple but actually very complex hammer that makes a dynamic tone character possible
4. Anatomy of a piano hammer – very simple concept
    a. Wood molding
        i. Wood species effects mass
        ii. Size and shape effects mass
    b. Inner felt
        i. Usually softer than outer felt
        ii. Basically a filler – makes a thinner outer felt layer possible
    c. Outer felt
        i. Characteristic of wool felt
        ii. Fiber structure
        iii. Felt density
        iv. Thickness
        v. Width of saddle
    d. Construction – materials and process – contribute to both the static and dynamic performance character of the hammer
5. When the hammer strikes the strings, two things happen
    a. The hammer compresses – indents – in the area immediately surround the wire at a non-linear rate
        i. The piano hammers behaves somewhat like a hardening spring
        ii. Hammers appear harder for high impact forces; softer for low impact forces
        iii. Non-linearity is partly due to the characteristics of wool felt and partly to shape
    b. Mass and hardness gradient – static hardness – determines basic voice of the piano
        i. Harrd hammers readily excite higher partials
        ii. Soft hammers do not excite high partials well
        iii. Dynamic hardness characteristic excites different partials at different impact forces
    c. The strings deflect – also at a non-linear rate – and start vibrating
    d. String deflection and the resulting waveform depends on:
        i. String mass and tension
        ii. Hammer mass and velocity

        iii. Hammer density and/or “hardness”
    e. Changing energy mix of partials at varying hammer velocities depends on non-linear spring rate
6. Both static and dynamic hammer hardness influence piano tone
    a. Hard hammers are good at exciting high frequency models of string vibration – tone is described as being “bright” to “harsh”
    b. Soft hammers arenot good at exciting high frequencies – tone is described as being “dark” to “dull”
    c. Static hardness has a large influence on the fundamental power and tone quality
        i. Hemmers can be hard or soft with infinite gradations in between
        ii. Static hardness is determined over a relatively long period of time (seconds); dynamic harness is a relatively short-term phenomenon(milliseconds)
        iii. Static hardness measure ignores hysteresis
            1. The loading and unloading rates of hammer felt are not alike
            2. Hysteresis has little effect on a piano’s voice
            3. Hysteresis is a greater factor on rebound than on attack
        iv. Contrary to popular belief, static hardness cannot be accurately measured with a durometer
    d. Dynamic hardness has a large influence on the piano’s ability to produce a changing waveform – a varying harmonic mix – with changes in hammer velocity (volume)
        i. Determining dynamic hardness requires accurate measures of hammer velocity and impact force
            1. Measuring dynamic hardness requires sophisticated, sensitive and expensive equipment
            2. Difficult to do outside of a laboratory
7. Static vs. dynamic hardness
    a. If the hammer behaved as a linear spring the relationship between force and compression would be F=Kx.
        i. F=force
        ii. K-a constant depending on the properties of the hamemer “spring”
        iii. X=compression
    b. Since piano hammers (usually) behave as a hardening, or non-lkinear spring this relatikonship becomes F=Kx P
    c.

Early Hammers

Cristofori called his pianoforte invention a harp-harpsichord that produces soft and loud. The part that makes the dynamic voice transition between pianissimo and forte possible is the hammer.

Piano hammers through time. The earliest hammers were like circle of paper – vellum – which advanced into a multi-layer of leather and felt. Felt piano hammers have been standard since about 1830. These early 1800;s Erard hammers are made with a combination of leather and felt.

