Factors Affecting the results

of the

‘Berlin Artificial Athlete’ shock absorption test

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1 Introduction

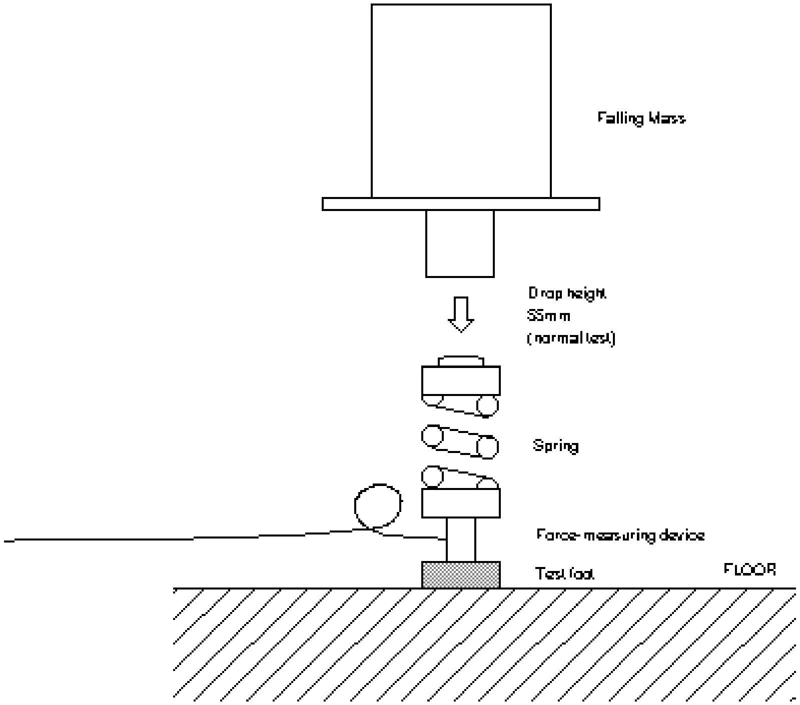
The Berlin Artificial Athlete test has been in use for many years as the first-choice method for the measurement of the shock absorption of surfaces for sporting and other uses. Although the test was originally developed for assessment of athletics surfaces it has since been adopted for use on Sports Hall floors, on impact absorbing playground surfaces and on synthetic turf surfaces.

Improvements in instrumentation have been applied to the test over the years, with different techniques being adopted for the acquisition and processing of the signals. As in many Standards written around a particular, pre-existing piece of apparatus, many aspects of the apparatus which, with hindsight may have been critical, were left undefined in the DIN.

This paper attempts to define the components of the equipment and to assess the manner in which they affect the results of the test and the magnitude of those effects.

2 Definition of the Apparatus

The mechanical components of the Berlin Artificial Athlete are as shown schematically in the drawing below.



The apparatus consists of the following main components;

i) A falling mass, defined as 20.0 kg and having a protruding component (of defined dimensions) on its impacting base.

ii) A spring, of spring rate 2 MN, fitted with a radiused top cap.

iii) A force measuring device, having a capacity of 10 kN and, in conjunction with its associated instrumentation, the ability to measure forces with an accuracy of 0.1%.

iv) A circular test foot, through which the impact is applied to the floor under test, having a diameter of 70 mm and a bottom surface with a radius of 500 mm.

In performing a test, the mass is allowed to fall from a height of 55 mm onto the spring top cap. The force applied to the floor is recorded. The amount by which the peak value of the force is lower than the peak value measured when the test is performed on a concrete substrate is reported.

Since the drop height and the floor can also affect the result, they must also be regarded as components of the apparatus.

Each of the components mentioned above may affect the test results to a greater or lesser extent.

3 Effects on Results of Variations in Components

In this section, the effect on the measured force of variations in each of the components listed is considered. In general the discussion is based on the theoretical analysis of the test when performed on concrete. Under those circumstances, the initial potential energy of the falling mass is equal to the energy stored in the spring when it is at its maximum compression, i.e. at the point of maximum force.

The potential energy of the falling mass is given by the difference between its height at the start of the test and its height at the point of maximum force;

$E = M.g.(H + x)$, where M = mass

g = acceleration due to gravity

H = Drop height

x = maximum compression of the spring

The energy stored in the spring at the moment of its maximum compression is given by

$E = ½ . k . x2$ where k = the Spring constant

x = the maximum compression of the spring

Equating the two quantities of energy gives the relationship

$½ . k . x2 = M.g.(H + x)$.

