Measuring Damper Forces at the Piano Key, using a Well-Controlled Plunger and Simultaneous Reaction Force Measurement

There is a longstanding practice of measuring "static" values of Down Weight, Up Weight, and (indirectly) Balance Weight and Friction, by applying "gram weights" to the keys of the piano action. New methods and apparatus were disclosed in U.S. Patent 8,049,090, "Apparatus and Method for Actuating Keyboard Mechanisms and Evaluating..." [ref. 1], by Rick Voit, which eliminated the need for the old "gram weight" techniques, producing more scientific and repeatable results. These new methods involved reaction forces at the Application Point (AP) of the key being measured continuously during constant-speed downstrokes and upstrokes, resulting in continuous force data for the stroke. Sophisticated equipment is required for both the well-controlled movement and the continuous force acquisition. In addition, averages of these forces were described, being declared as "replacements" for the old parameters of Down Weight, Up Weight, Balance Weight and Friction Weight. Additional information was disclosed, regarding all of these continuous "static" forces, in the article "The Key Force One: Measuring Real and Continuous "Static" Forces at the Key", pp. 19-23 of The Piano Technicians Journal, November 2013 [ref. 2]. The current disclosure discusses nearly identical techniques as those, but extended to the case where the damper levers (i.e. the sustain pedal mechanisms) are *not* temporarily disengaged or removed from the backs of the individual notes.

The structure and means of providing the well-controlled plunger, and the continuous reaction force measurement at the AP, may be identical with those discussed in references 1 and 2. The main goals will include:

– for any given note, determine the added "down force" produced, due to the damper lever (or damper underlever) becoming engaged on a controlled downstroke,

– for any given note, determine the added "up force" produced by the engaged damper lever (or damper underlever), during that region of a controlled upstroke,

– for any given note, determine the *additional* friction created in the keystroke, by the engagement and movement of the damper lever,

– for any given note, determine the *additional* "balance force" created by an engaged damper lever

– for any given note, determine the point in the keystroke – relative to either the "at rest" key position or some "zero position/plane" – where the damper lever begins to engage the key mechanism on a downstroke, or disengage the key mechanism on an upstroke. This point represents that key mechanism's Damper Engagement Point (or damper start point), which is more specifically defined below.

The forces measured (and the forces indirectly calculated from those) are continuous in nature, and can be easily graphed as a function of plunger and/or key travel. The terms Down Force, Up Force, Balance Force, and Frictional Force were introduced in references 1 and 2, along with their average values across the pre-let-off stroke. In this article, those terms will be re-used, and new terms of Total Down Force, Total Up Force, Total Balance Force and Total Frictional Force are added. These four terms apply to that part of the stroke where the damper lever is engaged by the key mechanism. Each "total" force, at any given point, is the sum of the non-damper force (e.g. Down Force, Up Force, etc.) and the corresponding "damper" force. Thus, four additional terms (Damper Down Force, Damper Up Force, Damper Balance Force, and Damper Frictional Force) are also introduced. One has the following equations then:

Total Down Force = Down Force + Damper Down Force (DDF)

Total Up Force = Up Force + Damper Up Force (DUF)

Total Balance Force = Balance Force + Damper Balance Force (DBF)

Total Frictional Force = Frictional Force + Damper Frictional Force (DFF)

The DDF is the additional contribution to the usual Down Force, produced by the engaged damper lever, at any given point in the stroke. The DUF is the additional contribution to the usual Up Force, produced by the engaged damper lever, etc.

As with their non-damper counterparts, these "total" and "damper" forces are continuous, but are only valid for that portion of the stroke where the damper is being engaged. Each of these damper (and total) forces may also be averaged across as much of the "damper region" as possible. A similar set of four equations thus also applies, with "average" placed in front of each term. As long as the damper engagement point occurs sufficiently above (i.e. *before* on a downstroke) the "let-off start point", the measured total force between those points is sufficient for obtaining a good average total force value. If absolutely necessary, the let-off buttons (and drop screws) can be raised beforehand, providing a much larger "damper to LOS (let-off start)" region for analysis and averaging. This applies to all four of the "total" and "damper" forces mentioned above (down, up, balance and frictional). The region of the stroke between the "damper engagement point" and the "let-off start point" will be referred to herein as the Damper to Let-Off (DLO) region.