Dynamics

The dynamics is made possible by the shape and construction of modern hammer made of dense wool felt. There is a difference between sound power and timbre. To learn about timbre we have to look at both spectrum and amplitude over some period of time. The initial impact starts out as noise for the first couple milliseconds. We need both sound power and timbre. There are two different kinds of tone. There is the initial impact sound, which is like chaos. It is made up of hammer impact against the strings, a lot of sound from the capo d'sastro bar, some of the vibrating energy is translated into the shank, flange and rails so some of the sound comes from the action, some comes from the plate. This is a brief impact and in a spectrum analysis it shows up just as noise. After a couple milliseconds it will start to coalesce into a basic frequency. In the tenor and treble it will be centered around the partials of the fundamental. As you go lower into the bass you will rarely be able to pick up the fundamental. It is what takes place on the initial impact wave form that

Piano hammers consist of a wood core or molding, the inner felt and the outer felt. The outer felt concerns ujs most. It is under considerable tension out and compression in. The wood molding takes up some of the mass. These molding must be strong enough to take up the impact and stress when the hammer strikes. Someone is currently experimenting with bamboo moldings for strength. The inner felt is a lower grade of felt, used mostly as a filler. It's primary function is to allow us to use a thinner outer layer. If the outer layer is too thick it is harder to bend and the tensions are greater. To bend thick felt it must be made moist; however, when it is too moist it will matt down and the fibers of the wool will be permanently changed. Therefore the inner felt builds out the size of the hammer to enable a thinner outer felt.

There are as many different types of wool fiber construction as there are manufacturers, and each believes their technique is the best. If a manufacturer specifies a certain density of hammer felt, there are two ways to achieve it: felt it or press it. Hammers that are Erratic and more on the soft side is pressed and layered. The more felting that is used, the fibers are interlocked tighter as the piece gets smaller and denser; these hammers are harder to sand. The layers are still there, but it's harder to get them apart because everything is more intertwined. Technicians think only of sound; manufacturers ask how it bends and how it presses. The firmer denser felts are harder to bend and can break.

When a hammer strikes the string, two things happen. The hammer surface deflects, and the string bends. These deflections are measurable. The hammer surface compresses – indents – in the area immediately surrounding the strings. How far the wire indents is a function of impact and velocity. If the hammer acted like a linear spring, then increasing the force would cause the deflection to go up. But instead, what we actually measure at impact is less. It is this non-linear hammer impact that makes the piano hammers behave somewhat like a hardening spring. Hammers appear hard for impact .This non-linearity and its measure is due to the nature of the felt, the shape of the hammer's striking area and the changes the felt has gone through during the pressing process. For the same felt density the longitudinal striking area is short with oval shape or pear shaped hammers and longer with round hammers. The round-shaped hammers strike more of the string. If the hammer is close to the agraffe there will be more damping and less partials.

FF=Kx is the spring constant, called Hooke's Law. (straight line on graph of force to compression). F= force, K =a constant describing the properties of a linear spring, x= compression
F=Kxp is the effective nonlinearity coefficient. (More force gives less compression) This is the characteristic of the piano hammer that makes dynamic sound possible. We don't want the soft sound at forte, although we do want it for pianissimo.

As hammers get harder, the curve gets straighter and closer to Hooke’s law/

A soft linear hammer and a hard linear hammer are different from a polyurethane hammer.
Spring constant follows Hooke’s Law
Should resemble a hel0cyckle sine curve
Hemmer contact time does not depend on the force of impact, so the hammer stays in contact with strings for the same amount of time for both soft and hard blows. Only the peak force will be different.

With a non-linear hammer the force is less.
Curves are not left-right symmetric.
Time of hammers contact does depend on impact force.
Hammers tays in contact with strings longer for soft blows than for hard blows.

Measuring dynamic impact:
Requires accurately measuring hammers velocity/position at impact
Requires accurately measuring force at impact
This method is described by Dan Russell in The piano hammer as a nonlinear spring, 1997
A velocity flag triggers two light gate just before impact.
A force transducer measures impact force

There is a short distance between the hammer and the V-bar. The cap-d’astro bar goes up and down, back and forth, and slightly rotates. Both the up and down and the fore and aft motions create sound. Fasten an accelerometer senses these motions. The problem with most hammer research is that they are done on single hammers, or hammers on a single piano. What we need is broad-spectrum measurements on set after set.
Another way to measure hammers was done by Stulov. This device is similar but more elegant and more complicated. A. Stulov at the Centre for nonlinear Studies, Institute of Cybernetics at Tallinn /Tech

In Del’s opinion, from the moment that hammers come out of the press, everything we do to them is destructive, starting with slicing the hammers apart, which tears the fibers apart. The blades in the factory get so dull that they actually rip the felts apart with sheer force. We want to do as little destruction as possible. The hammer coming out of the press should be very close to the sound we want so all our voicing is minimal. Frequently we have hammers that are way to hard, so voicers needle them down. The denser the hammer is, the closer it becomes to Hooke’s Law, making them sound nearly as hard as wood. The quality of felt in the hammer is not as big an issue as what we do to the felt. We can ruin even the best of felts.