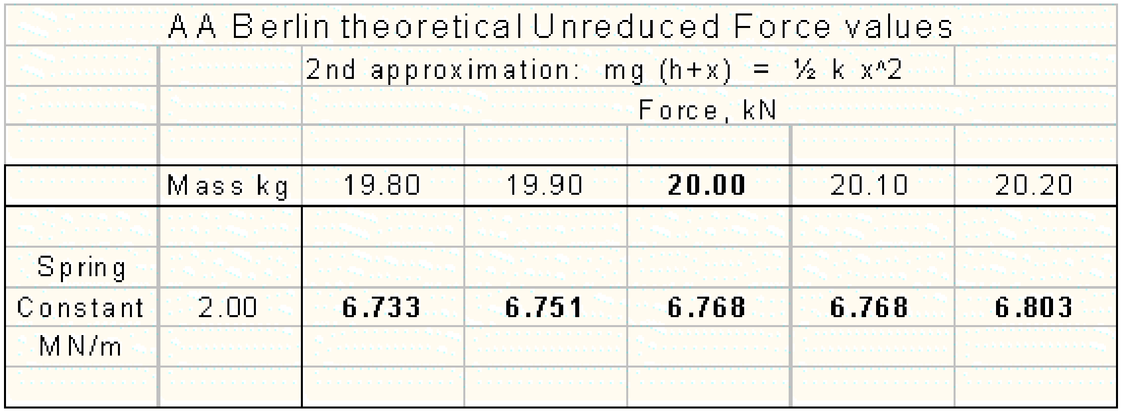
Since the force exerted by a spring is given by $F = k.x$, this may be re-stated as;

$F . x = 2 . M . g . (H + x)$

It is important to note that although this relationship applies both to the case of the concrete reference floor and to the testing of a sample. The only difference will be that the value of k is changed by the introduction of a second compliant component into the system, i.e. the sample itself. However, dependencies which derive from this relationship do not necessarily apply other than in the concrete situation.

3.1 Falling Mass

The result of the test is self-evidently dependent on the mass of the "hammer" on which the test is based. However, relationship is between the square root of the mass and the force produced. In the table below, derived from the relationship given above, we see that the effect of a 1% change in the falling mass is a change of approximately ½% in the force produced.



AA Berlin theoretical Unreduced Force values

2nd approximation: mg (h+x) = ½ k x^2

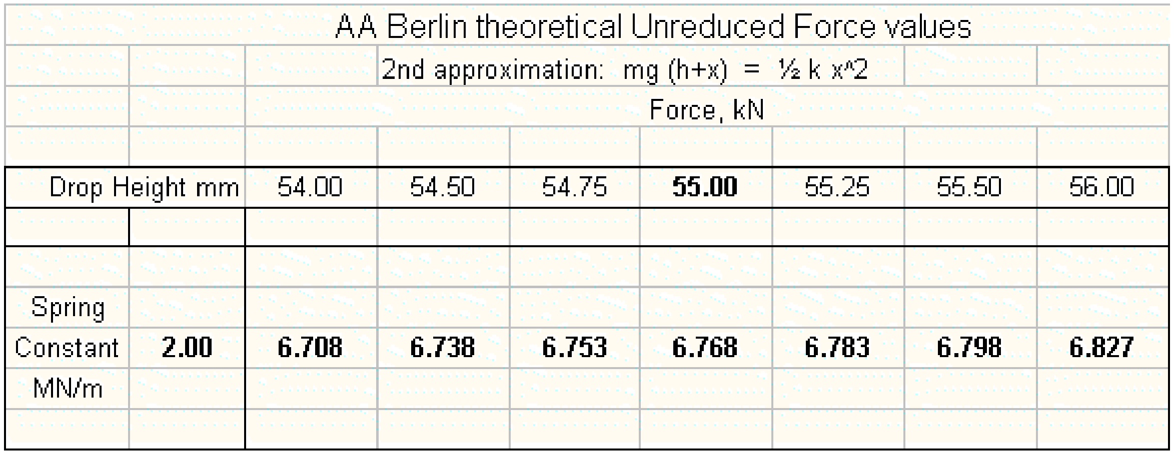
Force, kN

	Mass kg	19.80	19.90	**20.00**	20.10	20.20
Spring Constant MN/m	2.00	**6.733**	**6.751**	**6.768**	**6.768**	**6.803**

3.2 Drop Height

As stated above, although not a "component" as such, the drop height has a direct effect on the result of the test, so must be considered as such.

As before, the table below is derived from the theoretical relationship described. Again, because of the square root relationship, a 1% change in the drop height produces a change of ½% in the force.