Another option for maximizing the region where the Damper Down Force can be graphed, analyzed, and averaged is to utilize the results of a separate downstroke run, where the damper is fully disengaged from the key. Assuming that the "damper disengaged" downstroke is run at essentially the same speed as the damper downstroke, the reaction forces from the former can be subtracted from the reaction forces of the latter, leaving a graph of pure damper down force, versus key or plunger travel, for the entire downstroke! Essentially, this just invokes the first of the four equations listed just above: DDF = Total Down Force – Down Force. The Down Force term in this case *does* include entry into the "let-off region" of the stroke. Unfortunately, this technique doesn't typically work so well on the upstroke, since the tripping of the jack has such an upsetting effect on forces during the upstroke. That is why the methods for measuring Up Force, in references 1 and 2, include the caveat that the upstroke not be preceded by a tripping of the jack.

The point in space and/or time where the damper lever is first contacted by the pertinent part of the key mechanism itself (e.g., could be the back edge of the key, or a "spoon", depending on the type and design of the piano) during a downstroke, is referred to herein as the Damper Engagement Point (DEP) of a piano key mechanism. The DEP may also refer herein to the point in the resulting force data that corresponds to this actual event. The DEP also corresponds to the point in the upstroke where the pertinent part of the key mechanism ends its contact with the damper lever.

Total Down Force and Damper Down Force (Note 37)

Some runs were made on note A3 (37) of an actual grand piano action, with the action in its normal position within the piano. Runs were made both with and without the dampers engaged. To fully disengage the dampers, the pedal mechanism was simply chocked, so that none of the damper levers could be contacted by the individual key mechanisms. Of course, making the measurements on a workbench would have the same effect (no dampers involved). The well-controlled, force-sensing plunger was driven at constant speed, in both the down and up directions, as described in references 1 and 2. As described above, the upstroke forces are for an upstroke not preceded by tripping of the jack. In measuring the upstroke forces, the preceding downstroke went *only* to the approximate let-off start point, paused briefly, then began a constant-speed upstroke. Figure 1 is the resulting Force vs. Key Travel for a constant-speed downstroke on key 37. The motion profile followed was very similar to the downstroke portion of Figure 2, with the plunger moving down (after the short parabolic region) 1 mm every 86.4 ms. Positive y on the graph corresponds to the downward direction on the keyboard, and y = 0 corresponds to the plunger just barely touching the at-rest key. Thus, key travel equals plunger travel. The run of Figure 1 was with the damper fully *disengaged*. In order to see some or all of the let-off event forces, the downstroke should go fairly close to the "bottom out" point of the keystroke. If a previous "bottom out (key dip) determination" run is made, similar to the techniques described in references 1 and 2, then this downstroke run can go right down to the predetermined "key dip" point. That was indeed the case in the run producing the forces shown in Figure 1. The graph is shown versus time, but several distance values are also shown on the x-axis, in the constant-speed region. Note how the L-O Start Point is at y = 6.9 mm. The Average Down Force, calculated between approximately y=3 and y=6.85 mm, was calculated from this data to be 52.4 grams-force.

The pedal was then un-chocked, so that the damper lever engaged at its normal "as is" location. A slightly slower downstroke was employed than that of Figure 1, with corresponding continuous reaction force measurement, resulting in the force data of Figure 3. The same note (37) is the subject. The plunger moved 1 mm every 75 ms, once the constant-speed region was reached (approx. 1.1 mm into stroke). Again, the forces are graphed versus time, but with various distance values clearly shown as well. Note that the L-O Start Point still corresponds to y = 6.9 mm. Also note that the Damper Engagement Point (DEP) was found to occur at y=1.63 mm. Note also the "ramping up" that occurs in the force, as soon as the damper lever begins to be engaged by the key. It is therefore wise to not begin the force-averaging until this "ramp up" region is concluded. In fact, the collision creates a disturbance in the force data, extending beyond the "ramp up" region. In this example, the "total down force" averaging did not begin until the point corresponding to y = 3 mm. The average Total Down Force between y = 3 mm and y = 6.85 (just shy of LO start pt) was calculated from the data to be 75 grams-force. By subtracting the Average Down Force (52.4 from the data of Figure 1) from the average Total Down Force, one obtains the Average Damper Down Force. In the case of note 37, the Average Damper Down Force is 75 minus 52.4, or 22.6 grams-force. In those cases where the Down Force changes significantly across the stroke, it is more accurate to use an Average Down Force obtained over the same stroke region as was used for the average Total Down Force calculation.

In the DLO region, once the damper-induced forces have stabilized (after y = 3 in this example), one can subtract the continuous Down Force from the continuous Total Down Force, to obtain a graph of continuous Damper Down Force versus key or plunger distance. This is already indicated by the above equations. The resulting force graph would be zero until the DEP is reached, with a sharp increase just after that point, eventually leveling off to a more stable level.