Measuring static hardness and nonlinearity:
Concept is simple -- add force, measure deflection: add more force, measure deflection, etc.
An Excel spreadsheet processes the results and provides both the generalized hammer stiffness and the effective nonlinear coefficient
Like the piano, it requires no external power source
Accurate, repeatable results.

Del wanted to come up with a method of putting a number on two things: the generalized spring break and the non-linearity exponent. Given these two numbers we can define pretty closely how this hammer will respond. Of course there are other issues, like hammer mass, strings, etc. but this is a start. Then we, as technicians, would have a tool to define the mass and spring rate that we would like the manufacturers to make for us. There is no way that manufacturers are going to measure every single hammer, so we could look at three points: #10, #30, and #60. If we can find the limits, then we can define an ideal hammer.

Measure from the end of the molding to the tip of the felt, as you keep pushing the felt down you will increase the density. We can alter the same felt by pressing it tighter or looser. Consequently the same felt can be made to sound different ways. Hard dense hammers are brighter and louder. The differences between different kinds of felts are subtle. The overall sound of the piano may be similar, the subtleties will be different. Types of presses and methods of heating make a difference in the make-up of a hammer. Hammers that start out on the hard side are more difficult to voice because the voicing doesn't last long. The same goes for hammers that are made too soft.

If we can predict at a glance how a hammer will sound, we need to know the generalized spring constant and the nonlinearity component. Del devised a jig with a carriage that moves up and down, using a tough slider bearing and a stop block to accommodate different hammers. Zero the dial indicator, put a weight/mass that represents 2 Newtons of force and measure the deflection. Then put 4 N of force, let it stabilize, and record the reading. Add 16 N of force and record. These three numbers we then plug into a spreadsheet and we come up with one of three curves on a graph. This gives us both the numbers we are looking for.

Del removed three hammers and measured each as they were straight off the piano. Then he lacquered one 10:1 3x, and he needled another. The lacquered hammer went straighter up the chart, the untouched hammer was in the middle, and the needled hammer with 30 inserts using 3 needles on each shoulder was the most gradual curve.

Hammer mass and static hardness – the hardness gradient – determines the basic voice of the piano
When we talk about hammers being "hard" or "soft" we are referring to its static hardness (F=Kx) not its non-linearity property (F=Kxp)
The dynamic range we get from the amount of curve, or non-,linearity quality.
We have a non-linear hammer striking a string which also has a non-linear component. When we strike a string, we stretch it. The more we stretch it, the harder the string. Soft hammers do not excite higher partials well. Hard hammers readily excite higher partials.

High partials translate into a bright sound. The comparison between a soft and hard hammer is hard to tell on a time analysis, but when examined on a spectrum graph it is obvious. With a pianissimo blow, there is a more defined low-partial wave envelop, taken .1 sec. after impact. With a forte impact, there is a lot more junk, but it will quickly die out. The longitudinal sounds appear between the normal wave forms.

Design factors that affect hammer performance:

- Felting process (felting to size vx. Pressing to size)
- Molding shape and weight
- Quality of felt
- Density of felt
- Resilience of the felt
- Type of fibers in the misx
- Dt

Modern hammer presses are usually powered by hydraulic cylinders under very high pressure, and typically, very high temperatures. At each end there is an adjustable mechanical stop.

