EQUIVALENCY

In the study of Heart Force, what is actually being measured is the direct result of the heart movement in terms of acceleration propagating outwards from the heart structure. Because the heart's actual mass is unknown without surgery; there is an issue with a non-invasive science. The study of Force and acceleration requires mass. Or if provided Mass, and one of the other two (force or acceleration) the third can be computed. This is a basic fundamental of the science that:

$$\boldsymbol{F = ma} \quad \text{or} \quad \boldsymbol{m = \frac{F}{a}} \quad \text{or} \quad \boldsymbol{a = \frac{F}{m}}$$

When we are provided only the acceleration, it is strongly desired that we get some idea of force, because we really want to know about the mass. There are two places in the heart-beat cycle where there is very little doubt that there is indeed an impact Force. In an example the heart-cycle of acceleration the two intervals where force is clearly recognized are shown here in Figure 1 in Red.

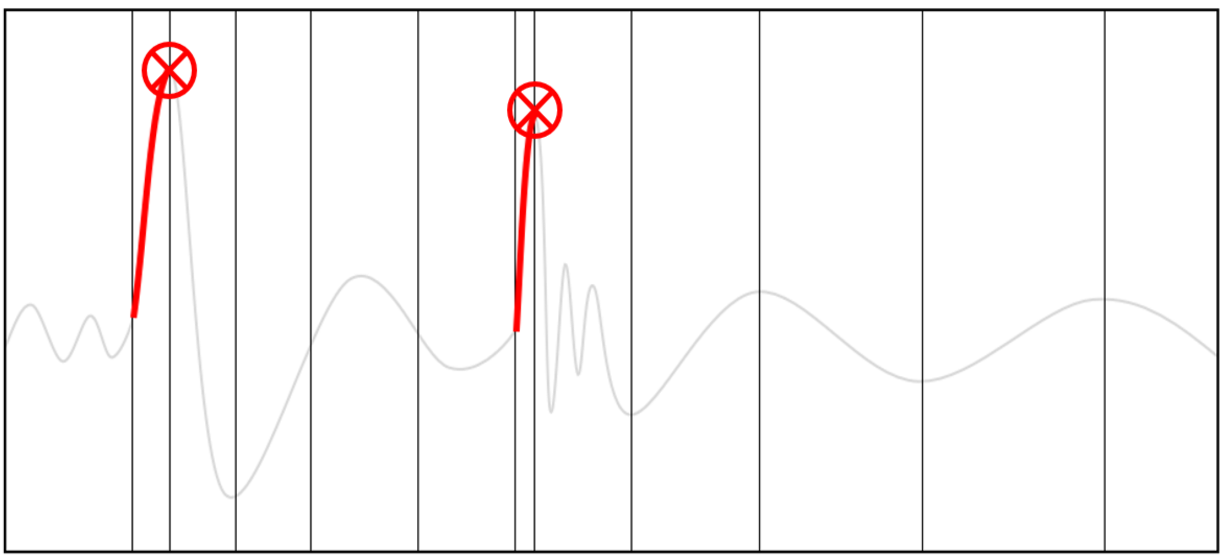


Figure 1

The characteristics of a sudden change in the rate of acceleration over time to that of a sharp positive rise up to a point where it crests, and reverses is unmistakable. This type of wave form has been seen and studied countless times in the practice of Modal Analysis with concentration on the peak at the top of the rise. Impact hammers, which are instrumented hammers calibrated in terms of lbs./Force (or newtons) are consistently used to provide such an impact for the study of structural characteristics.

The process for extracting structural characteristics in the practice of Modal Analysis is done in the frequency domain. There is a desire to have an optimum impact. An impact force that is a solitary point (red X's Figure 1) in the time domain used to represent a very wide frequency span of excitation force. This data of force and the resultant acceleration, are all computed with a Fast Fourier Transform signal analyzer with two or more channels of data where one channel provides the force as the solitary point in time and the other channels provide the resultant acceleration.

