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Aircraft Cockpit Ride Quality in Ground Maneuvers

Accelerometer Analysis Procedures and Preliminary Results

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OBJECTIVES OF THE STUDY

- Develop a rating scale for pilot’s subjective response to vertical cockpit vibrations excited by longitudinal pavement surface elevation disturbances.
- The scale to range from very smooth to exceedingly rough.
- Incorporate the rating scale in the ProFAA computer program as criteria for establishing limits of allowable roughness.
- Provide roughness condition input for airport pavement management systems.

USE A FULL-MOTION SIMULATOR INSTEAD OF OPERATIONAL AIRPLANES

- For:
  - Repeatable test conditions.
  - Can rapidly change profiles and test parameters.
  - Lowest cost for a realistic setting.
  - Safety.
- Against:
  - Concerns about fidelity of simulator response.

STUDY BEING DONE ON THE FAA'S FULL-MOTION 737 SIMULATOR IN OKLAHOMA CITY (AFS-450)

PROCEDURE FOR STUDY

1. Load selected elevation profile into simulator computer.
2. Run the simulator at constant speed for 30 seconds (20 knots for taxiway and 100 knots for runway).
3. Measure and record vertical cockpit acceleration.
4. The crew rates the vertical acceleration response on a scale of 0 (roughest) to 10 (smoothest).

PROCEDURE FOR STUDY (continued)

5. Repeat with more profiles covering a wide range of pavement roughness.
6. Repeat with more crews.
7. Process the measured acceleration records to produce an objective index value for each of the simulator runs.
8. Determine a correlation between pilot subjective response (0 to 10) and objective index value.

89 PROFILES MEASURED WITH THE FAA PORTABLE PROFILER

36 Asphalt Runways

24 Asphalt Taxiways

15 Concrete Runways

14 Concrete Taxiways

PROCESSING FOR COMPUTATION OF THE OBJECTIVE INDEX VALUES

- The measured acceleration records should be filtered in a defined manner for broad application outside the present study parameters.
- The function(s) used to compute the index values should:
  - be widely recognized as being suitable for representing human response to vertical vibration.
  - Capable of accounting for shocks.

IMPLEMENTED THE ISO ACCELERATION PROCESSING AND INDEX FUNCTIONS

INTERNATIONAL STANDARD

ISO 2631-1

Second edition
1997-05-01

Corrected and reprinted
1997-07-15

Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration —

Part 1:
General requirements

INTERNATIONAL STANDARD

ISO 2631-5

First edition
2004-02-15

Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration —

Part 5:
Method for evaluation of vibration containing multiple shocks

ISO STANDARDS 2631-1 AND 2631-5

- ISO 2631-1 includes clearly defined procedures for:
  - Filtering the acceleration record so that the resulting signal is weighted to be representative of human response.
  - Computing objective index values by three methods of increasing sensitivity to shocks.
- ISO 2631-5 includes a clearly defined procedure for simulating spinal response to vertical accelerations.

ISO 2631-1 WEIGHTING FUNCTION

- The filter for weighting the acceleration signal is implemented as a set of four differential equations defined by their frequency response functions.