A Word about Finding the DEP

The means in which the controlling program or data processing spreadsheet determines the DEP is very similar to how the Let-Off Point is determined. The latter was described briefly in Rick Voit's article entitled "Measuring Letoff Events and Finding the Key's Stroke Limits with the Key Force One", in the April 2014 edition of the Piano Technicians Journal, pp. 24-29 (reference 3). In essence, an algorithm looks for a sharp and overwhelmingly upward trend in the reaction force data from a downstroke. In general, a run will have already been done with the damper disengaged, so that the Let-Off Start Point is already known. That previous run will have also helped determine a more optimal downstroke speed as well, helping to minimize oscillations. The algorithm thus knows to not be fooled by the force bump due solely to the let-off event. Rather, it looks for the actual Damper Engagement Point, which typically occurs before the Let-Off Start Point, on a downstroke. Alternatively, one can determine the DEP visually, by simply looking at the force graphs themselves.

Total Up Force and Damper Up Force (Note 37)

The well-controlled plunger also performed constant-speed upstrokes similar to the one in the motion profile of Figure 2, while reaction forces were continuously measured between plunger and keytop. The resulting forces – graphed versus plunger/key displacement – are shown in Figures 4, 5 and 6. Figures 4 and 5 are for the case where the damper was *not* disengaged. Figure 4 shows the raw "up" and "down" force data, over a large extent of the keystroke. The upper tier of points (green) represents the downstroke forces. The lower tier (red) represents the upstroke forces. Figure 5 shows that data only over the "stable" region, between y = 3 and the Let-Off Start Point. In Figure 5, the Total Balance Force and Total Frictional Force lines were also added, based directly on the best-fit lines of both Total Down Force and Total Up Force. Figure 6 shows the best-fit results when the damper was fully disengaged from the key by chocking the pedal mechanism. Figure 6 thus shows the pure Up Forces, which were detailed in references 1 and 2. For convenience, the other three "static" forces (in best-fit line format) are also shown. In Figure 5 (i.e. damper included), the Average Total Up Force between the y-values of 3 mm and 6.85 mm was calculated to be about 41 grams-force. From Figure 6 (the "no damper" run), the Average Up Force was calculated as 22.5 grams-force. The difference between these two is the Average Damper Up Force, and equals 18.5 grams-force. Similar to what was stated above in the damper down force section, one can go ahead and graph continuous Damper Up Force, versus distance. This is done by subtracting the continuous Up Force from the continuous Total Up Force, for all displacements/points in the DLO region. Furthermore, with the average Damper Down Force and average Damper Up Force, one can get the average Damper Balance Force by simply taking their average. Finally, the average Damper Frictional Force is calculated as half the difference between the average DDF and the average DUF. With the average DDF and average DUF being 22.6 and 18.5 grams-force, respectively, the average DBF is 20.6 grams-force. This means that if the damper friction were totally and magically absent, the damper lever would add 20.6 grams-force to the normal Balance Force, at the AP. The average DFF is similarly found to be 2.0 grams-force. Thus, the damper mechanism, once it's engaged, only adds about 2 grams-force to the usual non-damper frictional force, as felt at the AP.

The Four Continuous Damper Forces

Just as the Damper Down Forces and Damper Up Forces are determined by subtracting the respective non-damper forces from the "total" forces, the same can be done to determine (and plot) Damper Balance Force and Damper Frictional Force. An alternative method (employed here) is to first plot the "down" and "up" damper forces in this way, then create the "balance" and "frictional" force lines from those. As with non-damper Balance Forces, the Damper Balance Force line simply bisects the Damper Down Force and Damper Up Force lines. At any key travel, the Damper Frictional Force magnitude is simply the vertical distance on the graph between the

Damper Balance Force and the Damper Down Force. For the Note 37 example, the four graphs of continuous "damper force" are plotted together in Figure 7.

The main reason for determining the DEP is so that shim or spoon changes can subsequently be made to those notes deemed to be out of specification, with regards to the damper start point. In the current example (Note 37), rather than shim or deform the spoon, the author simply slid the damper wire downwardly, relative to the damper wire block, and retightened the screw. This resulted in the damper lever being raised, relative to the back of the key, and the DEP being delayed. As far as resulting reaction forces are concerned, the end result is identical to delaying the DEP by de-shimming the back of key, or by deforming the spoon, etc. In general, the DEP should correspond to the hammer head being approximately halfway to the strings. One can temporarily "block off" the upper half of the hammer blow space, and then depress the key until the hammer hits the block. The resulting key depression is the corresponding amount of key travel needed to move the hammer halfway to the strings. As with all the other routines described herein, this measurement can be easily made with the Key Force 1 machine from Full-Measure Response, Inc. If one knows the traditional "action ratio", it can also be used (along with the hammer blow distance) to quickly determine how much key travel should occur before the DEP is reached.

