STANDARDIZED ACCELERATION PROCESSING FOR PAVEMENT ROUGHNESS EVALUATION

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ABSTRACT

Aircraft body vertical accelerations are frequently used to characterize the response of an aircraft to pavement disturbances during ground maneuvers. A standardized procedure is presented which can be used to process measured and simulated aircraft accelerations. In the procedure, an acceleration of interest is filtered according to the weighting functions defined in ISO Report 2631-1, "Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration, Part 1: General Requirements." Ride quality index values are computed from the weighted time histories according to four methods defined in the ISO report: 1) root mean square (r.m.s.); 2) running r.m.s.; 3) fourth power vibration dose; and 4) spinal response acceleration dose. These functions were previously implemented by the FAA in a standalone computer program called "ISO Accel Processing" written in the Microsoft VB6 language. They have now been implemented in a Microsoft Windows Presentation Foundation (WPF) development of the FAA computer program ProFAA. The new program is called ProView and the time history weighting and ISO index computations are applied to the acceleration outputs of the internal aircraft simulations. An additional function has been added to the program whereby an externally generated acceleration time history from any source can be read from a text file. The weighting and ISO index functions are then performed on the externally generated acceleration time history and the results displayed in the same way as the accelerations from the internal aircraft simulations. The implementation of the ISO functions is described in detail together with two examples: 1) the weighted time history and ISO index values computed from the internal aircraft simulation in response to an elevation profile measured on an airport runway and 2) the weighted time history and ISO index values computed from an external acceleration record measured on an aircraft operating on the same airport runway as in the first example.

INTRODUCTION

Aircraft body vertical accelerations are frequently used to characterize the response of an aircraft to pavement disturbances during ground maneuvers. The accelerations can either be measured from accelerometers mounted in an aircraft or from simulated aircraft response to measured pavement profiles. Accelerations are generally measured over an arbitrary band-width and with arbitrary amplitude shaping as determined by the characteristics of the accelerometer, the data acquisition system, and the anti-aliasing filters. Similarly, accelerations from computer simulation programs have characteristics determined by the sample spacing and integration procedures. But, for consistent application of acceleration signals to vehicle response analyses, some form of signal post-processing should be applied in order to standardize, to the extent possible, the band-width and amplitude shaping of the signal to be analyzed. However, consensus standards have not been established for processing the accelerations prior to characterization of the response.

If the response characterization is related to the ride quality of the aircraft then a candidate standard for pre-processing the accelerations is contained in reference 1, ISO Report 2631-1, "Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration, Part 1: General Requirements." The standard consists of a set of functions which weight the acceleration signal over frequency to compensate for the sensitivity of human response to acceleration. Weighting functions are defined in the standard for three linear and three rotational degrees of freedom. But only the seated vertical linear weighting functions are discussed here in relation to aircraft cockpit and center of gravity (cg) vertical accelerations.

The weighting functions are defined in detail below, but, in essence, they combine to form a band-pass filter which normalizes the input acceleration so that the output represents a flat subjective response to broad-band excitation. That is, if the subjective response at, for example, 10 Hz has a certain level, and the subjective response at, say, 20 Hz, is the same as at 10 Hz for twice the input acceleration amplitude, then the amplitude of the 20 Hz signal needs to be reduced by a factor of two for the weighted acceleration to represent a flat subjective response. Stated in the opposite sense, for the same input amplitude at 10 and 20 Hz, the 20 Hz signal needs to be reduced by a factor of two in order for the output to represent one-half the subjective response as at 10 Hz.

The weighting functions are defined in the ISO standard as Laplace transfer functions. For the numerical implementation described in this paper, the transfer functions are transformed into their equivalent differential equations and the differential equations solved by numerical integration. An alternative implementation is given in reference 2 using digital filtering techniques for converting analog transfer functions into digital transfer functions. Proprietary and public domain implementations are also available for use in engineering analysis software packages such as Matlab and DADiSP, and in National Instruments analysis tools.

The transfer functions are given first, together with the corresponding differential equations, followed by a description of the implementation in a roughness evaluation computer program called ProView. Four summary acceleration index functions from the ISO 2631-1 standard are then defined. Examples of numerical calculations using the weighting functions and the index functions are provided with the input acceleration derived from a Boeing 727-100 aircraft simulation and from an external data file recorded during tests run with a 727-100 aircraft.

ACCELERATION SIGNAL FREQUENCY WEIGHTING FUNCTIONS

The filter for weighting the acceleration signals is implemented as a set of four differential equations defined by their frequency response functions. The frequency response functions are defined in the standard as four separate sections and these have to be transformed into the base differential equations for solution in the time domain by numerical integration. The response functions, as defined in the standard, and the base differential equations are shown below with the following nomenclature.

p = imaginary angular frequency or Laplace operator
$H(p)$ = transfer function
$|H(p)|$ = frequency response function
ω = frequency in rad/s
f = frequency in Hz = $\omega / 2\pi$
ω_i, f_i, Q_i = response shaping parameters
x = input to the filter, acceleration in m/s^2
y = weighted output from the filter, acceleration in m/s^2

1. Band limiting - high pass section

   Frequency response function:

$$|H_{\mathrm{h}}(p)| = \left|\frac{1}{1+\sqrt{2}\,\omega_1/p + (\omega_1/p)^2}\right| = \sqrt{\frac{f^4}{f^4+f_1^4}}$$

   Differential equations for numerical solution in terms of y and z:

$$\begin{aligned}
\ddot{y} &= \ddot{x} - \sqrt{2}\omega_1\dot{y} - \omega_1^2 y \\
\dot{y} &= z \\
\dot{z} &= \ddot{y} = \ddot{x} - \omega_1\left(\sqrt{2}z + \omega_1 y\right)
\end{aligned}$$

2. Band limiting - low pass section

   Frequency response function:

$$|H_{\mathrm{l}}(p)| = \left|\frac{1}{1+\sqrt{2}\,p/\omega_2 + (p/\omega_2)^2}\right| = \sqrt{\frac{f_2^4}{f^4+f_2^4}}$$