AA Berlin theoretical Unreduced Force values

2nd approximation: mg (h+x) = ½ k x^2

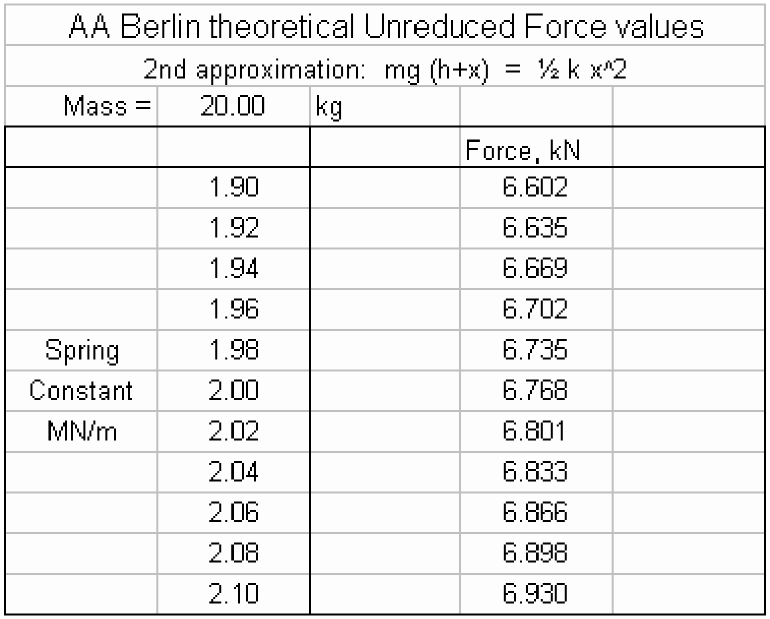
Force, kN

Drop Height mm		54.00	54.50	54.75	**55.00**	55.25	55.50	56.00
Spring Constant MN/m	**2.00**	**6.708**	**6.738**	**6.753**	**6.768**	**6.783**	**6.798**	**6.827**

3.3 Spring

The relationship mentioned assumes, of course, a perfect spring, having a linear relationship between force and deflection and being free from damping. In practice no such spring exists and these imperfections are difficult to quantify. The simplest approach to avoidance of their effects may be simply to ensure that the spring employed approaches perfection in these respects as closely as possible. This has been the philosophy behind the adoption of the triple-coil, milled 'Rein' spring, supplanting the older, single-coil wire spring.

The fundamental property of a spring is its stiffness or spring rate, measured in this case in MNm^{-1}. Again, a square root relationship applies.



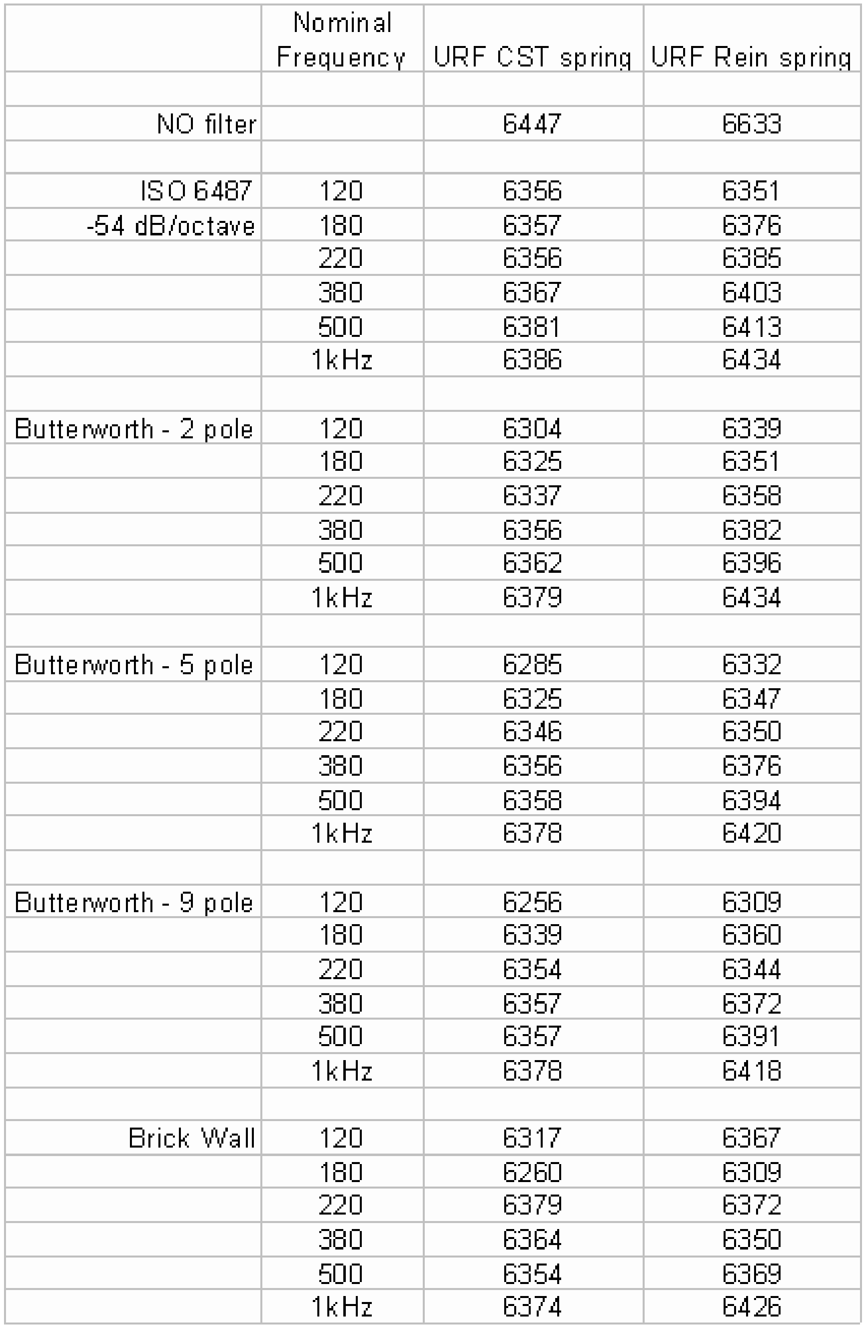
AA Berlin theoretical Unreduced Force values				
2nd approximation: mg (h+x) = ½ k x^2				
Mass =	20.00	kg		
			Force, kN	
	1.90		6.602	
	1.92		6.635	
	1.94		6.669	
	1.96		6.702	
Spring	1.98		6.735	
Constant	2.00		6.768	
MN/m	2.02		6.801	
	2.04		6.833	
	2.06		6.866	
	2.08		6.898	
	2.10		6.930	