After the damper lever of note 37 was moved upwardly by approximately 3.5 mm, the downstroke and upstroke runs were repeated. The resulting forces from a full downstroke – for this "modified damper" case - are shown in Figure 8. Since the balance rail is reasonably equidistant to both the AP of the key and the back felt of the key, one would expect a 3.5 mm raising of the damper lever to delay the DEP by approximately 3.5 mm. Figure 7 shows that this is certainly the case. The Damper Engagement Point is obviously approximately 5 mm, while it was only 1.63 mm before the modification was made. This shows that, with a machine like the Key Force 1, one can determine the "as is" DEP's for all notes across the piano, then use them to determine required shimming (or spoon deformation) to perform on any notes badly "out of spec". A spreadsheet is created that incorporates the balance rail-to-damper felt and the balance rail-to-AP distances. These would be measured for both a white key and a black key, and entered into the spreadsheet. Looking at the values of all DEP's across the piano, and comparing to the desired DEP line, one first obtains the "at the AP" differentials. These simply tell you how far the

AP is from where it should be, when the damper is engaged. Simple spreadsheet calculations, using the known distances mentioned above, then convert this "at the AP" differential into a shimming differential. That is, if there is less vertical movement at the key-to-damper contact point than there is at the AP, the amount of (de)shimming required will be less than the "at the AP" differential, and vice-versa. This same philosopy can be employed for grand pianos that have individual regulating screws for each damper lever.

For other designs, including pianos that employ spoons to move the damper away from the strings (as with most upright pianos), some up-front calibrating work on a couple sample keys can often be done. In the case of spoons, the goal here is to associate some known amount of deflection, or angular deflection, of a spoon with a differential *at the AP* of the piano key. For example, one would want to know that 5 degrees clockwise rotation of the spoon delays the DEP (which is defined at the AP!) by 1 mm, or 4 degrees CCW rotation of the spoon advances the DEP by 1.1 mm, etc. This type of constant, once determined for a small sampling of keys, is then used in the spreadsheet to yield the required spoon deformation for each out-of-spec note. All one needs is the "at the AP" differentials discussed previously.

The "force" terminology employed herein is consistent with other work by the present author. Other terms that could be utilized within the piano industry for these parameters might be: Damper Down Weight, Damper Up Weight, Damper Balance Weight, and Damper Frictional Weight.