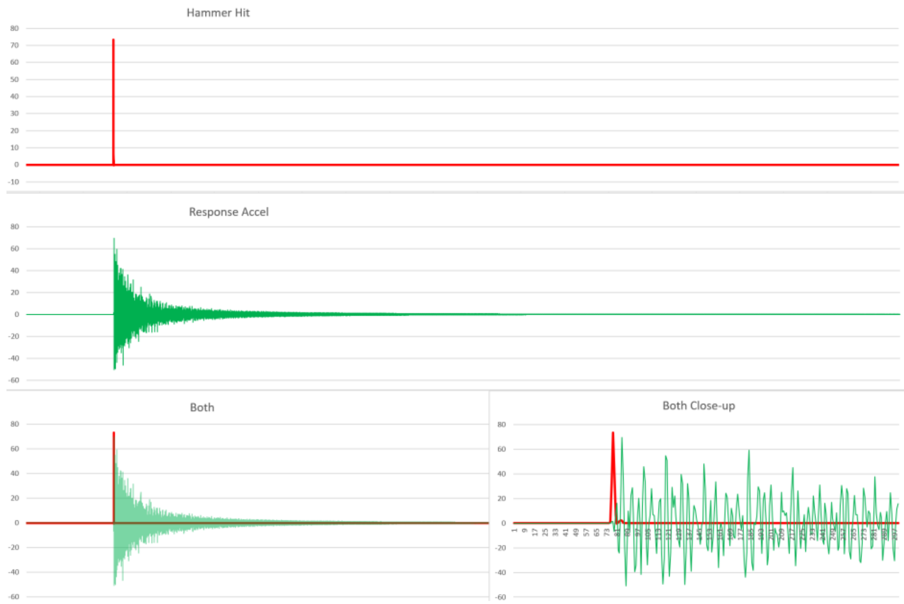


Figure 2

Figure 2 shows such a “hammer hit” (Red) and the resultant acceleration (Green) as measured by the force gauge of the hammer itself and the accelerometer on the object being hit. In the lower right corner of Figure 2 and enlarged in Figure 3 is the actual moment that the calibrated hammer impacts the structure upon which the accelerometer is mounted.

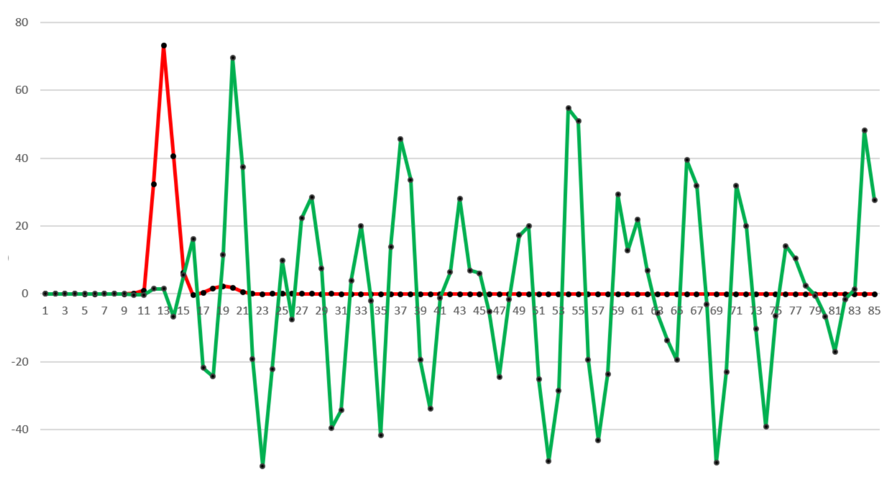


Figure 3

The closeup of Figure 3 shows the signal analyzer’s point by point (black dots) capture of both the hammer’s force gauge (red) and the accelerometer (green) mounted on the structure. It can plainly be seen that the hammer did not hit the accelerometer itself, as there is a slight delay between the sharp positive rise of the force to the black dot at the top, and when the accelerometer starts to portray the acceleration due to the impact force. Notice that the peak force is manifested in two points, the first being the force of the hammer contact, and the second being at the peak acceleration of that force contact. Which is the moment when the accelerometer registers that contact was made, and the force was transferred.