This is an example of a dependency which is applicable only to concrete. Introduction of a sample into the system affects the spring rate of the system, with the overall spring rate given by;

$$K = 1/k_1 + 1/k_2$$

The overall effect of an error in the spring rate, when a sample is present in the system, will therefore depend on the properties of the sample as well as the magnitude of the error.

The table below gives values of peak force measured on a concrete floor using two different springs.



	Nominal Frequency	URF CST spring	URF Rein spring
NO filter		6447	6633
ISO 6487	120	6356	6351
-54 dB/octave	180	6357	6376
	220	6356	6385
	380	6367	6403
	500	6381	6413
	1kHz	6386	6434
Butterworth - 2 pole	120	6304	6339
	180	6325	6351
	220	6337	6358
	380	6356	6382
	500	6362	6396
	1kHz	6379	6434
Butterworth - 5 pole	120	6285	6332
	180	6325	6347
	220	6346	6350
	380	6356	6376
	500	6358	6394
	1kHz	6378	6420
Butterworth - 9 pole	120	6256	6309
	180	6339	6360
	220	6354	6344
	380	6357	6372
	500	6357	6391
	1kHz	6378	6418
Brick Wall	120	6317	6367
	180	6260	6309
	220	6379	6372
	380	6364	6350
	500	6354	6369
	1kHz	6374	6426

Taking the values obtained by processing with a 220Hz, 9-pole Butterworth filter (for reasons explained later) it can be seen that there is little difference between the values obtained with the two springs. Nevertheless, as a matter of principle, where uncertainties can be eliminated, it is prudent to do so. In this case, there are more uncertainties (damping and possible end effects) with the old-style spring than with the new one, so it would be sensible to adopt the new one where possible.

3.4 Force Measuring Device

Force measurement is based on a device which produces an electrical signal proportional to the force applied. In assessing these complex devices it is usually necessary to rely on the claims of the manufacture. More important is the fact that the properties of the device cannot be assessed in isolation, since the data which finally result are produced by the combination of the mechanical device and its associated instrumentation. This may include amplifiers, filters, digitisers and software-based numerical processing. Errors or uncertainties can arise in any of these sub-system components.

3.4.1 There are at least two fundamentally different types of force-measuring device in use. Both strain-gauge load cells and piezo-electric force washers are used. The different characteristics of the devices can affect the measured signal in different ways.

A strain gauge load cell will normally have a free resonant frequency below 1kHz. Attachment of additional components, such as the test foot, will reduce this frequency still further.

A strain gauge load cell may also be significantly compliant, with a deflection of perhaps 0.1 mm at maximum load. In the case of a 10kN load cell, this is a spring rate of 100 MN/m, which is only 50 times the spring rate of the measurement spring. If the main spring has a rate of 2.00 MN/m, the spring rate of the load cell and main spring combined will be 1.96 MN/m. It is important, if using strain gauge load cells, to carry out calibration of the apparatus spring rate in conjunction with the load cell.

Piezo-electric force washers have very low compliance/high stiffness. Partly as a result, they also have much higher resonant frequencies. This can be a disadvantage, since it means that some means of band-limiting the load cell signal will almost certainly be needed before it is fed to the digitiser, in order to avoid aliasing.

3.4.2 Amplification and hardware filtration

In operation, the amplifier, if properly set up, should have little effect on the practicalities or on the detail of the signal acquisition and recording process. The connectors on piezo- charge amplifiers must be kept clean, since loss insulation as a result of contamination can degrade low-frequency response.

In many cases, some means of altering the frequency response of the amplifier will be provided. This may take the form of a switchable low-pass filter or of plug-in low-pass modules. If such a facility is available it must be used, to ensure that any signal components having frequencies greater than half the sampling rate are removed.