Press factors that affect hammer performance:

- Moisture content of wool
- Press straight on or pre-press?
- Type, thick ness and length of inner felt
- Type, thickness, shape and width of outer felt
- Shape of cauls
- Press pressure
- Amount of compression
- Time in press
- Temperature through working part of hammer
- Slicing and trimming

The idea of heating the cauls did not come into practice until the new non-hide glues came out. At 170 degrees F the glue will kick over in about five minutes. Heating speeds up the process. The side cauls have to be up somewhere around 200-210 F (100C) for the heat to vibrate through the felt, get to the glue joint, heat the glue joint enough and cure it. Within 20-25 minutes a set using heat will be cured.

However, there are a lot of problems with this technique. Hammers that were pressed in the morning were different from those pressed in the afternoon. The morning hammers had heat on the sides but the bottom cauls were still cool. As the day went on, the heat transferred down into the bottom aluminum cauls which then heated the crowns and created a different kind of hammer. The bottom cauls should remain cool.

Manual presses are cold presses. Inject air, especially to the bass side, to keep it cool. The glass transmission point of wool is under 50. Above 60 the wool fiber will be permanently altered: the felt is ironed and the resilience is removed. Cold-pressed hammers take hours to cure. Without heat the felt balance is ideal, but this system doesn't work. As long as the heat is on the side cauls where the glue is and keeps the bottom part cool where the hammer strike point is, the hammer will be ideal. Above 110C the felt will burn. Some hammers are made with too much heat.

Factors affecting voicing

- Hammer shape
- Hammer mass

- Radius at strike point has an effect on hammer nonlinearity
- Overall hammer density and hardness

More resilient hammers, improved tone across the timbral spectrum, less voicing required, improved voicing stability.

Everybody has problems. In China, after each holiday a third of the employees don't return. There is a high turn-over rate. Some hammer companies just want the their hammers to look pretty. A shordurometer measures how long people last.

Generally piano hammers are heavier than they need to be, particularly in the upper third of the sacale. What happens when hammers are too massive in the treble? Several things. In terms of tone, you get a lot more hammer knock, to the point that the knock will over-power the actual tone we are after. The obvious solution would be to lacquer the hammer. This was Baldwin's solution, but they got a terrible reputation for breaking strings. When hammers are lacquered, they become even more massive. Hammer mass in the treble is not good. On the other hand, go too light and the sound becomes thin. For the high treble, we need to reduce mass from the hammers. WNG hammer shanks are hollow.

The hammer maker has control over everything but the felt itself. The specifications for measuring hammer felt from the vendor are worthless. We give them the weight of the sheet, and the thickness at different areas. This, in theory, gives the density of the felt, but it doesn't tell us whether the felt was pressed or felted. The shorduromete tells us the first quarter of a mm, but tells us nothing about what is below that level.

One of the most frequently overlooked part of the hammer is the shape at the striking point: rounded or pointed. Del prefers a rounder shape. Often we take a round hammer and sand it to an oval shape. The hammer depends on a continuous layer of felt for its foundation. When the sides are sanded, the tension is cut and they need to be hardened up with lacquer. With a more felted hammer this is less of an issue. The oval shape is ideal, but it should be pressed this way, not shaped by sanding.

The ideal hammer comes off the press and does not need shaping. In hammer production, to get an oval-shaped hammer you need:

- A narrow saddle to keep control of the shape.
- This shape tends to break felt, so they use a shield or carrier strip to distribute the load and take the friction load away from the shoulder so more of a curve can be pressed into the felt.
- The other way to compress felt is to wet it, but that defeats our purpose.
- Cupped hammers are an indication of either very dull knives or that the manufacturer did not sand them.

Del does not like hydraulic presses because he has not seen a hydraulic tool that doesn't leak. We don't want oil around felt or wood. Hydraulic presses are definitely very fast.

On making piano hammers:

- Hammer-maker has control over size and shape, density, mass, resilience, etc.

- Hammer characteristics determining basic voice of the piano should come from the design of the hammer, not from voicing
- This starts with the shape of the caul and the shape and density of the felt strip.