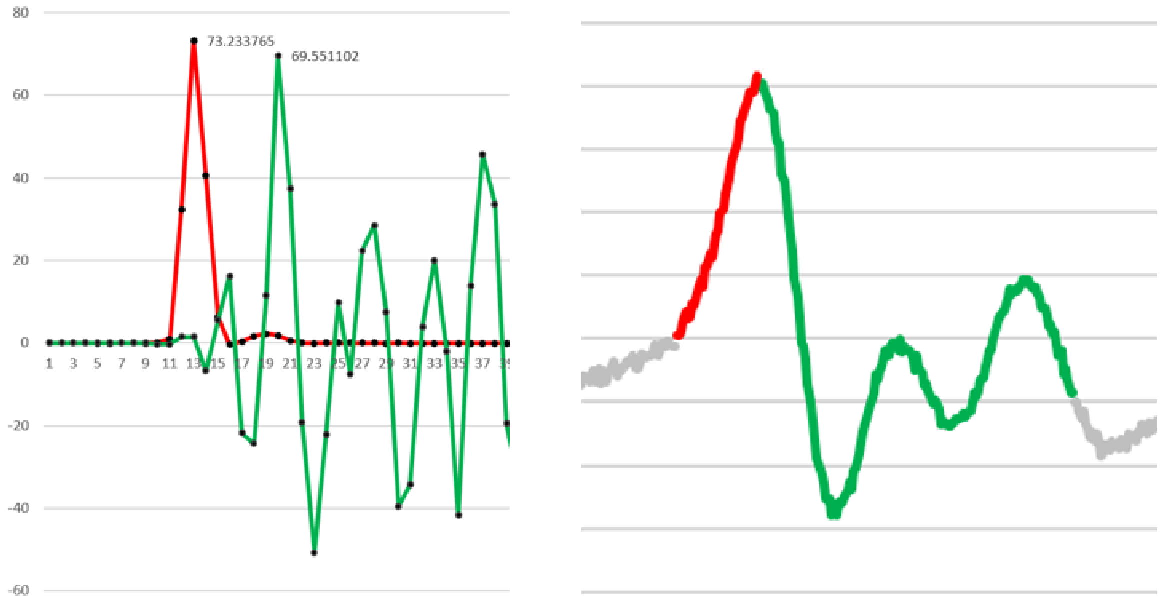


Figure 4

In Figure 4 the two sets of the structural impact data are shown; the known impact force (73.233765) on the left and the highest peak of the resultant acceleration point created by the impact (69.551102) overlaid. On the right shown in comparison is the heart force acceleration data. The clearly recognized wave forms of red (force) and green (response) of the heart force acceleration data can be seen in the single data trace; which is presented in units of acceleration. The only difference in appearance between the left and the right of Figure 4 is "coincidence".

It is this observation of the two science's data that brings to light the concept of EQUIVALENCY. It is very well acknowledged that the data presented in Figures 2, 3 and on the left of Figure 4 is very much different from that shown in Figure 1 and on the right of Figure 4. As there is an obvious separation between the red and the green of force and acceleration in the two examples. It is clearly acknowledged that there is indeed a structure that can be defined in terms of mass in between the hammer impact and its response on the structure. The time delay between the force and the impact represents that structure. Whereas there is no time delay with the single accelerometer. The only factual comparison between the two is strictly waveform comparison. This visual comparison is based on the similarity of the red and green portions of the two waveforms.

The concept of EQUIVALENCY is the idea that; what if a close approximation of the practice of Modal Analysis could be applied to a measurement similar to that of the single sensor's measurement of heart-force. The difference currently being that the heart-force is performed with a single sensor measuring the impact of the propagated force waves coming to that common sensor. It is acknowledged that the actual force created by the actual forcing function is removed by distance and mass. However, when the effect of that force's propagated wave form arrives at the sensor, it is not a strict response, it is indeed a propagated force. The response takes place following the impact of the force, which in this thinking is the propagated wave front. Therefore, we come back to Figure 1 and the two sharp rises in acceleration, for more examination in Figure 5.

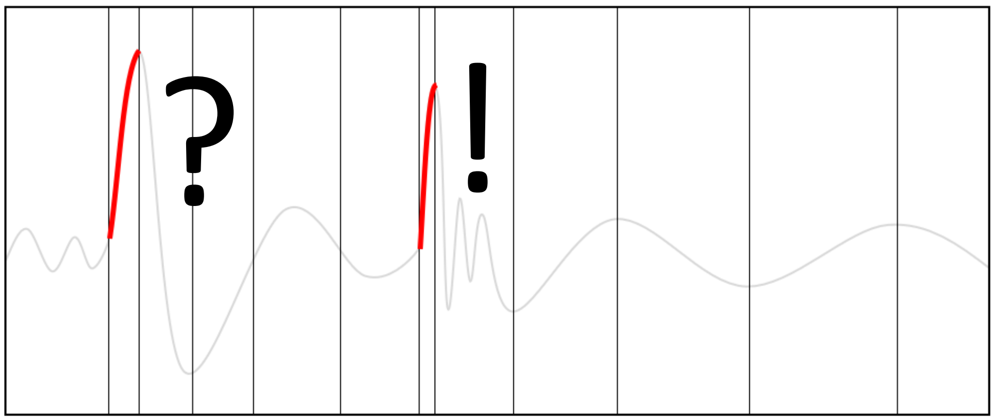


Figure 5

In the study of the waveform that illustrates the twelve heart-force intervals the two primary representations of force are clearly recognized. These two representations are clearly co-incident with that of the acoustic sounds heard with a stethoscope (a sign of force) and that of the ECG generated signals of heart valve closure and openings and the associated contraction and relaxation (also confirmed forces). But which of the two are the best representations for the concept of equivalency?