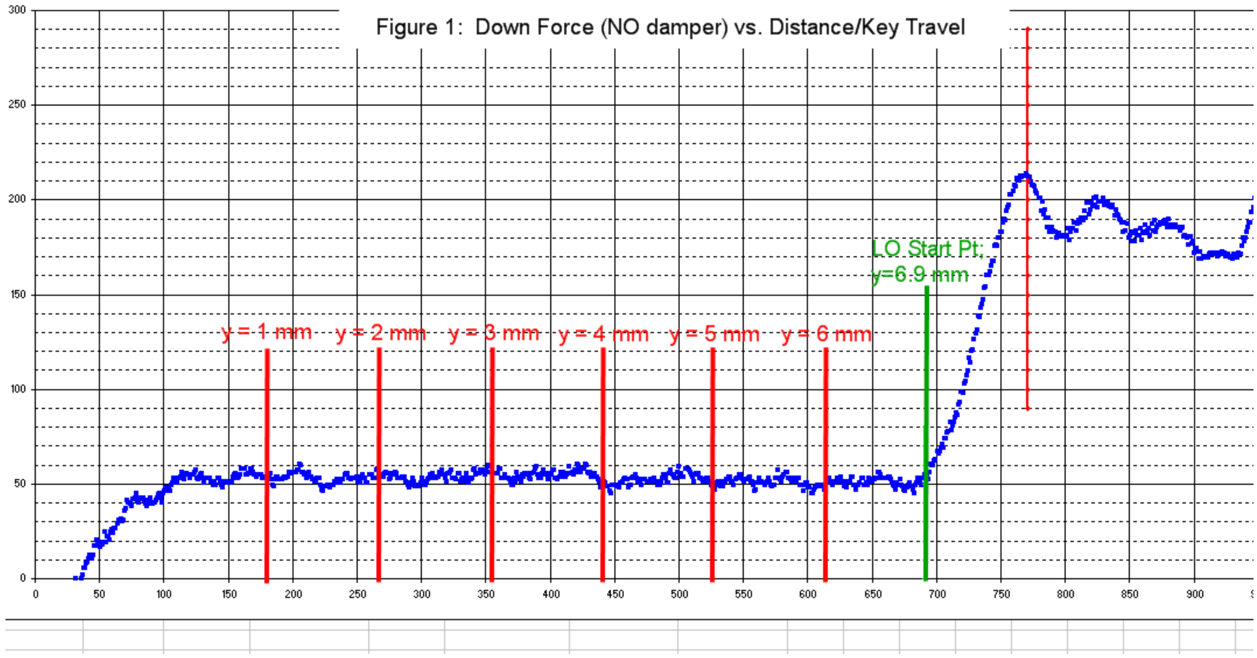

Figure 1: Down Force (NO damper) vs. Distance/Key Travel

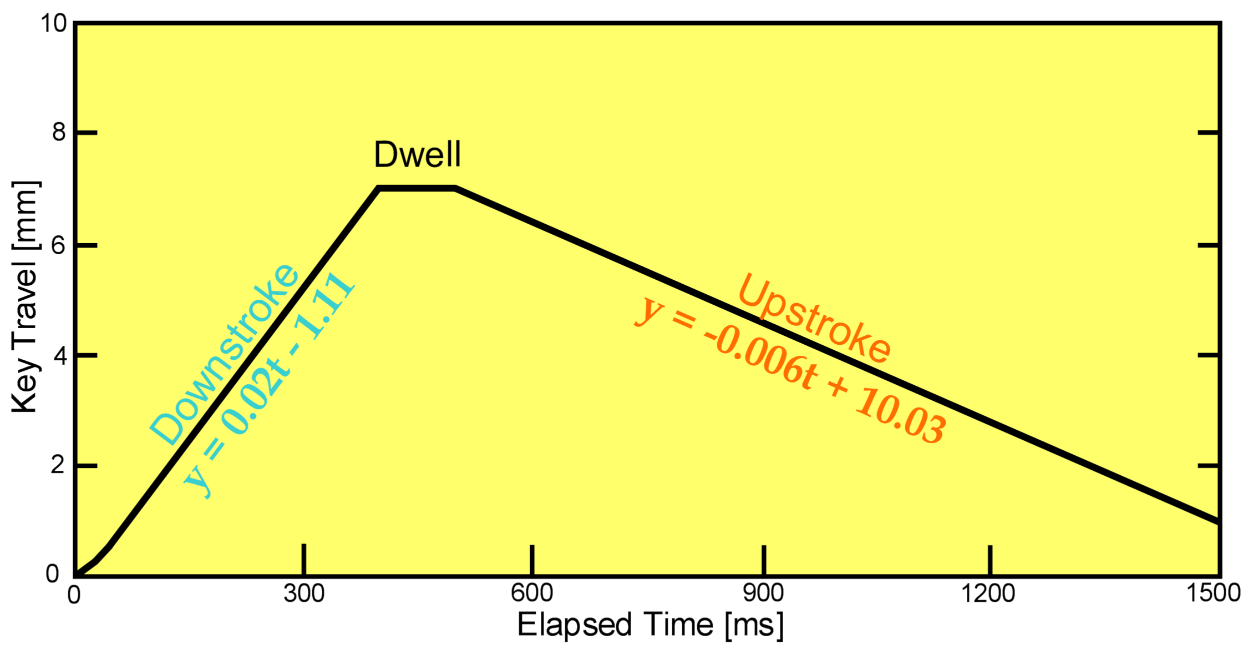

Figure 2

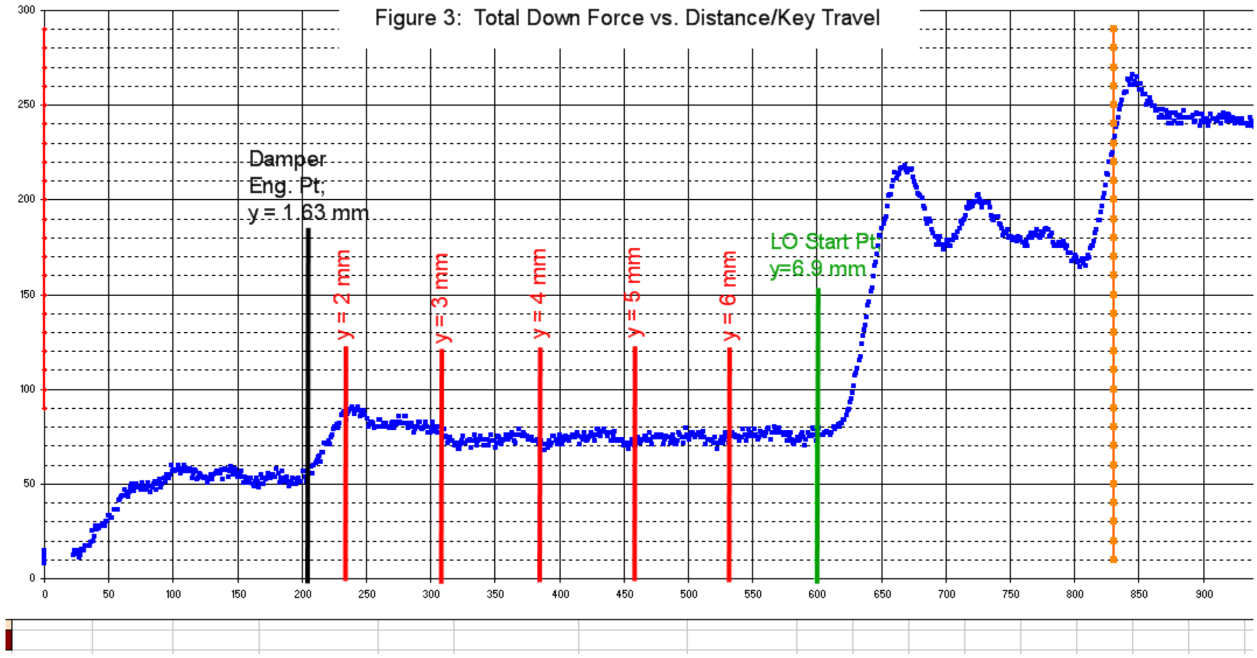
Figure 3: Total Down Force vs. Distance/Key Travel
Damper
Eng. Pt;
y = 1.63 mm
y = 2 mm
y = 3 mm
y = 4 mm
y = 5 mm
y = 6 mm