Imadegawa hammers were as hard as rocks, but their shape was perfect. Del epoxied a set and used them to make cauls.

There is a third method of measuring hammer resilience. That is to put a force gauge down below, hit it, and measure the sound transition between the force-gauge. The speed of the sound is a measure of the density of the felt and is an indication of how the hammer is on the wood. Del would like to get his jigs in the hands of manufacturers and rebuilders so we can establish a universal database on hammers. Once we have a set of standards, we can provide the density and mass of what we want and the manufacturer can consistently provide that quality. Right now, how do we know whether to use Renner, Ronson, Abel, or other brands? There are three distinctly different hammer parameters even depending on the mm distance from the strike point to the wood.

Del developed a hammer analysis chart. He measured weight, force, compression, spring constant, reference, to come up with stiffness and resilience, rated from soft to hard. The hammers he tested had probably already been previously lacquered. By getting reasonably predictable hammers, the amount of voicing required is minimized, thus reducing the amount of destruction involved. The more chemical added, the less resilient the hammer is and the less gradient change there is in the dynamics. In the high treble we want hammers closer to Brooke's law. The hammers should be pretty hard.

Strings

How tightly were the strings wrapped?
How fast were they wrapped?
What grade of wire was used?
Which diameters were chosen?
Bass string scales are a compromise.

Test #1
Core Diameter: *Thin Core vs. Thick Core (Same speaking lengths & tension)*
When two notes tuned the same sound different, the

Stiff wire cores do not like to bend as much, so they won't bend as much at the low frequencies.
The thinner core provides more of the fundamental
The thicker core decays sooner than the thinner core.
A core of.49 is as small as can be used. You could not put a single wrap on this core. Go smaller than .49 and you will get a fuzzy sound. Del tried a triple-wound string, but it was too stiff. Find out where something stops working, and then ask why?

Test #2
Tension: *High Tension vs. Low Tension (same speaking lengths & %BS)*
Because the wave-lengths are different, the partials we hear are different. There is a whole different energy mix. The lower tension string has a thinner core wire.

Bass section verticals often have problems with dampers because most manufacturers make the damper pads longer -- which don't help -- or they make the damper springs stronger, which also won't work; they have taken all the mass out of it. Some of the best bass dampening pianos were made by Chickering because they used big brass barrels and brass plates with dampers stuck in there. Added mass does not like to respond to quick-changing direction. No amount of spring pressure will take away the higher partials. By adding mass and stiffness, which is not a factor at higher frequencies, but at lower frequencies there is a change. Higher frequencies are mass-controlled, whereas lower frequencies are controlled by stiffness. Mass, such as brass barrels, is far more effective than heavier springs, which increase resistance when pushing down the keys.

Test #3
Wraps: *Single vs. Double-Wrap (Same lengths & overall diameters)*
Compares two wrapped strings, one having a double layer wrap and the other having a single layer wrap. The speaking lengths, back-scale lengths, core diameters, and overall diameters are all the same. String tensions are the same.
More fundamentals on the double wrap. The double-wrap sounded better.

Test #4
Lengths: *Different Speaking Lengths (same tensions)*
Compares two wrapped strings having different speaking lengths. The core and wrap diameters are adjusted to maintain approximately the same tension and inharmonicity coefficient. The back-scale lengths are the same.

Test #5
Back-scale: *Different Back-Scale Lengths (same speaking lengths)*
This test compares two wrapped strings having different back-scale lengths. Both strings have the same speaking length, core diameter and overall diameter, hence the same tension.
Add the twist to the end of the string on a short back-scale and that section of string turns into steel rod; how can the bridge move much with such rigidity? The compromise is that we have a finite length of space to fit the string. We could increase string angles. However, the tenor sound comes out from the left and the bass comes out on the right. The floor space is more than a competently designed larger piano. Listening to the two notes, even though they are equally tuned, the string with the short back-scale sounds flat, is a duller tone, and the decay is a bit quicker. The string with a long back-scale sounds noticeably richer.