The systolic surge on the left is not a good choice as even though it is typically the sharper rise and higher peak amplitude, it is not followed by an easily recognizable response. Whereas the Diastolic Surge is almost always followed by a recognizable oscillating response of two or three cycles. Observational assumptions can be made of the Hammer hit compared to the Diastolic Surge in a four-part process shown in Figure 6, which is repeated un-numbered on the following page to describe steps A, B, C & D. The Hammer hit is shown un-marked up at the top of Figure 6, whereas it's components to be observed are labeled below it in Figure 6; A, B, C &D.

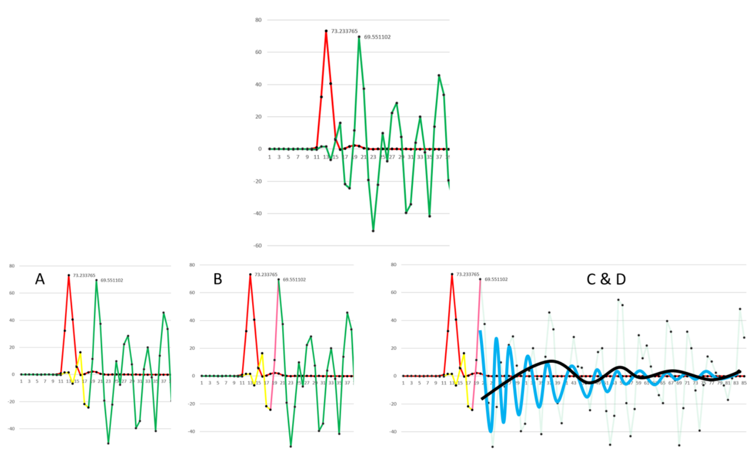
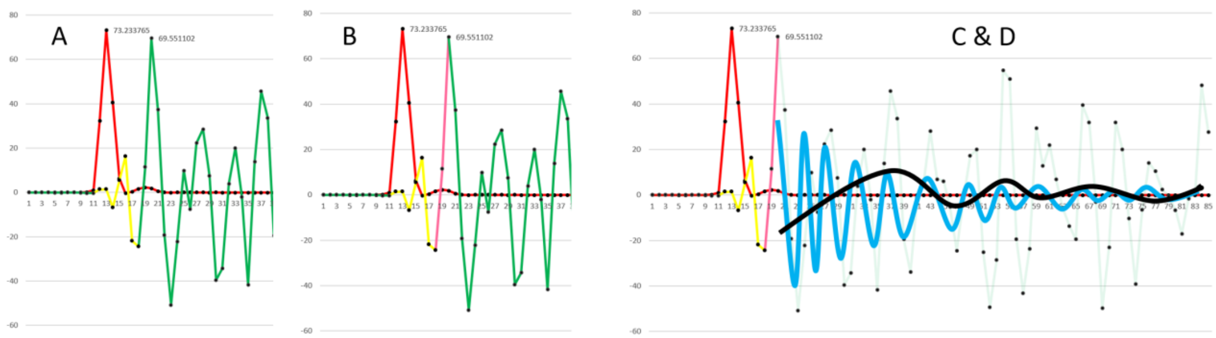


Figure 6



Step A, is the first observation, which is the delay in time between the hammer making contact with the structure, and the fact that not all of the impact energy has been transferred to the structure at that point. This time difference is shown in Yellow.

Step B, is the second observation, where there is a sharp rise in the force from a point below zero acceleration to a very high positive acceleration; in this case 69.551102 millivolts. This sharp rise is shown in pink. It represents the major transfer of energy from the hammer to the structure. That sharp rise ends with the 69.551102 millivolt representation. That specific moment in time is the moment of EQUIVALENCY.

With the time delay of Step A, and the Sharp Rise shown in Step B, that terminates when there is no more hammer energy being transferred. Both Steps C and D can take place and directly compared to the Diastolic Surge Response, for the purpose of validating the response.

Step C is the third observation. One should look for a low frequency recovery of the structure's acceleration in terms of the overall impact force. The structure being hit should move and then slowly return to zero after the impact force has been dissipated. In this hammer hit the thick black line shows this slow return to a biased zero acceleration level.