   Differential equations for numerical solution in terms of y and z:

$$\begin{aligned}
\ddot{y} &= \omega_2^2 x - \sqrt{2}\omega_2\dot{y} - \omega_2^2 y \\
\dot{y} &= z \\
\dot{z} &= \ddot{y} = \omega_2\left(\omega_2 x - \sqrt{2}z - \omega_2 y\right)
\end{aligned}$$

3. Acceleration-velocity transition (proportionality to acceleration at lower frequencies and proportionality to velocity at higher frequencies)

   Frequency response function:

$$|H_{\mathrm{t}}(p)| = \left|\frac{1+p/\omega_3}{1+p/(Q_4\omega_4)+(p/\omega_4)^2}\right| = \sqrt{\frac{f^2+f_3^2}{f_3^2}}\cdot\sqrt{\frac{f_4^4\cdot Q_4^2}{f^4\cdot Q_4^2 + f^2\cdot f_4^2(1-2Q_4^2)+f_4^4\cdot Q_4^2}}$$

   Differential equations for numerical solution in terms of y and z:

$$\begin{aligned}
\ddot{y} &= \frac{\omega_4^2}{\omega_3}\dot{x} - \omega_4^2 x - \frac{\omega_4}{Q_4}\dot{y} - \omega_4^2 y \\
\dot{y} &= z \\
\dot{z} &= \ddot{y} = \omega_4\left(\frac{\omega_4}{\omega_3}\dot{x} + \omega_4 x - \frac{1}{Q_4}z - \omega_4 y\right)
\end{aligned}$$

4. Upward step (steepness approximately 6 dB per octave, proportionality to jerk)

Frequency response function:

$$|H_s(p)| = \left|\frac{1 + p/Q_5\omega_5 + (p/\omega_5)^2}{1 + p/(Q_6\omega_6) + (p/\omega_6)^2} \cdot \left(\frac{\omega_5}{\omega_6}\right)^2\right| = \frac{Q_6}{Q_5} \cdot \sqrt{\frac{f^4 \cdot Q_5^2 + f^2 \cdot f_5^2(1 - 2Q_5^2) + f_5^4 \cdot Q_5^2}{f^4 \cdot Q_6^2 + f^2 \cdot f_6^2(1 - 2Q_6^2) + f_6^4 \cdot Q_6^2}}$$

Differential equations for numerical solution in terms of y and z:

$$\ddot{y} = \ddot{x} + \frac{\omega_5}{Q_5}\dot{x} + \omega_5^2 x - \frac{\omega_6}{Q_6}\dot{y} - \omega_6^2 y$$
$$\dot{y} = z$$
$$\dot{z} = \ddot{y} = \ddot{x} + \frac{\omega_5}{Q_5}\dot{x} + \omega_5^2 x - \frac{\omega_6}{Q_6}z - \omega_6^2 y$$

All of the frequency response functions except one require differentiation of the input signal. The following difference equations are used to differentiate numerically:

$$\dot{x} \approx \frac{\Delta x}{\Delta t} = \frac{x(t+h) - x(t-h)}{2h}$$
$$\ddot{x} \approx \frac{\Delta^2 x}{\Delta t^2} = \frac{x(t+h) - 2x(t) + x(t-h)}{h^2}$$

Where h = sample spacing = 1 / (sample rate)

PROCEDURE FOR COMPUTER IMPLEMENTATION OF THE WEIGHTING FUNCTIONS

Each of the four weighting functions is implemented in a separate subroutine in a Visual Basic computer program. The subroutines are called in series with the measured cockpit acceleration used as input to the first subroutine and the output from the first subroutine fed into the input of the second subroutine, and so on through all four subroutines. The subroutines are called in the following order:

1. Low pass section.
2. Acceleration-velocity transition.
3. High pass section.
4. Upward step.

The order was selected primarily to reduce inaccuracies at high frequency during differentiation of the input. The low pass section does not require differentiation and attenuates the high frequencies before differentiation in the following sections. The acceleration-velocity transition filter requires only first order differentiation so that section follows the low pass. The other two filters require second order differentiation so they are executed last.

The overall transfer function is calculated from the frequency response functions as:

$$|H_{\text{Overall}}(p)| = |H_l(p)| \,.\, |H_t(p)| \,.\, |H_h(p)| \,.\, |H_s(p)|$$

The frequency response shaping parameters are specified in the ISO standard as shown in table 1.

Table 1.
Parameters of the transfer functions of the principal frequency weightings (reproduced from table A.1 of reference 1).

Weighting	Band-Limiting		Acceleration-Velocity Transition			Upward Step			
	f_1, Hz	f_2, Hz	f_3, Hz	f_4, Hz	Q_4	f_5, Hz	Q_5	f_6, Hz	Q_6
W_k	0.4	100	12.5	12.5	0.63	2.37	0.91	3.35	0.91
W_d	0.4	100	2.0	2.0	0.63	∞	–	∞	–
W_f	0.08	0.63	∞	0.25	0.86	0.0625	0.80	0.1	0.80

Weighting W_k is applicable to the present study and is for vertical motion of a seated subject.

Also, $\omega_i = 2\pi.f_i$

The principal steps in the weighting procedure are:

1. Read the input acceleration signal into an array either as the result from an aircraft simulation or from an external data file. The sample rate should ideally be greater than 100 Hz to fill the entire width of the low-pass section of the weighting function. If this is not possible, any summary index values computed from the weighted acceleration will be attenuated somewhat if there is significant content in the original signal above half the sample rate.
2. Fit cubic splines through the accelerometer data points and interpolate to a sample rate of 1,280 Hz.
3. Extend a mirror image of the first one-second of the profile in front of the profile as a leader and smooth the leader with a raised cosine multiplier to suppress start-up transients during filtering.
4. Apply the weighting functions in series as explained above.
5. Fit cubic splines through the weighted data record and decimate down to a sample rate of 160 Hz.