Test #6

Direct vs. Cantilevered Bridge *Same speaking lengths*

Compares direct bridge coupling (a bridge with no cantilever) and offset bridge coupling (a cantilevered bridge). The speaking lengths , core diameters, over-all diameters and the back-scale lengths are the same.

Test #7

Modified Bass Bridge: *Same OAL/Short vs. Long Back-Scale/Cantilevered vs. Direct Bridge*

Test #7 compares two mono-chord strings when the bass bridge is modified to remove a cantilever. One string has a shorter speaking length and a longer back-scale length. The wrap diameter is changed to maintain approximately the same tension.

The speaking length is longer but the back-scale is very short on one string. On this string the partials decay much more quickly. The strike point is extremely crucial on note 88, and is increasingly less important the farther down the piano we go. There could be a strike point disparity at the transition. In this particular test, both strings are exactly the same length. The difference is that although the bottoms of the bridges are at the same position, the cantilevered bridge extends the speaking length but shortens the back-scale length. The further down the scale we go the more movement we need in the soundboard to get more power. We need physical motion. By ting the motion down with the clamping effect of the short back-scale, the bridge is not able to move as well. The longer string does provide more partials. On the cantilevered bridge there is more movement on the lower partials. The idea is to make it possible for the soundboard to move. There is more decay on the cantilevered bridge. The string with the shorter speaking length but longer back-0scale sustains more, which Del prefers.

Test #15:

Plain steel tensions: *Long strings, low tension vs. high tension IG wire*

Test #15 compares two plain steel unisons having the same speaking length and the back-scale lengths. They have different wire diameters and tensions. Both use the same type of wire: IG. What is the problem between the bass-tenor transition? There is a tension and inharmonicity change, but we are also at the end of the bridge. The string has to move the wood on both sides of the bridge to convert the energy into sound. At the end of the bridge there is no load to one side of the bridge, so the movement is a lot less than in the middle of the bridge. To compensate, some companies used a transition bridge, others went to wrapped bi-chords on the same bridge, and some did nothing.

The stiffer string sounds worse. It decays sooner, it sounds thuddier, and it does not ring as well, even though on paper it looks good. Size 20 string sounds noticeably better than size 22.

Test #16

IG vs. Paulello Wire *Long strings, low tension*

This test compares two plain steel unisons having the same speaking length and the same back-scale lengths. They have different wire diameters and tensions. One uses IG wire and the other uses Paullello Type 2 wire. The IG wire has more upper partial content. Paulello wire is much softer. The tone quality of the Paulello wire is more pure. This wire is the most extreme available. Paulello also makes a nickel-plated wire. This wire is an answer to a problem that doesn’t exist. Originally it might be that this wire was designed to make Stewart’s 108-note piano possible. The advantage of this wire is higher tensile strength. The speaking length is really long.

Low tension scales are 68-73 kgf (150-160 lbf).
High tension scales are 82-90 kgf (180-200lbf)

- Harder, more strident, punchier sound
- Reduced tonal dynamis, generally mus use more massive, less

Extremes:
Short scales, thick wires, higher inharmonicity.
Long scales with thin wires produce relatively more flexible stirngs, low inharminicity;
String scale formulae for string tension are readily available.
Inharmionicyt is directly related to diameter and indirectly relate to tension;

Developin ght e sctring scale is done in reverse order
Start from a single line for the strike line and start drawing from there.
The curve of the bridge is called the bridge sweep.
If ist is a fully logged scales, start with C88 down
Multiply by 50mm times some constant based on the 12th root of 2.
Walter pianos Del put a transition at 1756.
Most bass sections are hooked around and are not on a logarithmic progression.
The low tenor scale uses the hockey stick, which is what Steinway did. The origins of this go back to the harpsichord. To improve the power they went from iron to brass strings, which broke readily unless they made them a little shorter. Therefor they made the bass a little shorter to prevent breakage. Why we continue to do this today probably comes from Woolfendon who says to do whatever is appropriate. That’s the way it’s done.
The strings at the low end of the bridge where the hockey stick starts does change the tonal quality. When you play chromatically and carefully listen to the voice you can hear the transition; but when the piano is being played we don’t want to hear the transition.
Sometimes a hockey-stick doesn’t look like a hockey-stick hook. Follow the sweep and it will look almost straight; what they did was to go to large and larger wire.