3.4.3 Digitisation

If the signal has been properly prepared, as mentioned above, there should be no difficulties associated with the digitisation process.

The only important aspect is to ensure that the relative sensitivities of the ADC and the preceding amplifiers are properly matched, so that the signal level never falls below, say, one eighth of the ADC’s full scale voltage. With a 12-bit ADC, this will mean that the signal resolution is never less than one part in 500, or 0.2%. However, any other inaccuracies in the ADC (such as non-linearities or other errors) will be in addition t this.

3.4.4 Signal processing

Determination of the peak value of a recorded signal is a simple mathematical process. However, the recorded signal often contains additional, unwanted information which must be removed. The difficulty arises in defining which of the information is unwanted noise or interference and which is the genuine signal.

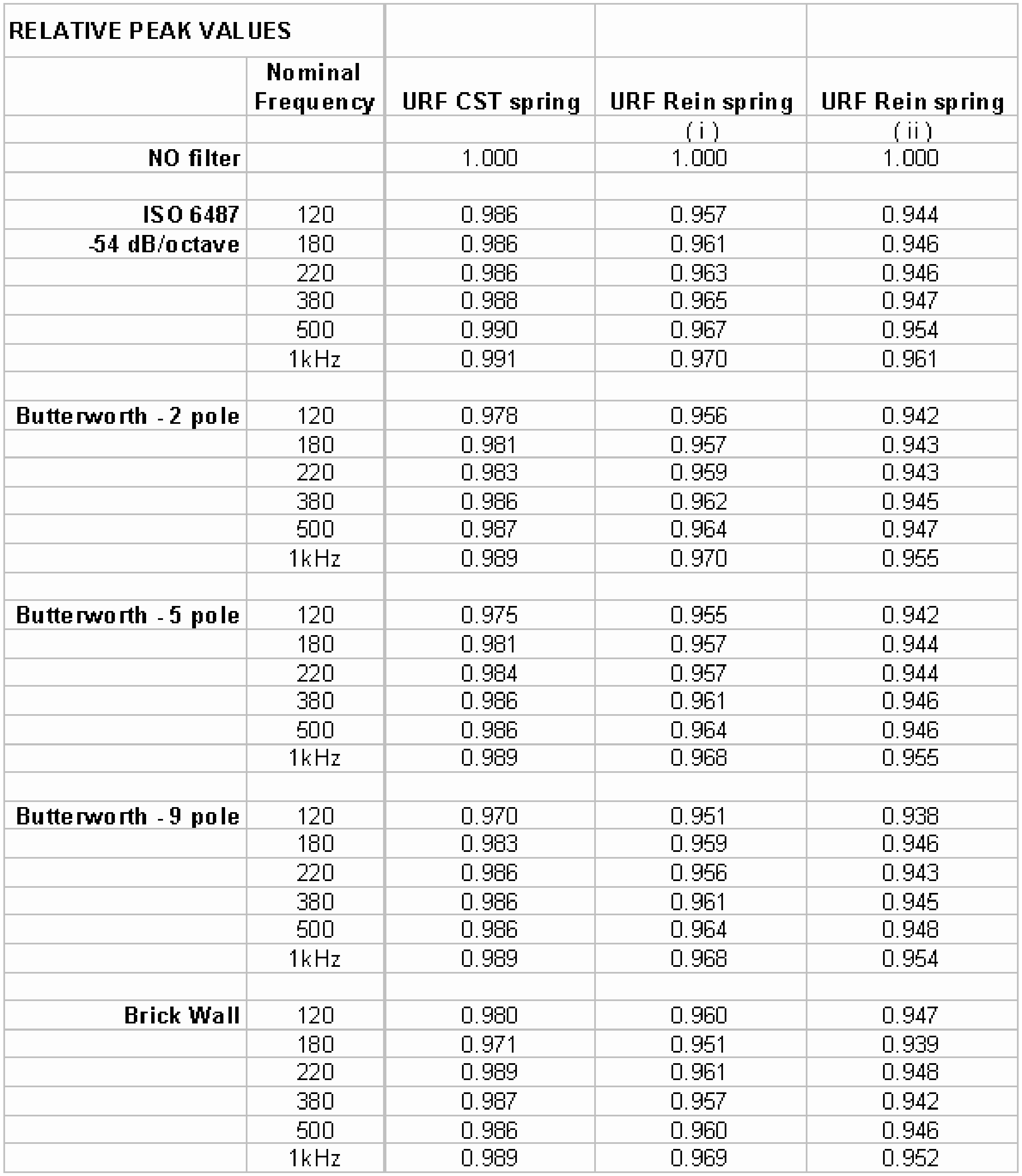
When the test is carried out on concrete, the apparatus consists of a single mass and a single spring, so the ‘wanted’ signal should consist of a single, half-sinusoid pulse. In practice, unwanted components are present as well; these may be pseudo-random noise or components of significant amplitude and recognisable frequency, or a combination of the two. Graphs 1 to 3, Appendix 1, show these points.