Step D is the fourth and final observation. Also in the response data from the hammer hit should be a primary structural resonance (oscillation) that damps out over time. And again the hammer hit has a clear representation of that fundamental 1st order of oscillation shown with a thick blue line, where both the black and blue lines are easily seen in what was the green line of the response interval.

Moving the observation to the Diastolic surge, one can eliminate the data in Step A and B as they deal with the time difference of the full transfer of force to the structure, as in the Diastolic

Surge these two happen at precisely the same instant. All the energy that was going to be transferred did so.

The combined energy of the two fundamental responses Steps C &D (structure initial movement due to impact and the structural resonance) should look virtually identical. IF SO, the Diastolic Surge and Response are directly equivalent to the well-known forces of a hammer's impact.

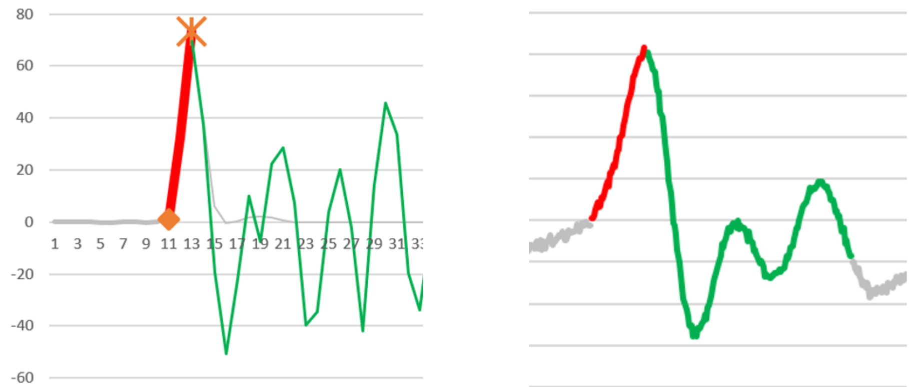
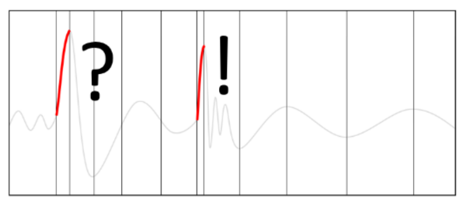


Figure 7

Figure 7 shows the slightly modified hammer impact (Step A and B are eliminated) and the response (again in red and green) on the left are compared to the Diastolic Surge on the right. The two different sensor's data now appear to be very close to that of the single sensor presenting the heart-force, but alas that data is presented in G's of acceleration. Again, the concept of equivalency.



With the observations of Figure 6 made, Figure 5 is again examined. The question over using the Systolic (left of figure 5, marked with a "?") or the Diastolic (right of Figure 5 marked with a "!") is made. Because there is no reliable sign of a true impact force response in the Systolic peak when compared to the Diastolic; the systolic peak is not used as true "equivalency" cannot be determined. The observations of steps C and D are not possible on a reliable basis. Whereas the two primary manifestations of true response of the structure are indeed present on a reliable basis in the Diastolic Response. It is hoped that for the analysis of all the forces that once the structure's figure of merit for equivalency is determined using the closest representation of an actual impact that, that figure of merit can be used for that particular set of data.

With the proper impact response selected of the two original; attention is now shifted to the "point" of impact. That single solitary sampled point where the moment of maximum force transfer is made. The astute observer of Figures 4 and 7 will bring yet another challenge to the concept of equivalency. At the outset, it is to be acknowledged that equivalency is just that; it's equivalent, not identical. There are differences.