High Pass

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

Low Pass

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

Acceleration-Velocity Transition

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

Upward Step

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

SOLUTION OF THE WEIGHTING FUNCTION DIFFERENTIAL EQUATIONS

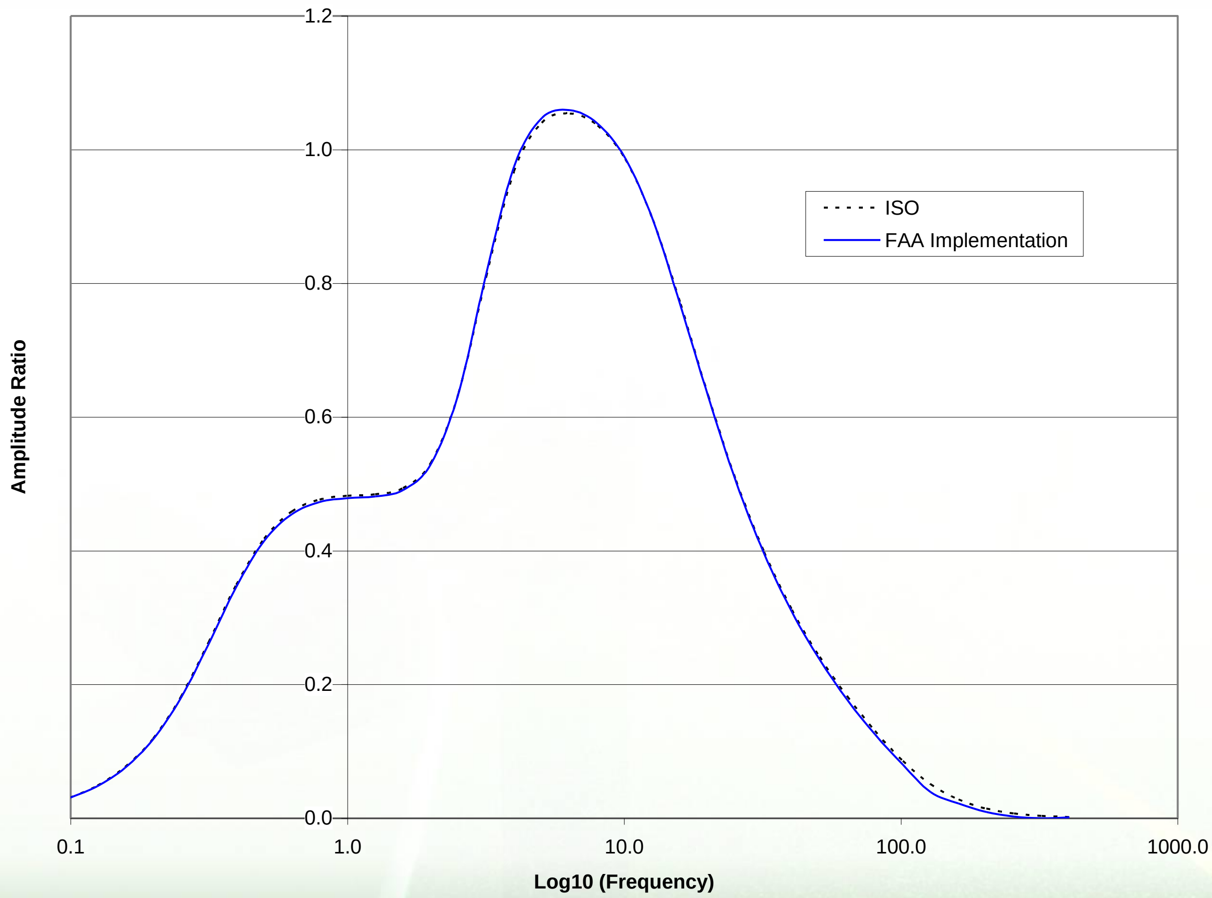
1. Increase the accelerometer sample rate from 60 Hz (as digitized by the simulator) to 1280 Hz by interpolating a cubic spline fit through the samples.
2. Multiply the first second of the record with a raised cosine to suppress startup transients.
3. Solve the differential equations in sequence using a fourth order Runge-Kutta procedure.

SOLUTION OF THE WEIGHTING FUNCTION DIFFERENTIAL EQUATIONS (continued)

4. Decrease the sample rate to 160 Hz with a spline fit in reverse.

- The sample rate is first increased so that the numerical solution of the equations does not excessively distort the frequency response of the solution over the frequency range of interest.
- A final sample rate of 160 Hz was selected to be compatible with the spinal response simulation in ISO 2631-5.