Where, as in Graphs 1 to 3, the wanted and unwanted components are of clearly and widely differing frequency, their separation is not difficult. This may be seen in the table below, which shows the relative values of the peak force in each of graphs 1 to 3 under different conditions of filtration. There are no other variable involved here, since all the values were obtained by repeated processing of the same three, stored records of impacts.

The table overleaf gives the same figures as are shown in the Table on page 8, except that here, in each column, the values are expressed relative the unfiltered peak. The table shows that the effect of the filtration on the signal produced with the Rein spring is in all cases greater than the effect on the signal produced with the old-style spring. The traces show why this is so; the old spring’s trace is much cleaner than the ‘Rein’ traces.

When filtration is introduced, at 1kHz, an initial reduction in peak value occurs, as a result of removal of signal components above 1kHz. For the old spring, these components have amplitude about 1% of the total peak; for the Rein spring, they are 3 to 5% of the total signal peak.

As the filtration frequency is reduced, further components are removed. If there were an absolute separation between the wanted and unwanted components, there would come a first point at which further reductions in filter frequency had no effect on peak value, and a second point at which the peak value started to fall again as the wanted components were removed. In practice there is not such a clear-cut relationship between the components of the signals. However, there is in almost all cases, for all filter types, a levelling off of the peak value from 220 Hz to 500 Hz. In some cases the level region extends lower and in others there is little difference between 500Hz and 1kHz. The implication of this is that, for the test on concrete, selection of any filter frequency in this range will be acceptable. In practice, because there are small difference and it is desirable to remove as many differences between pieces of apparatus as possible, a single frequency must be selected. It is suggested that this should be as low as possible within the constraints outlined, in order to ensure that all unwanted components are removed. A frequency of 220 Hz is suggested.



RELATIVE PEAK VALUES				
	Nominal Frequency	URF CST spring	URF Rein spring (i)	URF Rein spring (ii)
NO filter		1.000	1.000	1.000
ISO 6487	120	0.986	0.957	0.944
-54 dB/octave	180	0.986	0.961	0.946
	220	0.986	0.963	0.946
	380	0.988	0.965	0.947
	500	0.990	0.967	0.954
	1kHz	0.991	0.970	0.961
Butterworth - 2 pole	120	0.978	0.956	0.942
	180	0.981	0.957	0.943
	220	0.983	0.959	0.943
	380	0.986	0.962	0.945
	500	0.987	0.964	0.947
	1kHz	0.989	0.970	0.955
Butterworth - 5 pole	120	0.975	0.955	0.942
	180	0.981	0.957	0.944
	220	0.984	0.957	0.944
	380	0.986	0.961	0.946
	500	0.986	0.964	0.946
	1kHz	0.989	0.968	0.955
Butterworth - 9 pole	120	0.970	0.951	0.938
	180	0.983	0.959	0.946
	220	0.986	0.956	0.943
	380	0.986	0.961	0.945
	500	0.986	0.964	0.948
	1kHz	0.989	0.968	0.954
Brick Wall	120	0.980	0.960	0.947
	180	0.971	0.951	0.939
	220	0.989	0.961	0.948
	380	0.987	0.957	0.942
	500	0.986	0.960	0.946
	1kHz	0.989	0.969	0.952

A further variable is the type of filter function to be applied. The filter function is the function which describes the rate at which the signal is attenuated with respect to frequency. In ISO 6487 the description is not in terms of a function, but rather as a prescription of a number of constant rates of attenuation over various frequency ranges. It is important to note that with the filtration described in this standard, no attenuation at all occurs below a frequency 1.65 times the nominal filter frequency.

The "Brick Wall" filter can have strange effects on signals with sharp transients near the filter frequency, so cannot be recommended.

The Butterworth filter function is well-known, is available in most standard packages or is otherwise relatively simple to implement. Its response to transients is good and its cut-off can be sharp.

It is important to select a filter which cuts off adequately steeply. The rate of attenuation may be expressed in terms of dB per octave or of the number of poles in a hypothetical hardware filter. The graph on page 15 shows the rate of attenuation given by Butterworth filters of 2, 5 and 9 poles. With a 2-pole filter, significant attenuation occurs below the nominal frequency of the filter while significant proportions of components of the signal remain unremoved at frequencies well above the filter frequency. This effect is less marked with a 5-pole filter and, of course, less so still with a 9-pole filter. The use of a 9-pole filter is suggested.