LO Start Pt;
y=6.9 mm
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900

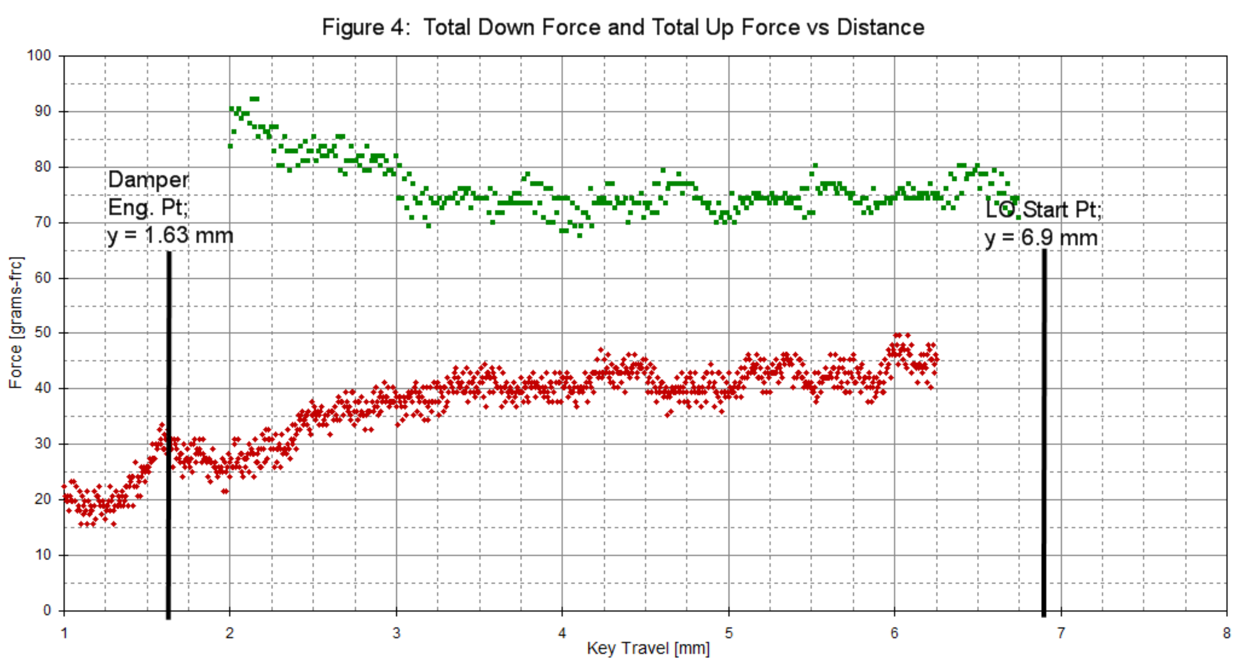
Figure 4: Total Down Force and Total Up Force vs Distance
Damper
Eng. Pt;
y = 1.63 mm
LO Start Pt;
y = 6.9 mm
Force [grams-frc]
Key Travel [mm]
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8