The weighting function equations are solved using Runge-Kutta integration. The sample rate is increased from 60 Hz to 1,280 Hz to minimize numerically induced distortions over the frequency range of interest (about 0.02 to 100 Hz). The final sample rate of 160 Hz was selected because the Spinal Response Acceleration Dose index must be computed at a sample rate of 160 Hz and the same rate was used to compute the weighted indices for compatibility. Increasing the sample rate is particularly important in differentiating the input signals. This is illustrated in figures 2 and 3 where the amplitude response for differentiation at a sample rate of 1,280 Hz is shown.

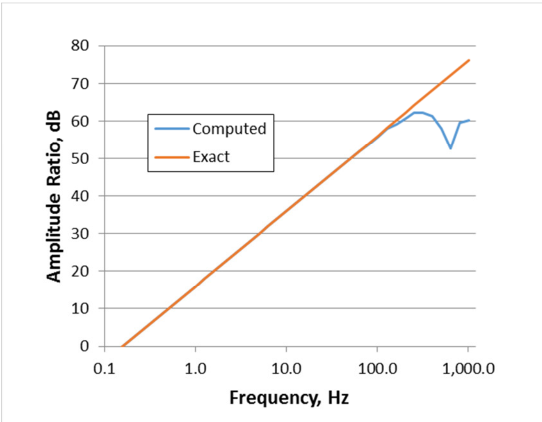

Figure 1. Computed and exact amplitude ratios for first order differentiation.

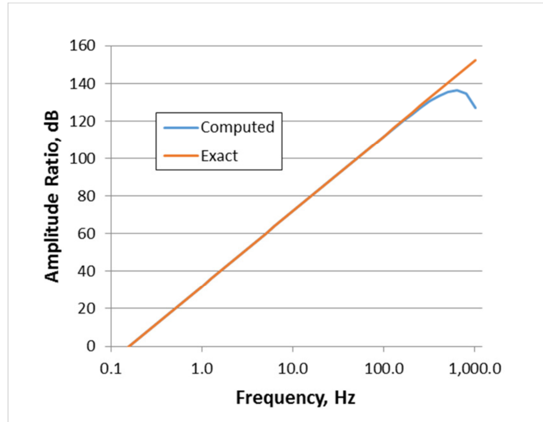

Figure 2. Computed and exact amplitude ratios for second order differentiation.

The overall frequency response, $|H_{\text{Overall}}(f)|$, of the weighting procedure is shown in figure 3. The dashed curve marked "ISO" was produced by direct computation from the frequency transfer functions given above. The solid blue curves marked "FAA implementation" were produced by running unit amplitude sine waves through the weighting function computer program and plotting the amplitudes of the output sine waves. At each frequency, the initial transient was allowed to reduce to a negligible level before measuring the output sine wave amplitude.

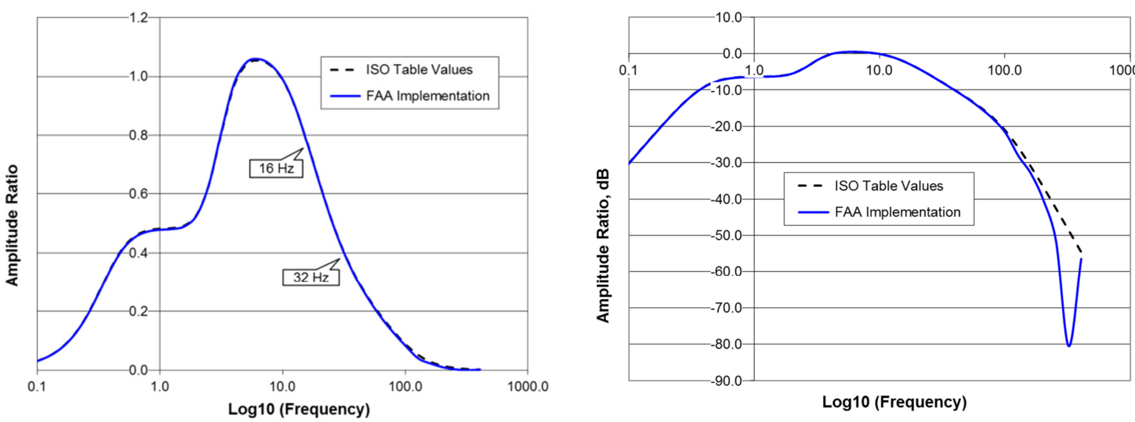

Figure 3. Frequency response of the weighting procedure compared with the ISO specified frequency transfer function for Weighting W_k. Amplitude ratio is plotted on a linear scale, left, and a logarithmic scale, right.

VIBRATION EVALUATION INDICES

Reference 1, ISO 2631-1, also contains procedures for computing indices which can be used to evaluate the effect of human whole-body vibration on human health, comfort, and safety. Three index formulations are defined for evaluating the effects of vibration applied in six degrees of freedom for standing, seated, and recumbent bodies. However, vertical vibration acting on a seated person is the only case of interest in the current work and the description given here of the application of the ISO formulations is for that case only. Part 5 of ISO 2631, reference 3, provides a fourth index for vertical acceleration acting on a seated person, but its implementation is not discussed because of space constraints. The three indices from Part 1 are as follows:

1. Basic evaluation method using weighted root-mean-square (r.m.s.) acceleration.
2. Running r.m.s. method.
3. Fourth power vibration dose method.

The frequency weighting functions must be applied to the raw acceleration signal before calculation of the indices. In addition, a weighted acceleration signal crest factor is defined for determining when the second and third indices should be reported as a supplement to the basic r.m.s method. The applicable section of ISO 2631 is reproduced below in sufficient detail to define the procedure required to calculate each of the indices.

Index Definitions

1. Weighted r.m.s., reproduced from ISO 2631 Part 1, units = m/s^2

$$a_{\mathrm{W}} = \left[\frac{1}{T}\int_0^T a_{\mathrm{W}}^2(t)\,\mathrm{d}t\right]^{\frac{1}{2}}$$

Where

$a_{\mathrm{W}}(t)$ is the weighted acceleration (translational or rotational) as a function of time (time history), in meters per second squared (m/s^2) or radians per second squared (rad/s^2), respectively;

T is the duration of the measurement, in seconds.