3.5 Test Foot

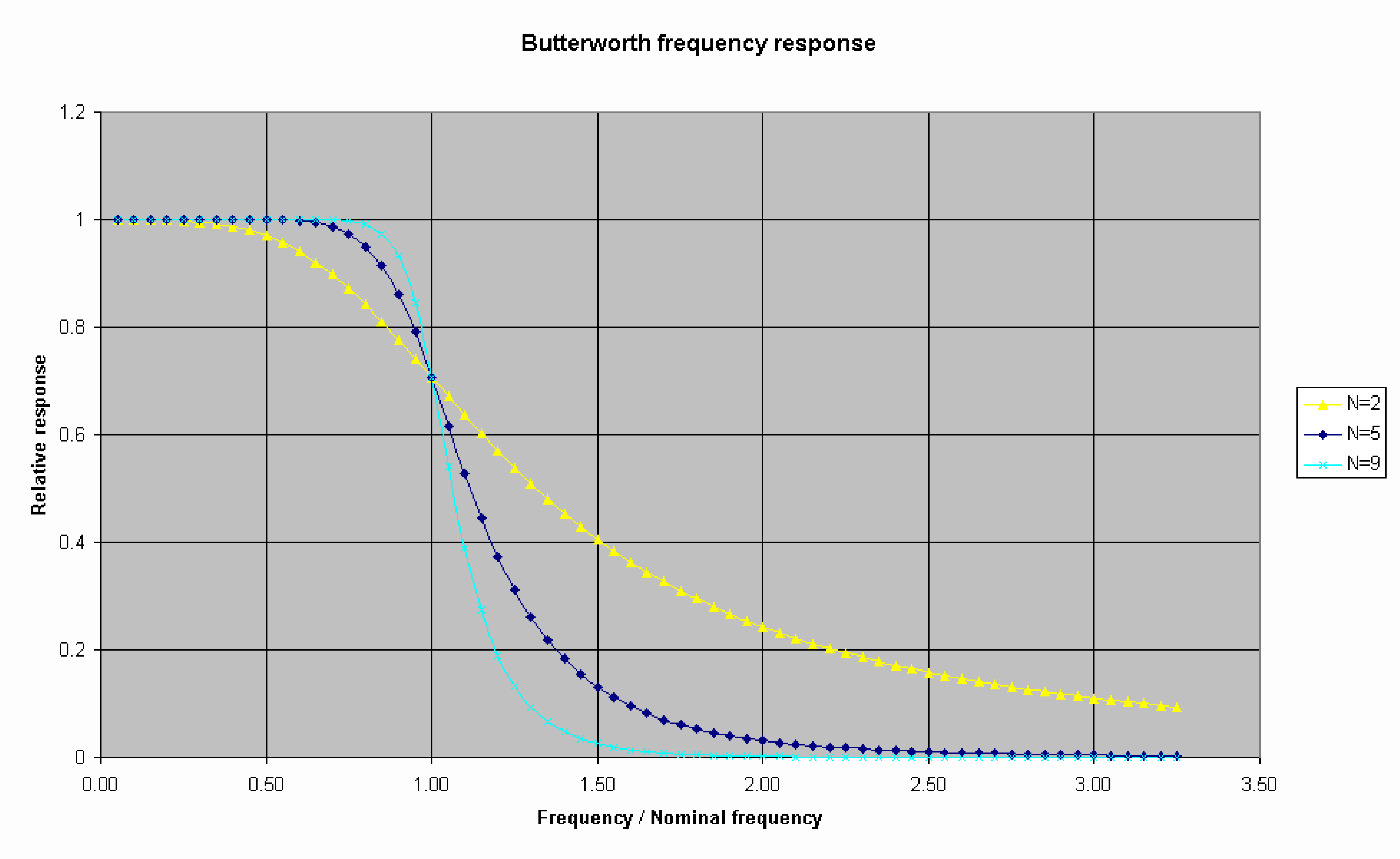
The test foot is simply defined and should need no further definition, though it is difficult to quantify the effects any errors in its construction might have. The most likely fault would be that the radius of the base could be too small. This would have different effects under different circumstances, depending on the properties of the surface under test.

It is suggested that a tolerance be added to the defined radius of the face of the test foot. 500 ± 50 mm is suggested.

3.6 Floor

When carrying out site tests, the floor is not a component of the apparatus, but is part of the sample. However, when carrying out measurements of sample properties in the laboratory, it is important that the floor play no part. Its properties should therefore be indistinguishable from the properties of the concrete reference floor used to define the baseline value of force for the test. In effect, for laboratory tests, all tests must be carried out with the sample placed on the concrete reference floor.

It is a general guideline in impact testing that the anvil against which the impact occurs should have a mass at least 100 times that of the mass of the hammer. In the case of the A.A. Berlin, where the falling mass is 20 kg, the concrete base should have a mass of at least 2 tonnes. The concrete must be a good quality, dense, high-strength material. It is suggested that it should be no less than 300 mm thick. To avoid local crushing of the concrete at the point of impact, a steel plate at least 20 mm thick should be set into the surface of the concrete.



4 Overall Repeatability

All the components of the test discussed above are capable of affecting the results produced. In order to set tolerances on most of them, it must first be decided what level of uncertainty is required of the whole test method.