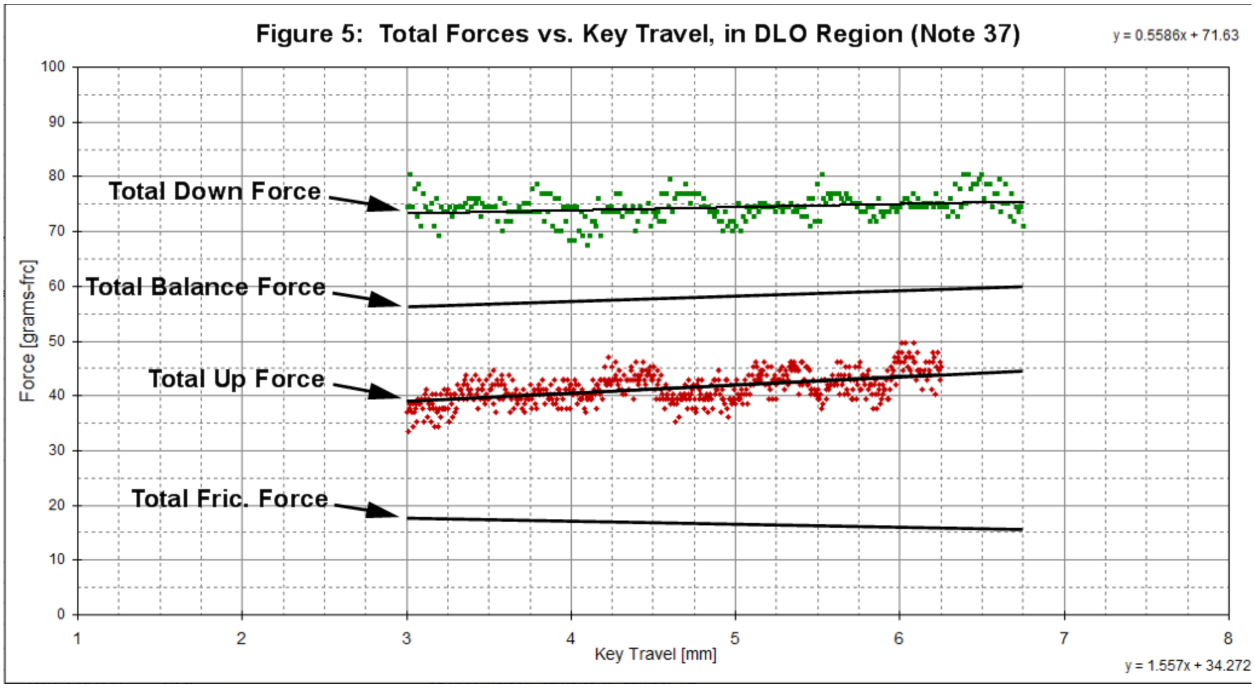

Figure 5: Total Forces vs. Key Travel, in DLO Region (Note 37)

Figure 6: Non-damper “static” Forces vs Key Travel (Note 37)