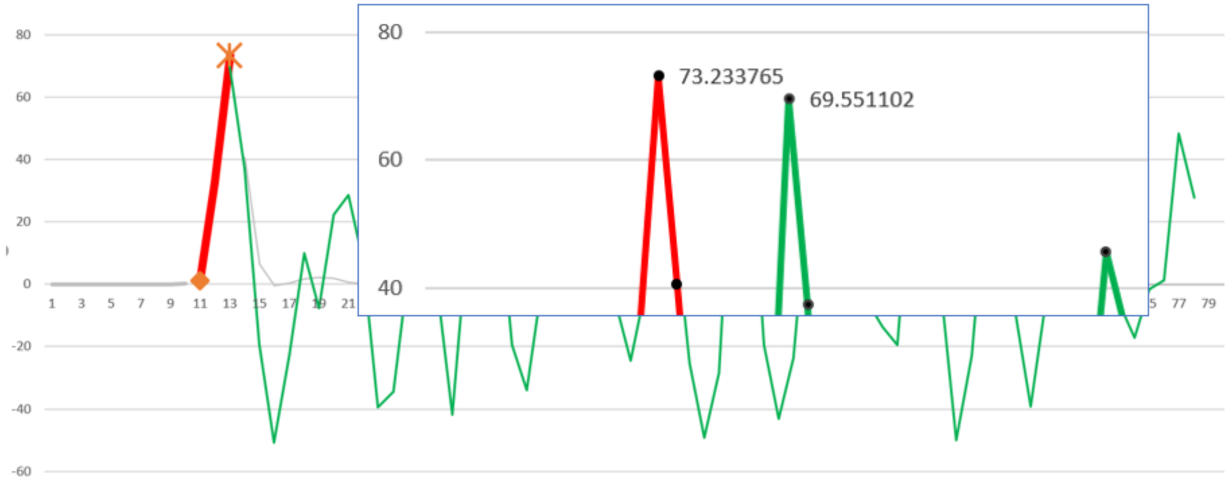


Figure 8

Figure 8 brings into focus the observations of the astute. There is a difference between the highest peak of the impact and that of the resultant peak acceleration of the response. The numbers shown in Figure 8 are expressed as millivolts per their respective units. The Red is 73.233765 millivolts where 100 millivolts = one-pound force and the 69.551102 is millivolts where 100 millivolt = one G of acceleration. It is assumed at the beginning that there would be a difference. It is also understood that the differences would have two factors. The first factor is strictly the calibration of the sensors, the second is that there is some loss due to the structure. Both of these causes of difference, in the concept of equivalency are considered tolerable.

In the first difference, the force in this example is approximately 73% of a pound of force, and the peak response (again not all of it) is approximately 69% of a force of Gravity (1G), while again different units of measurement the sensitivities of the two sensors presented with millivolt values are within 4% of each other. This difference is more than acceptable.

The second difference, as stated before, is that the structure itself creates a “loss”. This was proven during the “fitting” of actual data (Reference “Prony Method applied to Diastolic Response”). Shown in Figure 9 are the “fits” to an example interval of Diastolic Response. At the extreme left from the very first sample point to sample point 10 it can be seen that the components (black and green) of the resonance are at lower levels than that of the fit of the original data (blue). Keeping in mind that the amplitude level (vertical scale) is in micro-volts and not the milli-volts shown of the hammer hit, so the actual levels of acceleration are indeed very small. Therefore, the “loss” is indeed a small proportionate loss. The differences are indeed lower than the original impact force, but when broken down into their contributing components (Structure movement, Resonance, and others) most of the original force is accounted for.

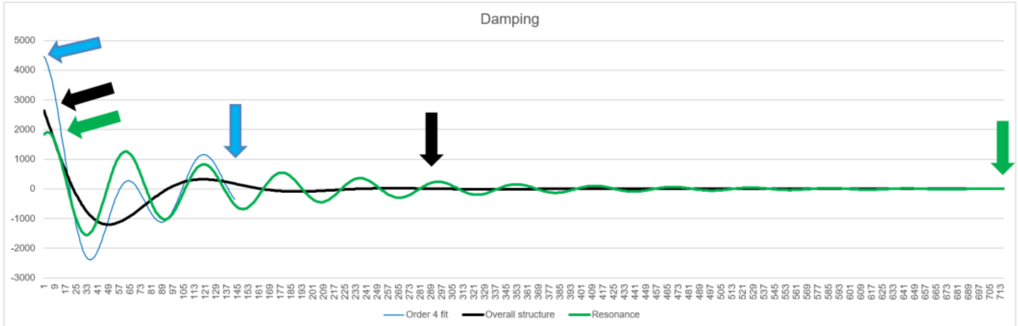


Figure 9

Never-the-less the point of loss due to the material of the structure is evident. Although in terms of equivalency consider Figures 10 and 11.

Figure 10

Figure 10 shows the "Impact" interval in red and the Response interval in green, bracketed from the original data shown as the blue line. The shared point of equivalency with the red and green vertical lines in Figure 10 (point #118) is shown in greater detail with just the vertical green line of Figure 10 "equivalency" as point #1 (green arrow) in Figure 11.