One exception to this is the Floor, whose effects cannot be quantified. The concrete used must therefore be of high quality and the steel plate must be installed with great care to ensure that there are no bubbles beneath it.

A second exception is the filtration, where, again, the effects of changes are not quantifiable. However, for the reasons discussed, the suggested filtration should be universally adopted. Provided this is done, there should be no variabilities introduced by this aspect of the test.

There are four further components contributing to the test result; the mass, the spring, the drop height and the force measurement/recording system. Uncertainties in the calculated force are proportional to the uncertainties in the force measurement/recording system and are proportional (as a first approximation) to the square roots of uncertainties in the spring rate, the mass and the drop height. If the uncertainty in each of these areas were 1%, the overall uncertainty on the measured force would be approximately 2%. Two of these sources of error (the mass and the spring rate) are systematic, so will always contribute errors of the same type, which will reduce the uncertainty on the calculated force reduction, where the result depends on the ratio of two values of force.

In practice, instrumentation having an uncertainty significantly less than 1% is unlikely to be feasible, particularly for equipment for site use.

Spring rate cannot be adjusted after manufacture of the spring and 3% appears to be the limit on the tolerance within which the ‘Rein’ spring can be made, giving an uncertainty on the measured force of about 1½%. As a systematic error, the effect on the uncertainty in the final result is much less than this.

The falling mass can be adjusted to ensure that its mass is within 0.25% of the nominal value (as required by the DIN). The effect on the final result of errors in the mass will be very small.

Errors in the setting of the drop height are random. The height must be set twice for each result (once for measurement of the force on concrete and once for the test on the sample). The contribution to the uncertainty in the final result is therefore potentially significant. The tolerance allowed in the DIN is ±0.25 mm, which is approximately ½% of the drop height, giving an uncertainty of approximately ¼% in the measured force and approximately ½% in the calculated force reduction.

In total, it seems unlikely that it is possible to achieve force reduction values which carry an uncertainty of less than about 1½%.

5 Value of Peak Force Measured on Concrete

As shown in et tables above, the peak force measured on concrete with all variables at their nominal values should be in the region of 6.75 kN. In practice, the force is found to vary from this level, usually but not always lying below it.

This is likely to occur for two reasons for this.

The first concerns the mass, thickness and quality of et concrete reference floor. If any of these parameters is below the ideal, the peak force measured will be low.

The second is the fact that not all of the energy of the falling mass is transferred to et spring. Some energy is lost as noise, heat, vibrations etc. Any loss of energy will result in a reduction in the peak force.

Variations in the components of the apparatus within the permitted tolerances will produce variations in the peak force on concrete. Using the expression on Page 5 to calculate the peak force on concrete with all variables set to the upper an lower limits of their tolerances and applying an additional 1% variability for instrumentation errors gives a range of values for F_c of 6.58 to 6.96 kN These values will be reduced by the losses mentioned. Loss of 1% of the potential energy will reduce the peak force by approximately 60N.

It is therefore suggested that unless the peak force on concrete falls in the range 6.40 kN to 6.95 kN the condition of the apparatus and/or the test floor should be regarded with suspicion and corrected.

6 Discussion

The greatest difficulties with the reproducibility of this test have occurred with samples at the harder end of the range, giving force reduction values below about 25%. It is at this end of the scale that the test is most sensitive to variations in spring rate and filtration. With the unavoidable limits which exist on the accuracy of manufacture and calibration of the spring, it may be that the only way to avoid this problem is to impose a limit on the rage of validity of the test method. The test was originally devised for athletics track surfaces, whose Force reduction values generally fall into the range 30 to 55%. The imposition of a lower limit of validity of 25% could be considered. Alternatively, for test results below this level a more closely selected spring may be required, perhaps having a spring rate of 2 ± 0.02 MN/m.

This point requires further discussion.

7 Suggestions

In summary, to achieve acceptable repeatability with the Berlin artificial athlete, the following precautions should be adopted;

i) The tolerances currently set on the various key components of the apparatus must be strictly adhered to.

ii) The signal should be processed using a 220Hz 9-pole Butterworth filter.

iii) The peak force on concrete should always lie in the range 6.40 to 6.95 kN

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Appendix 1

Graphs showing effects of Filtration on various curves

1 Old-style Berlin spring

2 ‘Rein’ spring

3 ‘Rein’ spring

4 Reference Standard A

5 Reference Standard B

6 Reference Standard C

7 8 mm thick prefabricated rubber shred sheet

8 Spray-finished athletics track sample

9 Two layers of 8 mm thick prefabricated rubber shred sheet

All graphs show the recorded trace before and after the application of the filter function described.

In some cases, the filtered trace departs significantly from the original over the last eighth of the record. This is a deliberately introduced artefact, required to equalise the signal levels at the start and end of the record before the filtration is carried out.