By manipulating the wire sizes, this transition drops off. However there is usually a noticeable timbral change at the tenor break. Often the end of the tenor bridge ended on a rib.

Usually single wires usually go too far down the scale. Plate cross-over point and scale transitions need not be the same. Tri-chord wrapped unisons are never a good thing
Bi-chord wrapped string in tenor section should be placed on a separate transition bridge
Reasonably uniform unison tensions should be maintained across all plate and scale transition

String impedance (Z) is a function of the number of strings divided by tension. In general Z should be as uniform as possible. We try for consistency.

- There is no ideal number of bass strings; it just has to be buildable. The Length of scale determines transition point between plain steel and wrapped strings.
- An ideal range:
    - Physical room for low tenor strings – speaking plus back scale

- Use of transition bridge – number of unison on bass bride n=does not necessarily equal number of unisons using wrapped strings
- Balance stress on plate braces

What determines where you switch from bi-chord to mono cords is the diameter of wrap on the monochords. Once they get so big they start unravelling, it's time to switch.
Tension limits on core wire of high mono-chord
Generally there are more mono-chords in short scales, fewer in long scales
In short scales this may be B-15 or C-16
In long scales it may be D-6 to

There is no fixed rule for the number of unisons using bi-chords. We want a balance between tension limits and physical wire sizes. The transition between plain and wrapped strings varies with the overall length of the piano. String flare angles – physical placement of bass bridge, and string tension schedule (short & thick or long and thing) are the parameters.

Mixing plain and wrapped strings on the long bridge should not be done.
The object in smaller pianos is to get the strings as long as possible. Unfortunately conventional wisdom is once again wrong. Longer is not necessarily better. Remember the back-scale. In most pianos A1 speaking length is usually too long. "Long strings" is a sales feature that limits good bass tone production.

The back-scale is not the waste end. Within reason it should be as long as possible. The back-scale should be long enough to allow good bridge and soundboard mobility at the lowest anticipate fundamental frequency. Some resistance to bridge mobility is inevitable. Bridge mobility decreases exponentially with decreasing back-scale length.

With vertical hitch pins, keep the strings as close to the plate as possible without creating buzzing. Some pianos used vertical hitch pins to compensate for inconsistencies in plate construction. Keep the strings down on the hitch pins.

Hammer strike points are most important in the high treble. The point along the sting speaking length at which the centerline of the hammer strikes is what creates the purest tone. Typically the point at C88 is 1/12-1/16 of the speaking length of the string. Hammer strike points are not always where they appear to be. Strike points can be quite noticeable across scaling transitions.

Nowadays V-bars are cast wide and then milled to shape, so if they are off these days it's a design error. If it was off in the early 1900's it could be a cooling error. Modern milling machines are so accurate that they will all come out the same.

$Tc=NsxT/Lsp$

The strike-line and the scale-stick in theory should be a straight line, but in practice they are not, especially in historic pianos. No modern piano maker any more uses a scale stick, which was a 4-sided stick of wood. On one side would be the action centers. On another side would be the string fan angle. These two points would be pretty consistent. If the factory burned down but they had this one stick, the factory could resurrect the same scale.

In the 70's Wurlitzer decided to resurrect an old grand piano scale model. There were no models out there, but they found an old piano, so they used the original plate as a pattern. However, iron shrinks. Wurlitzer already has tight spaces. Since they wanted to make a high quality piano, they decided to use Renner parts, which are on the wide side. They ended up with a piano that had a plate too small, parts too big, and grand piano that didn't work.

In the bass, there is still impact, but the proportion to impact vs.sound is much less. The motion will die out at a rate of the stiffness of the soundboard and the mass of the string. The process of selecting a combination of string types, lengths and diameters for each note that will have