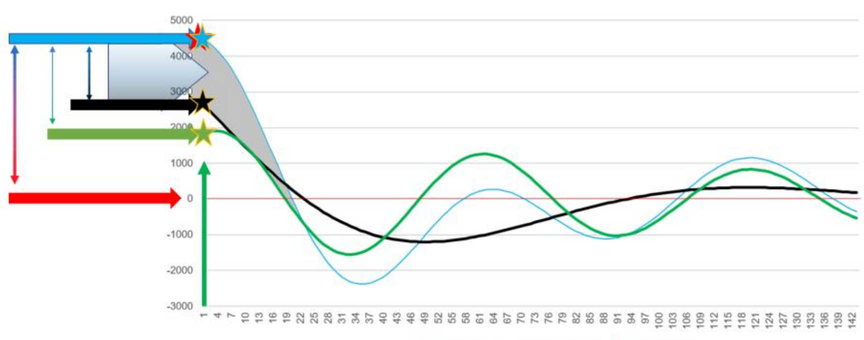


Figure 11

Notice that the point in question for equivalency (point #1), is the single point to be considered. The blue line (original data) is the highest amplitude at point #1 of the 142 points shown. The structure being moved by the impact force (black line) is down considerably from the blue. And the curve fit "response" of the structure to the impacting force is lower yet. It is plain to see that "most" of the Force energy went into those two components, the structures movement and the response of the structure itself. The differences are the shade of Gray, or the other losses of the structure.

The concept of Force Equivalency (F_e) in this application takes into account there is indeed a difference between actual force and response acceleration due to the losses described above. Those losses account for the difference between the two superbly "fit" points of origin (black and green) compared to the blue original when measured in comparison to the origin of the force (red arrow = 0). It is clear that most of what is F_e is indeed the original response of the structure being hit with the force (black), and the fundamental resonance (green); but the construct of the heart mass itself does absorb that energy. In Figure 11 the difference between the origins blue, black, and green arrows in relationship to the red arrow (zero force).

To validate point #118 in Figure 10 and Point #1 in Figure 11, a demonstration of the transfer of Force energy without loss is required. Shown in Figure 12 is the equipment set-up for the measurement of the sensors used in this paper and critical for the concept of equivalency.

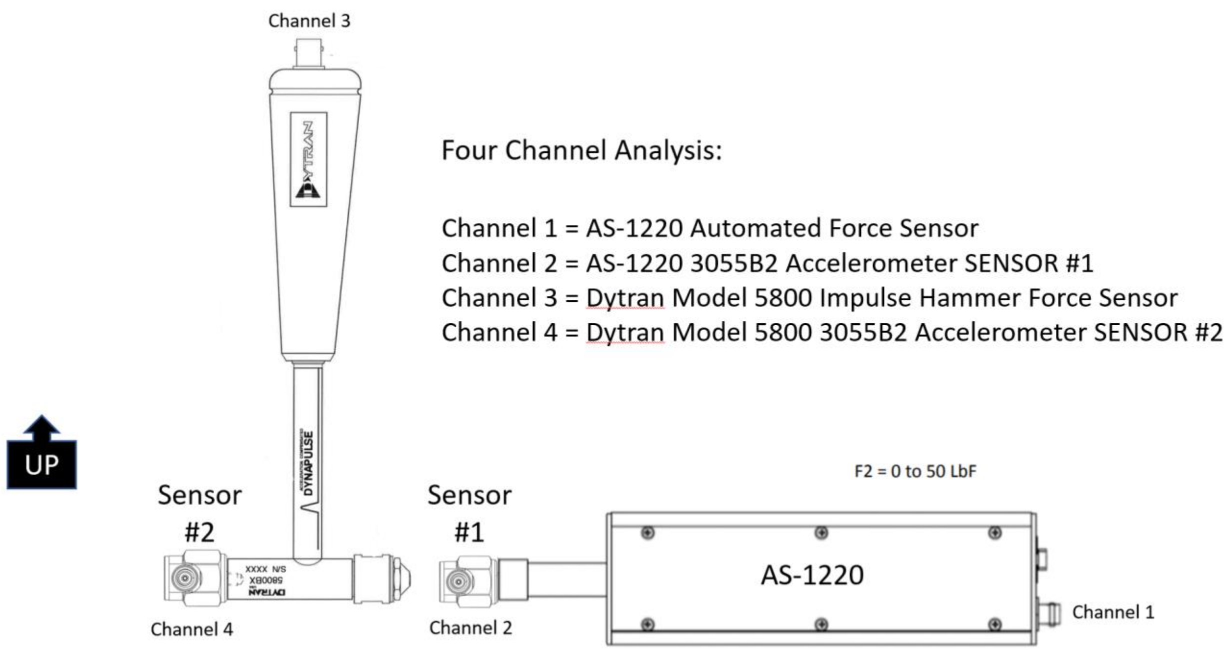


Figure 12

The automated impact hammer made by Alta Solutions Inc. provides consistent impacts without human variables. The Dytran Model 5800 Impulse Hammer with the integral force sensor, is the exact hammer used in many Modal Analysis studies of the structure used in this paper. The two sensors (#'s 1 and 2) are identical (within a 5% tolerance) of those used for the example data of the heart-force data shown in this paper. Having the accelerometers of the same type used to measure the heart force mounted as they are to the known mass of the hammer (and their own) eliminates the possibility of any structural losses.