2. Running r.m.s. , reproduced from ISO 2631 Part 1, units = m/s^2

$$a_{\mathrm{W}}(t_0) = \left\{\frac{1}{\tau}\int_{t_0-\tau}^{t_0} [a_{\mathrm{W}}(t)]^2\,\mathrm{d}t\right\}^{\frac{1}{2}}$$

The maximum transient vibration value from the running r.m.s., MTVV, is defined as:

MTVV = max[$a_{\mathrm{W}}(t_0)$]

i.e. the highest magnitude of $a_{\mathrm{W}}(t_0)$ read during the complete measurement period (T).

The standard recommends using τ = 1 second, corresponding to an acceleration time constant, “slow,” in sound level meters.

3. Fourth Power Vibration Dose (reproduced from ISO 2631 Part 1, units = m/s$^{1.75}$)

$$\mathrm{VDV} = \left\{ \int_0^T [a_\mathrm{W}(t)]^4 \, \mathrm{d}t \right\}^{\frac{1}{4}}$$

Where

$a_\mathrm{W}(t)$ is the weighted acceleration (translational or rotational) as a function of time (time history), in meters per second squared (m/s^2) or radians per second squared (rad/s^2), respectively;

T is the duration of the measurement, in seconds.

COMPUTER IMPLEMENTATION

Originally, the weighting functions and the evaluation indices were implemented and tested in a standalone computer program written in Microsoft Visual Basic 6. The program is called "ISO Accel Processing." Subsequently, the functions and indices were implemented in a development of the computer program ProFAA, which is a full roughness analysis computer program with significantly more functionality than the ISO Accel Processing program. The development of ProFAA is called ProView and includes the capability to process accelerations generated by the internal aircraft simulation as well as externally generated acceleration signals. In December, 1997, the FAA ran tests with its instrumented Boeing 727-100QC aircraft at a dual-use regional airport. Profiles were measured with the FAA pavement profiler at the same time so that measured aircraft responses could be compared with responses computed with the ProFAA simulation program. A brief review of the full-scale aircraft responses is given, followed by results obtained from running the full-scale and the simulation results through the ISO weighting and index computations.

BOEING 727-100QC AND PROFILER TESTS

The primary test runs made with the instrumented 727 were made on a 10,000-ft-long (3,000 m) runway. The aircraft was turned onto the runway, accelerated to a target speed of 100 knots (168.8 ft/s, 51.4 m/s), held at the target speed for as long as possible, and then decelerated and turned off the runway at the other end. Figure 4 shows a screenshot of the computer program used to read and display the data from the aircraft's data acquisition system and figure 5 shows the speed of the aircraft during the run. The data acquisition sampling rate was 234.4 Hz, giving a signal bandwidth of 117 Hz. The constant speed portion of the acceleration response records was cut out and and saved in text files. During the constant speed tests, the flaps were fully retracted and the spoilers were fully deployed. The runs were made with the left main gear just to the right of the centerline.

Aircraft weight from the computed empty weight and the fuel weight at the start of the run shown in figure 4 was 138,060 lbs (62.6 MT). Small aerodynamic pitch moment and vertical forces were active at the target speed, as can be seen in figure 4. The sum of the main gear forces increases during acceleration and the nose gear force decreases by a lesser amount. The nose gear force at the start of the run was about 15,000 lbs (6.8 MT) and about 7,000 lbs (3.2 MT) at the target speed. The sum of the main gear forces was about 123,000 lbs (55.8 MT) at the start and about 140,000 lbs (63.5 MT) at the target speed.

Within a day of running the aircraft tests, profiles were measured on the same runway with the FAA profiler. The profiles were measured from threshold-to-threshold and recorded at a sampling distance of 25 mm (0.082 ft). The profiles corresponding to the aircraft run used as illustration of the results below were run just to the right of the centerline, 10 ft (3 m) right of the centerline, and 20 ft (6 m) right of the centerline. The right-most profile, named "Profile Right," was used to compute the internal aircraft simulation results shown below.

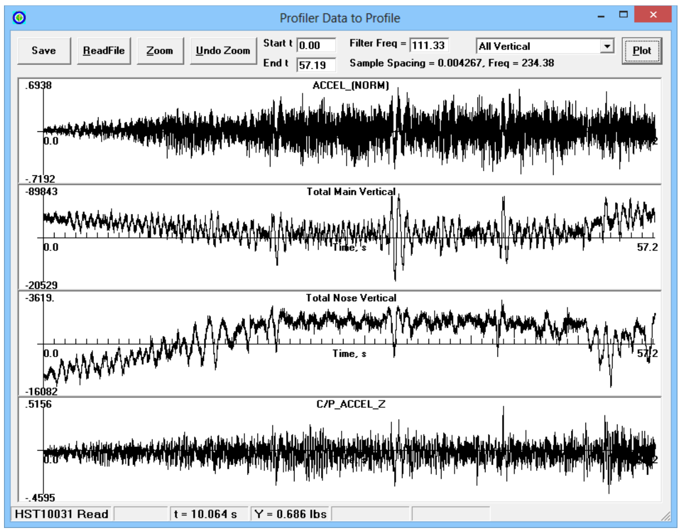

Figure 4. Cockpit and cg accelerations and main gear and nose gear forces measured with the 727-100QC instrumented aircraft.

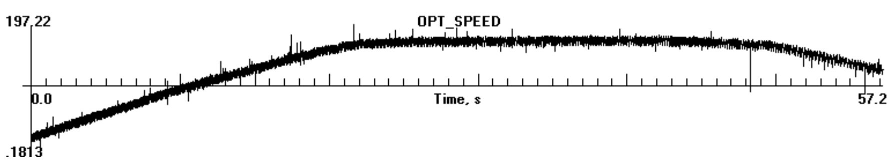

Figure 5. Aircraft speed for the measured responses in figure 4, ft/s.