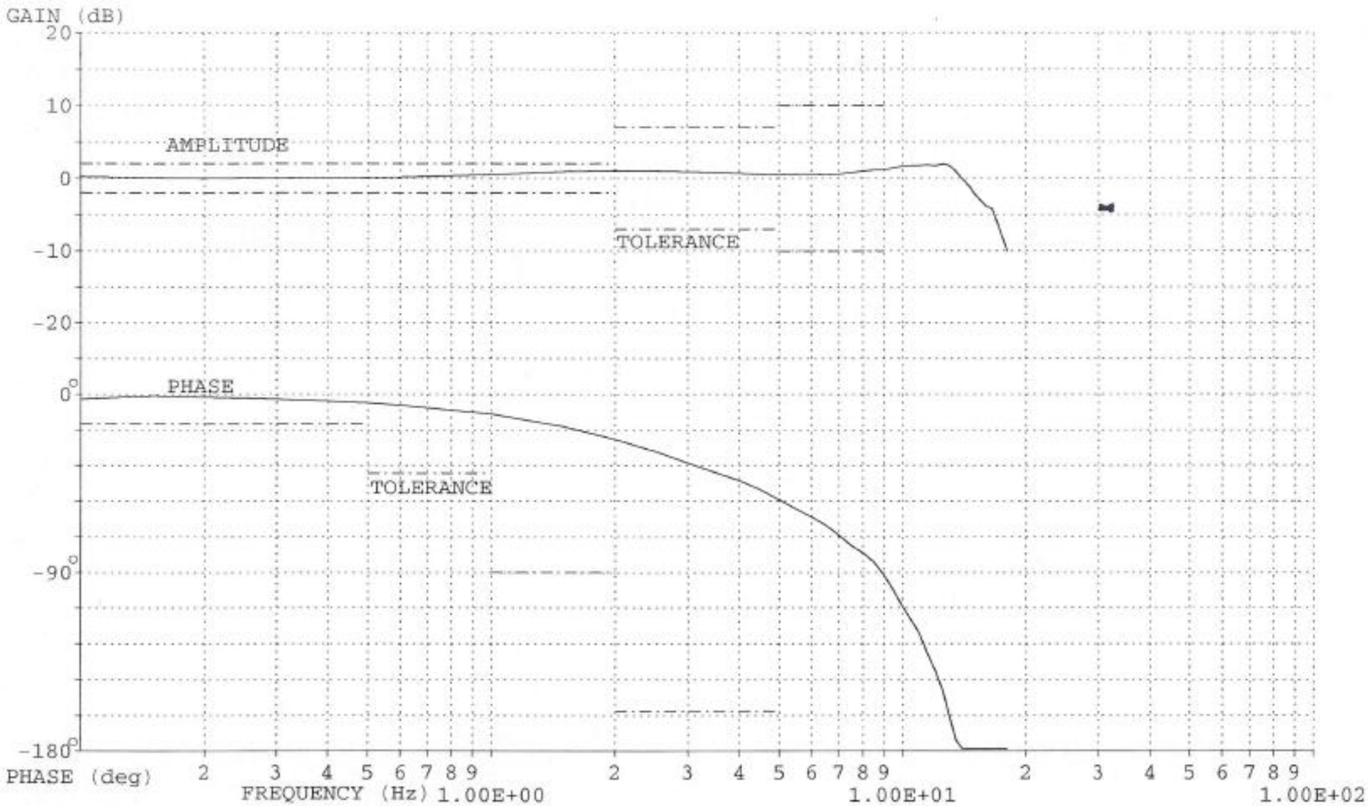
ISO ACCELERATION WEIGHTING FUNCTION FREQUENCY RESPONSE



The curve marked "ISO" was produced by direct computation from the frequency transfer functions in ISO 2631-1 shown on slide 12.

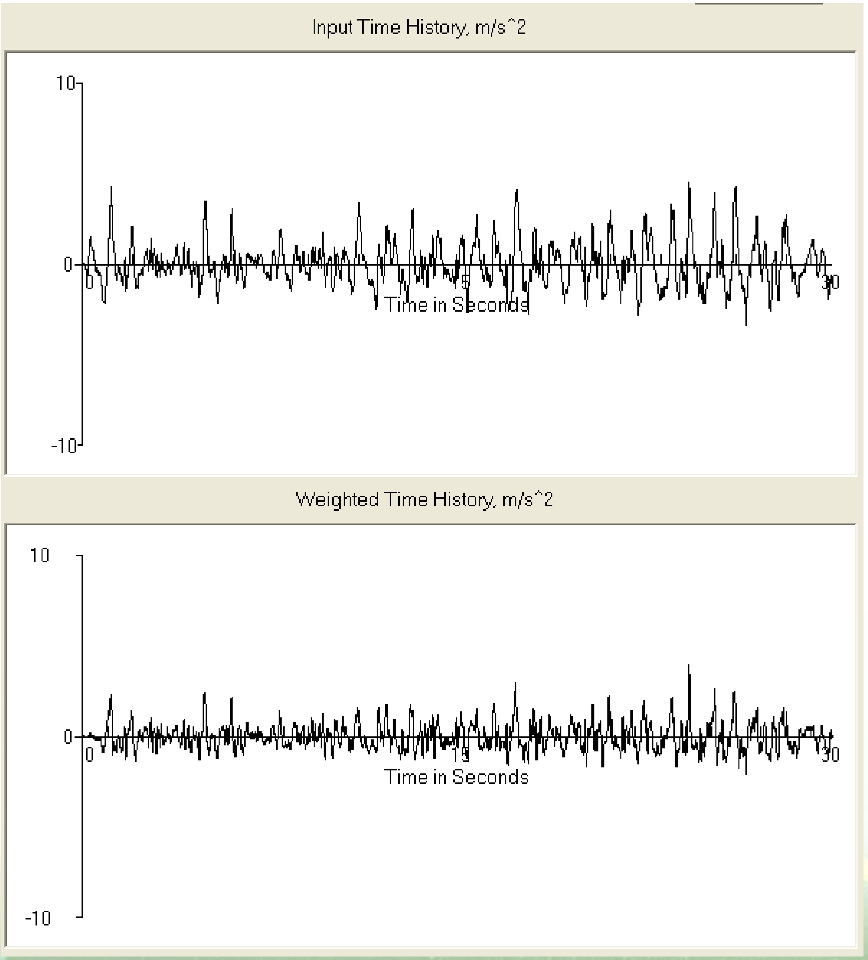
The curve marked "FAA implementation" was produced by running unit amplitude sine waves through the filter and plotting the amplitudes of the output sine waves.