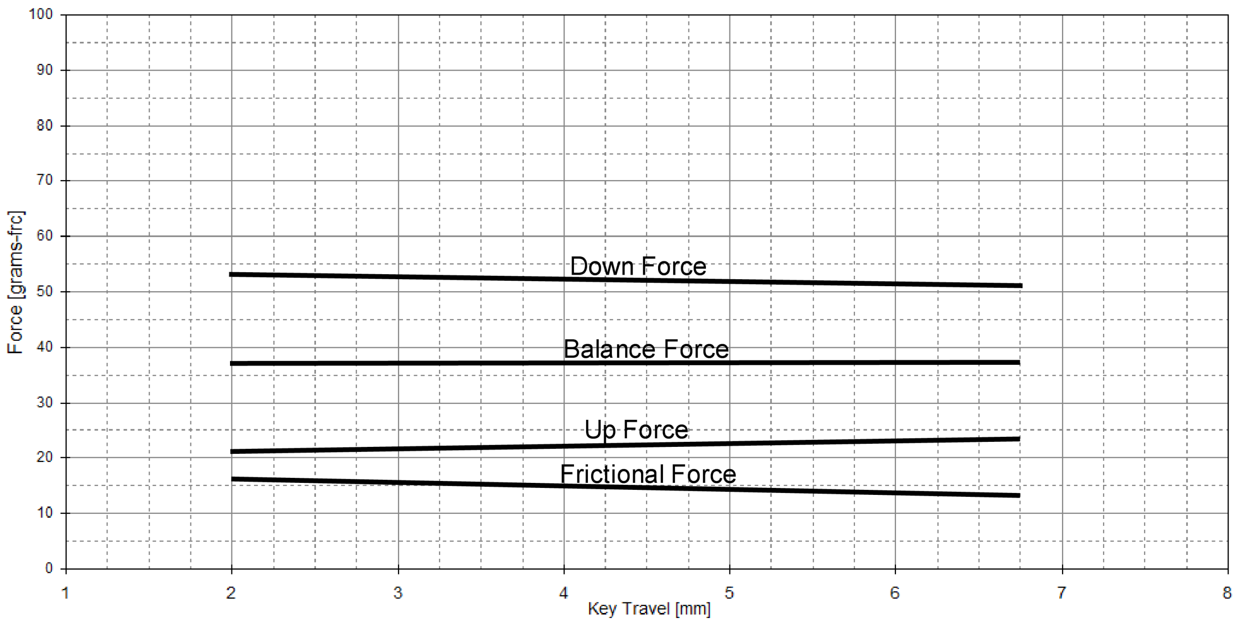

Figure 7: Damper Forces vs Key Travel (Note 37)

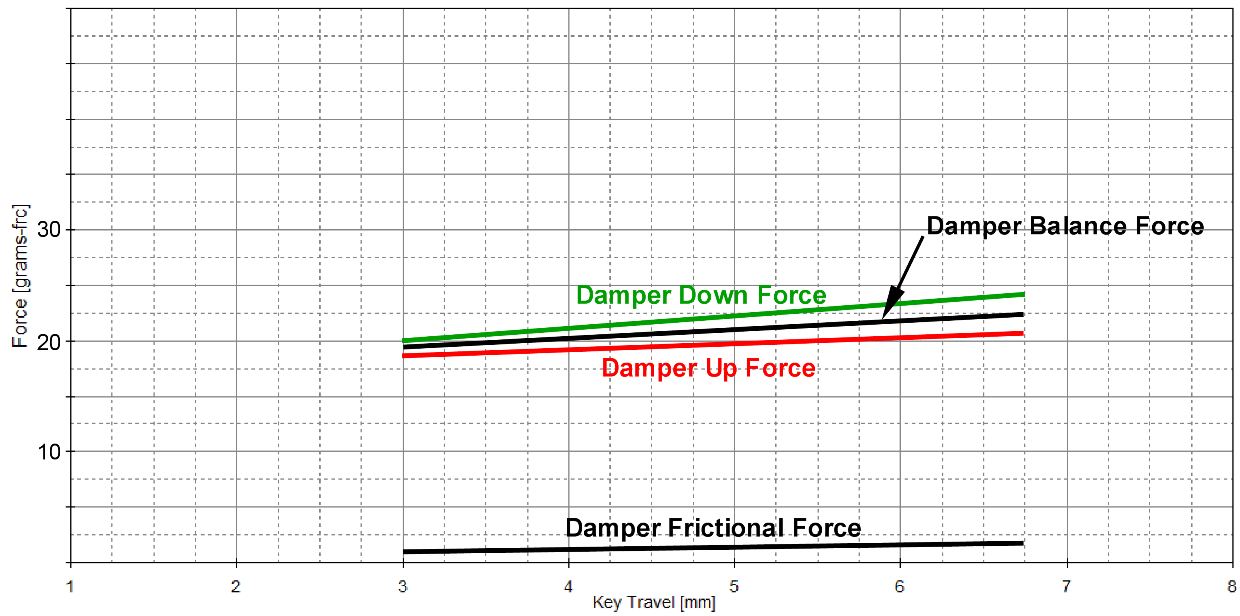

Figure 8: Downstroke Forces on the Modified Note 37