DISPLAY OF EXTERNAL AND SIMULATION ACCELERATIONS IN PROVIEW

As explained above, ProFAA was originally written to read profiles measured with the FAA profiler and to compute and display profile indices for airport pavement roughness analysis and evaluation. An aircraft simulation function was added to expand the roughness analysis capabilities of the program. With the development of the ISO weighting and index functions for use in a study of subjective roughness evaluation by pilots, the ISO functions have subsequently been added to an updated version of ProFAA called ProView. This allows the acceleration output from the simulations in response to a measured profile to be processed in a standardized manner and the ISO indices to be computed and reported. An additional function has been added to allow independent acceleration records to be read into the program and processed to report weighted ISO index values.

Figure 6 is a screenshot of ProView after reading in a comma-separated file containing the acceleration at the center of gravity shown in figure 4 (ACCEL_(NORM)). The original record is displayed without any processing (Unweighted) in the second picture box from the top and after ISO weighting in the third picture box. Figure 7 shows expanded views of the acceleration records. It can be seen that the weighting has removed some of the high frequency content and considerably reduced the range of the accelerations from -0.688 to 0.725 to -0.382 to 0.431, all in gravity units (g). The effect of the weighting is to provide a standardized way of processing measured accelerations leading to a rational way of comparing peak accelerations obtained from different measurement and processing systems. (Note: Left clicking on any of the picture displays in ProView (or ProFAA) copies the picture to the clipboard. The picture can then be pasted into a document, as was done to produce figure 7.)

The sign convention in figure 4 and in figures 6 and 7 is that forces and accelerations are positive downward. Strut forces acting on the airframe are upward and therefore negative and upward accelerations are also negative.

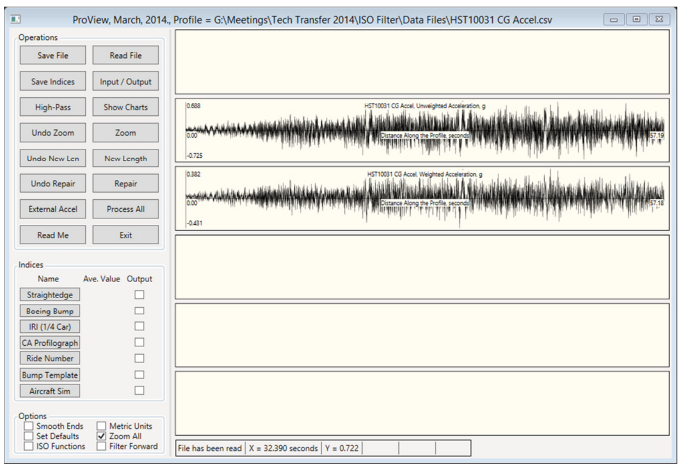

Figure 6. Screenshot of ProView after reading an independent accelerometer record using the "External Accel" function.

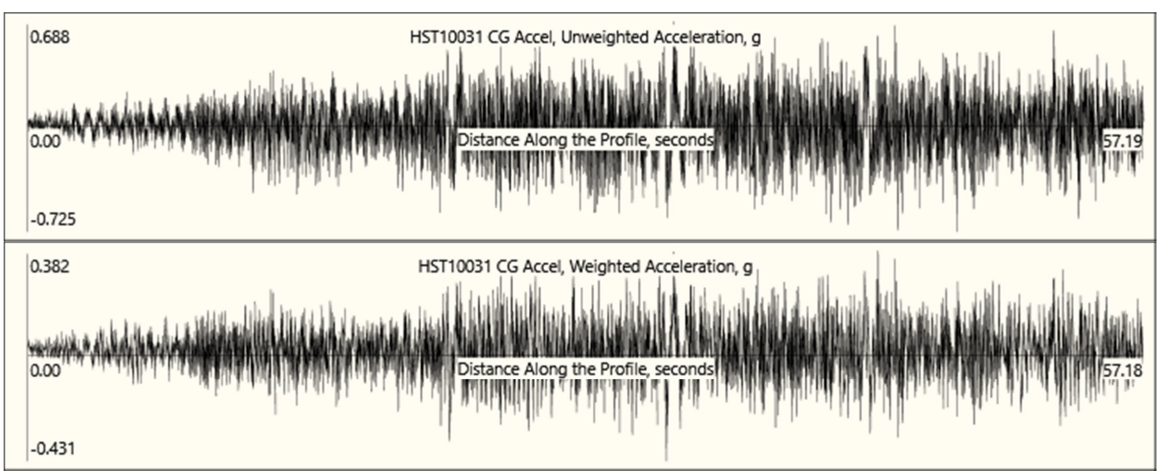

Figure 7. Expanded view of the external acceleration records in figure 6. The upper view is the original record and the lower view is after applying the ISO weighting functions.

When running the aircraft simulation in both ProFAA and ProView a single profile is applied to all of the landing gear in the aircraft being simulated. Appropriate lags are applied where there is a longitudinal offset between the landing gear. These lags are present in the nose gear versus the main gear in all aircraft and also between body and wing gear for the Boeing 747. The measured profile “Profile Right” was selected and used to drive the Boeing 727 aircraft simulation in ProView for comparison with the aircraft results of figure 4. Strut characteristics and flexible mode characteristics are taken from reference 4. In accordance with the discussion given above on the 727 test, the gross weight of the simulated 727 was set at 138,000 lbs (62.6 MT) and the static weight on the main gear was set at 0.9 times the gross weight. The wheelbase was set at 53.25 ft (16.23 m) and the pitch moment of inertia about the cg was set at 2.59×10^{6} slug-ft^{2} (3.512×10^{6} kg-m^{2}). In contrast with the full-scale test run, the simulation was run at a constant speed over the full length of the profile. Aerodynamic forces are evident in the full-scale test run at the target speed, as noted above. A constant upward force of 8,000 lbs (3.63 MT) was applied to the airframe at the nose gear location and constant downward forces of 8,500 lbs (3.86 MT) were applied to the airframe at the location of the two main gears to adjust the gear forces in the simulation to approximately match the strut forces measured in the full-scale test results.

Figure 8 is a screenshot of ProView showing the output of the 727 simulation in response to the profile at a speed of 100.8 knots (170.1 ft/s, 51.9 m/s). The order of the displays from top to bottom is: profile, cg acceleration; cockpit acceleration; nose gear force; main gear force at one gear.