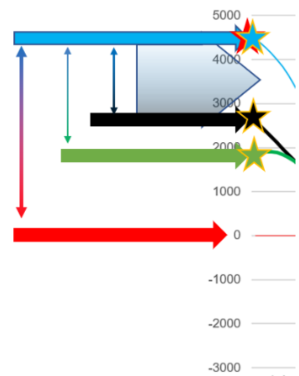
This experiment allows for four channels of data; two channels of force and two channels of acceleration. Sensor #1 solidly affixed to the head of the Automated hammer and therefore able to provide the exact impact force in terms of acceleration, whereas Sensor #2 solidly affixed to the Model 5800 Hammer, provides the received impact force also in terms of acceleration. Since the head of the hammer being impacted is absolutely a solid mass, and the sensors being in the direct line of the applied force, the two readings are equivalent. Two sets of acceleration data can then be compared to the force data of both the AS-1220 and the Model 5800 in lbs./Force. The comparisons of the two sets of two forms of data provide the answer to the calibration differences, and provide the basis of Equivalency or F_e.

YouTube Video of the Experiment: "**Moment of Equivalency**"[1] - https://youtu.be/NE1mmcr9QQM

The hammer hit experiment provides two thoughts:

The first being that there is no loss between the accelerometers and the force sensors, other than calibration values of the devices themselves. The amount of force delivered by the AS-1220 proves an impact that is virtually identical and the sensor values at the point of impact are identical other than the accels are providing acceleration in G's and the Force Sensors providing Force in terms of lbs. There is no indication of true "losses" due to structure with this experiment. On the contrary; the experiment also provides for the computation of Dynamic Mass. This computation confirms the units of measurement of all the sensors utilized. Therefore; the concept of Equivalency or F_e has merit. At the moment of impact, the value even though provided as lbs./ Force can indeed be considered EQUIVALENT in G's of acceleration.

The second thought is; AT the instant of contact 3 KNOWNS are provided. And because of the theory of Equivalency these three points can provide insight into the Structural Dynamics, shown in bold of the heart, with the validation of Dynamic Mass (shown in red).



Dynamic Mass = Force/Acceleration

Mechanical Impedance = Force/Velocity

Dynamic Stiffness = Force/Displacement

Compliance = Displacement/Force

Mobility = Velocity/Force

Inertance = Acceleration/Force

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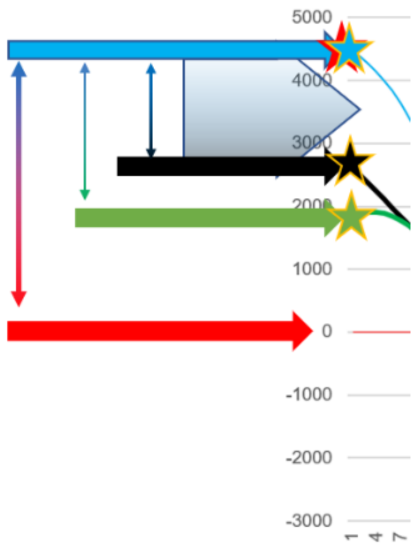
[1] In the video the Auto-Hammer is on the left, which is opposite to that shown in Figure 12.

The grayed-out computation remains questionable, as the accepted definition of **Inertance** is a validation of “pressure” in a liquid, and the hammer is far from being a liquid.



IF the values of the individual starred values are used together. However, if computations are made between the different color-coded points, than the results might prove promising.

However, both Dynamic Mass and Inertance computations might prove useful if the **F_e** is used to compute “Loss” in comparison to the results of the other four computations for each of the results for the **Black** and **Green** data points. It is believed that the only time that those two computations are invalid is when the **F_e** is used to compute anything related to the original **Blue** data point, as it is derived from the same original value.

It is important to keep in mind that the very structure of the heart absorbs a considerable amount of the Impact Force Energy. Therefore “Loss” of some kind is a given, which can only be estimated.