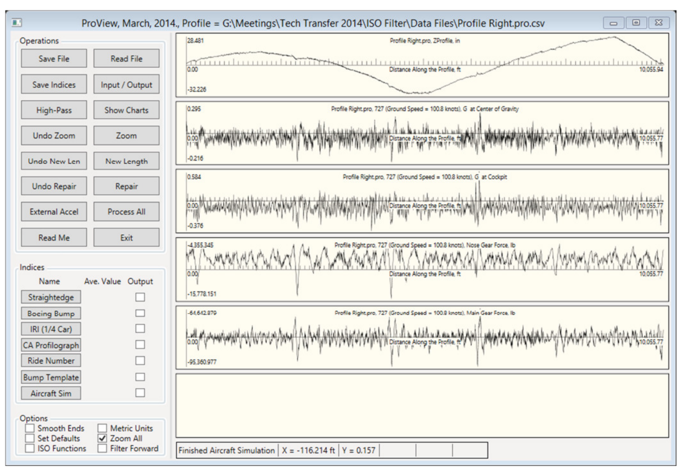

Figure 8. Screenshot of ProView after running “Aircraft Sim” on the “Profile Right” profile.

In order to compare the measured and simulation results using ProView, the measured acceleration record was reduced in length to include only the section where aircraft speed was approximately constant (see figure 5). This section ran from 21.0 to 49.5 seconds in the original record. Average speed over the isolated section was 100.8 knots (170.1 ft/s, 51.9 m/s). For the simulation accelerations, the displays in ProView were zoomed over a distance which gave the best correspondence with the measured acceleration record (considering that speed was not exactly constant over the measured record) after running the simulation over the full length of the profile. The zooming distance was from 4,100 ft (1,250 m) to 8,950 ft (2.728 m).

Figure 9 shows the weighted cg accelerations from the external file and the simulation responses for the shortened record lengths as described above. Three roughly matching disturbances are evident in the records: one at the start; one close to the middle; and a third about three-quarters along the record. The disturbance at the start does not closely match in time because the largest deviation from constant speed for the external acceleration occurs at the start of the record. Despite having applied the weighting functions, there is still considerable high frequency content in both records which obscures the shape of the lower frequency disturbances. Therefore, both records were further low-pass filtered at 10 Hz to remove most of the high frequency content, as shown in figure 10.

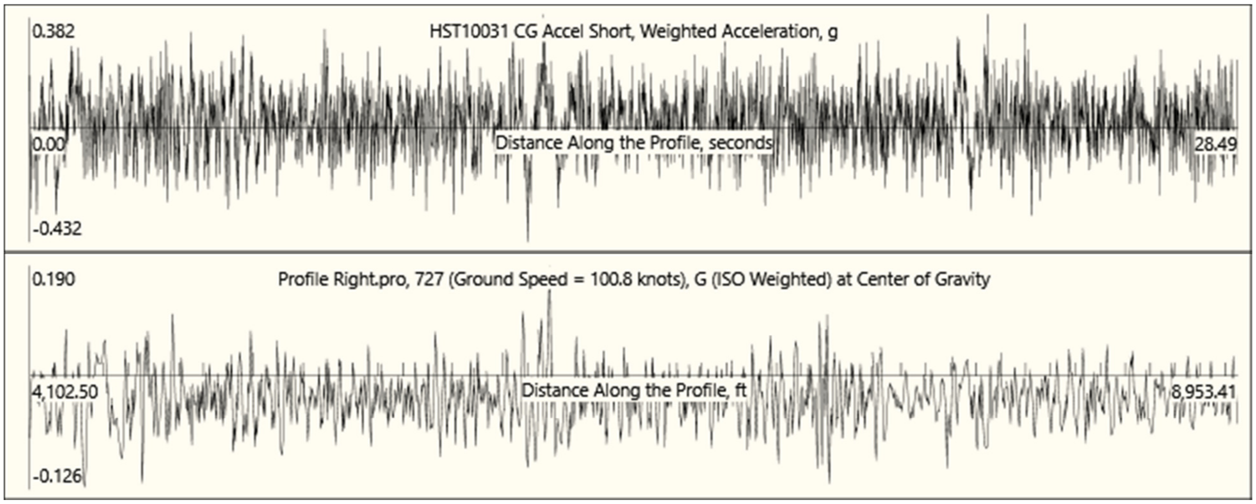

Figure 9. View of weighted cg accelerations from the external file (top) and the simulation response (bottom).

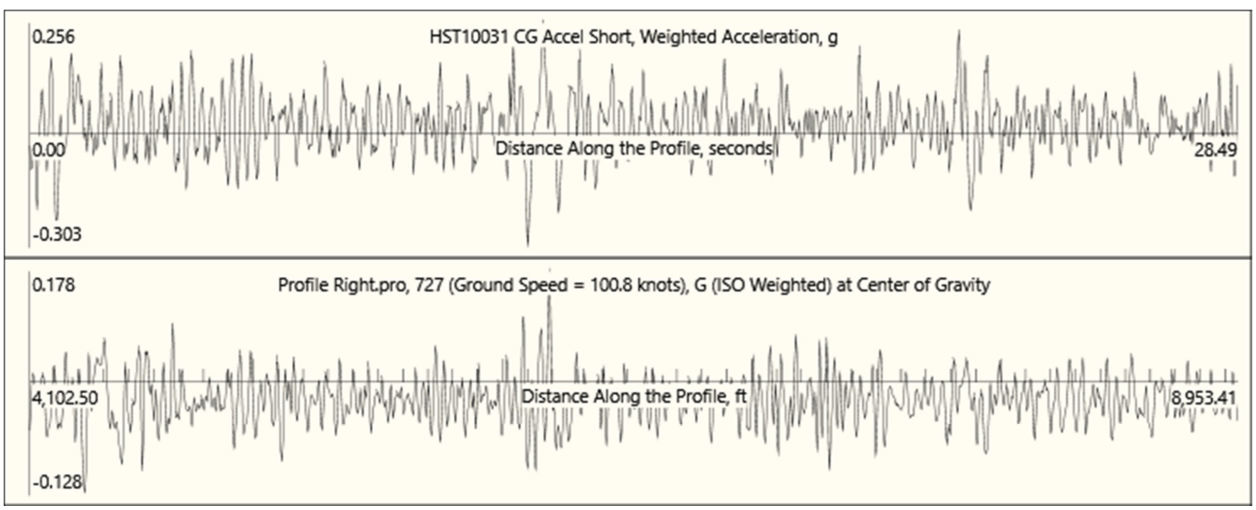

Figure 10. View of the weighted cg accelerations in figure 9 after low-pass filtering at 10 Hz.

It is clear from figures 9 and 10 that it is very difficult to make a numerically based comparison between the measured and simulation results from the time histories alone. Although it is also clear that the effects of three significant disturbances in the pavement profile are identified by both of the acceleration records (full-scale and simulated) as shown in figure 11, where the simulated cg acceleration with all of the flexible modes suppressed is plotted above the Boeing Bump Index computed from the profile (also compare with figure 10). (All other simulation results were obtained with 10 flexible modes ranging in natural frequency from 2.4 to 15.0 Hz). Bearing in mind the very large number of parameters needed to describe aircraft response to pavement disturbances, a more reasonable approach might be to combine averaging over time using, for example, the ISO indices, and averaging over frequency using spectral analysis.

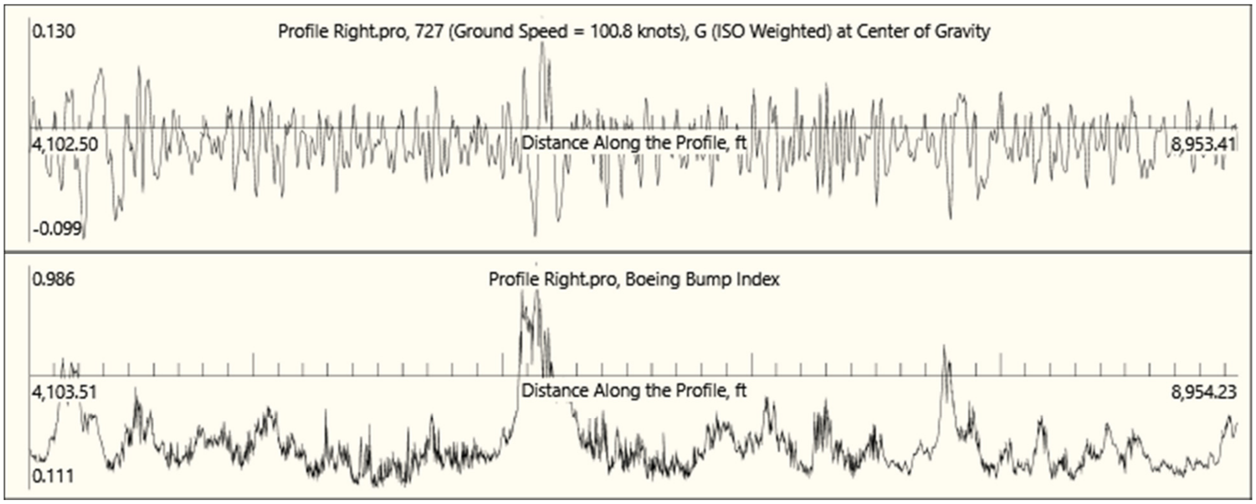

Figure 11. Simulation cg acceleration filtered at 10 Hz and with all of the flexible modes suppressed (top) and the Boeing Bump Index computed from the profile (bottom).

The functionality in ProView for computing and displaying the ISO indices is illustrated below. A spectral analysis module is included in ProFAA and ProView, but its functionality is currently hidden in both programs and space does not allow its illustration. Additionally, the use of time-averaged indices is by far the most common way of reporting pavement roughness.

COMPUTATION OF THE ISO INDICES WITH PROVIEW

Whenever the “ISO Functions” checkbox is checked in ProView, all of the ISO indices are computed according to the standard and the results are displayed through the use of a window activated with the “Show Charts” button. A header can also be included in the external acceleration csv file and in the profile csv file to define sections over which the indices should be computed. (To read in profile records, ProView accepts csv text files as well as the binary formatted ProFAA pro files.) One of the lines in the headers is reserved to read in the boundary values of the desired sections. The units are seconds for external acceleration files and feet for profile files. The following headers were used to compute the index values for the records used in previous sections:

External Acceleration File

```
sample,0.004266667 `                          = sample spacing, seconds
sections,0.0,5.29,11.17,17.05,22.93,28.5 ` = section boundaries, seconds
0.14209 `                                     = first acceleration sample, g
```

Profile File

```
0.082021 `                                    = sample spacing, ft
122603 `                                      = number of samples
```

```
0.0,4100,5000,6000,7000,8000,8950,11000 `  = section boundaries, ft
0.00000 `                                  = first acceleration sample, g
```

The section boundaries have to increase in sequence, but they do not have to increase in equal increments. If the last section boundary is greater than the record length, then it will be adjusted by the program to be equal to the record length.

For the external acceleration record shown in figure 9, the “Show Charts” window provides the following output:

```
Summary of External Acceleration Data File Properties
Original accel data file    = G:\Tech Transfer 2014\HST10031 CG Accel Short.csv
Total length of record      = 28.5 seconds
Original record step length = 0.004267 seconds
Weighted record step length = 0.006250 seconds

ISO Weighted acceleration computed over the full length of the profile.
 Units       Min          Max          RMS
   g      -0.43201     0.38166     0.10740
 m/s^2    -4.23654     3.74285     1.05326

ISO Index values computed over the full length of the profile.
  Type     RMS    Crest Factor     MTVV        VDV     Spinal Dose
 Index   1.05326     4.02231     1.53650    11.45834     4.92287

External acceleration summarized over each profile section.
Section  Length     RMS     Average     Max
  No.   seconds      g         g         g
   1        5.3   0.12088  -0.00242   0.31773
   2        5.9   0.09850  -0.00077   0.32825
   3        5.9   0.11205  -0.00049   0.38114
   4        5.9   0.10787   0.00061   0.38166
   5        5.6   0.09610   0.00000   0.34822

Weighted acceleration ISO Index values, m/s^2, computed over each profile section.
Section  Length    RMS     Crest     MTVV     VDV    Spinal
  No.   seconds           Factor                      Dose
   1        5.3  1.18564  2.92801  1.30262  8.17041  3.84819
   2        5.9  0.96604  3.35132  1.13662  7.08449  3.07914
   3        5.9  1.09881  3.85557  1.53650  8.19554  4.37916
   4        5.9  1.05786  3.53813  1.37284  7.69574  3.46132
   5        5.6  0.94245  3.62345  1.14813  6.83341  3.13895
```

And for the aircraft simulation acceleration output record shown in figure 9, the “Show Charts” window provides the following output:

```
Summary of Aircraft Response
Aircraft type = 727
Aircraft speed = 170.1 ft/s = 100.8 knots
Profile file = G:\Tech Transfer 2014\Profile Right.pro.csv
Profile total length = 10,055.8 ft
Profile decimated distance step length for simulation = 0.8202 ft
Simulation time step length = 0.004822 seconds
GroundNInner = 2
Simulation inner time step length = 0.002411 seconds

Center of gravity (Gcg) and cockpit (Gcp) accelerations, gravity units.
Gcg and Gcp are ISO weighted. They are summarized over the full length of the profile.
Location        Min          Max         RMS
```

```
   cg        -0.13573     0.18987     0.03361
 cockpit     -0.26376     0.38369     0.06775

Vertical landing gear forces, lb, summarized over the full length of the profile.
  Location         Min         Max       Average
    nose          -9,973      -3,470       5,863
    main         -85,401     -56,364      70,649

ISO Index values, m/s^2, computed over the full length of the profile.
Location   RMS     Crest Factor    MTVV        VDV     Spinal Dose
   cg    0.32960     5.64941     0.69563     4.60844     1.92944
 cockpit 0.66440     5.66333     1.56039     9.49240     3.55373

Aircraft responses summarized over each profile section.
Gcg and Gcp, gravity units, are ISO weighted.
Section  Length   Gcg RMS   Gcp RMS   Gcg Min   Gcp Min     Nose     Main
  No.      ft                                             Ave, lb   Ave, lb
   1      4,100   0.03327   0.06939  -0.13573  -0.26376     5,856    70,585
   2        901   0.04152   0.06732  -0.12626  -0.22734     5,926    70,821
   3      1,001   0.02867   0.05827  -0.08124  -0.21624     5,854    70,691
   4      1,001   0.03891   0.08234  -0.09920  -0.24541     5,858    70,715
   5      1,001   0.03596   0.06977  -0.11782  -0.20971     5,833    70,673
   6        951   0.02594   0.04977  -0.06071  -0.15814     5,824    70,527
   7      1,102   0.03007   0.06682  -0.09198  -0.20223     5,913    70,732

Weighted Gcg ISO Index values, m/s^2, computed over each profile section.
Section  Length    RMS      Crest     MTVV     VDV    Spinal
  No.      ft              Factor                      Dose
   1      4,100  0.32626  4.07976  0.57782  3.58505  1.62909
   2        901  0.40716  3.04101  0.57304  2.90921  1.69604
   3      1,001  0.28102  3.18778  0.35447  2.07150  0.99735
   4      1,001  0.38177  4.87743  0.69563  3.28579  1.26447
   5      1,001  0.35267  3.27606  0.47461  2.62233  1.08225
   6        951  0.25443  2.76350  0.32376  1.77851  0.77415
   7      1,102  0.29406  3.37327  0.39164  2.16214  1.15868

Weighted Gcp ISO Index values, m/s^2, computed over each profile section.
Section  Length    RMS      Crest     MTVV     VDV    Spinal
  No.      ft              Factor                      Dose
   1      4,100  0.68050  3.80095  1.33736  7.49673  3.32203
   2        901  0.66053  3.37522  0.91960  4.74002  2.29200
   3      1,001  0.57181  3.70850  0.86700  4.43713  2.28635
   4      1,001  0.80755  4.65939  1.56039  7.29391  2.36187
   5      1,001  0.68437  3.00505  0.80138  4.99758  2.12137
   6        951  0.48791  3.17854  0.64262  3.44902  1.63731
   7      1,102  0.65515  3.02705  0.77552  4.66564  2.06620
```

Table 2 summarizes the cg and cockpit ISO weighted RMS results for the full-scale and simulated acceleration records. (So far, the cockpit acceleration records have not been discussed, but the processing was exactly the same as described for the cg accelerations.)

Table 2
Summary of ISO weighted acceleration results, the rms units are m/s^2.

Section Number	cg weighted rms acceleration			cockpit weighted rms acceleration		
	Full-Scale	Simulation	Ratio	Full-Scale	Simulation	Ratio
1	1.18	0.41	2.87	1.07	0.66	1.62
2	0.97	0.28	3.46	0.72	0.57	1.26
3	1.09	0.38	2.87	0.87	0.81	1.07

4	1.05	0.35	3.00	0.73	0.68	1.07
5	0.94	0.25	3.76	0.66	0.49	1.35

CONCLUSIONS

A procedure is described which can be used to evaluate vertical aircraft accelerations according to an international standard which is based on the characteristics of human response to vibration. The procedure promises to improve the ability to compare accelerations produced from different sources and with different data processing characteristics. A computer implementation of the procedure is described with examples from a computer program designed for roughness analysis of airport pavement profiles and which includes an aircraft simulation. Comparisons are made between accelerations measured with a full-scale test aircraft and accelerations produced by the aircraft simulation. Poor correlations between the two are obtained for accelerations at the center of gravity, but good correlations between the two are obtained for accelerations at the cockpit. The true fidelity of the simulation method cannot be decided without further work which includes spectral analysis and a parametric sensitivity study.

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