SIMULATOR FREQUENCY RESPONSE ON THE ACTUATORS



MOTION SYSTEM FREQUENCY RESPONSE		
Oklahoma 15-Jun-2010 23:22:11	Printed on : 06-Jan-2011, 17:51:43	Test axis : [vertical]
Airline/Operator : FED Aviation B737NG		Simulator : B737-800 FFS
Reference : 4.3.A		Page 1 of 1

VISUAL BASIC COMPUTER PROGRAM FOR ISO COMPUTATIONS



ISO 2631-1 OBJECTIVE FUNCTIONS

Weighted Root Mean Square

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)\, dt \right]^{\frac{1}{2}}$$

where

$a_w(t)$ is the weighted acceleration (translational or rotational) as a function of time (time history), in metres per second squared (m/s^2) or radians per second squared (rad/s^2), respectively;

T is the duration of the measurement, in seconds.

ISO 2631-1 OBJECTIVE FUNCTIONS (continued)

Running Root Mean Square, τ = 1 second

$$a_W(t_0) = \left\{ \frac{1}{\tau} \int_{t_0 - \tau}^{t_0} \left[a_W(t) \right]^2 \, dt \right\}^{\frac{1}{2}}$$

The maximum transient vibration value, MTVV, is defined as

$$\text{MTVV} = \max \left[a_W(t_0) \right]$$

i.e. the highest magnitude of $a_W(t_0)$ read during the measurement period (T in 6.1).

Fourth Power Vibration Dose

$$\text{VDV} = \left\{ \int_0^T \left[a_W(t) \right]^4 \, dt \right\}^{\frac{1}{4}}$$

ISO 2631-5 OBJECTIVE FUNCTION

- Simulation of compression in the lumbar region of the spine.
- A MATLAB program is provided for running the simulation. Translated into Visual Basic for the FAA implementation.

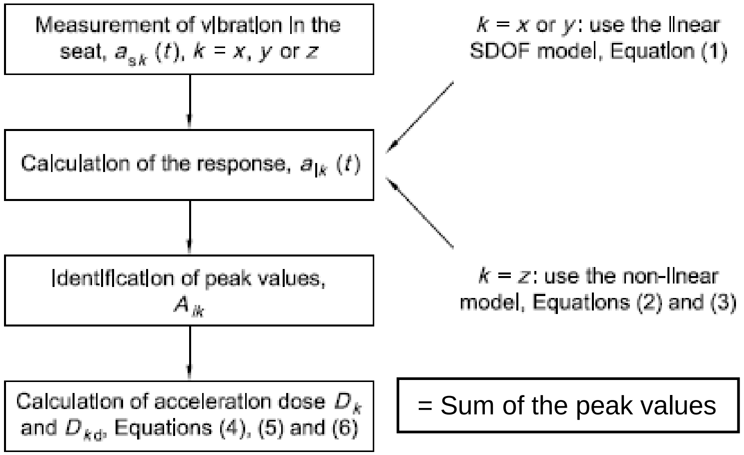


Figure 1 — Flowchart for acceleration dose calculation

ISO 2631-5 OBJECTIVE FUNCTION

5.2.3 Spinal response in vertical direction (z-axis)

In the z-direction, the spinal response is non-linear and is represented by a recurrent neural network model.

The basis for this modelling technique is discussed in Annex C. Lumbar spine z-axis acceleration, a_{lz}, in metres per second squared, is predicted using the following equations:

$$a_{lz}(t) = \sum_{j=1}^{7} W_j u_j(t) + W_8 \quad (2)$$

$$u_j(t) = \tanh\left[\sum_{i=1}^{4} w_{ji} a_{lz}(t-i) + \sum_{i=5}^{12} w_{ji} a_{sz}(t-i+4) + w_{j13}\right] \quad (3)$$

The model coefficients in Equations (2) and (3) are specific to a sampling rate of 160 per second. Therefore, data collected at a different sampling rate shall be resampled to 160 samples per second.

5.3 Calculation of acceleration dose

The acceleration dose, D_k, in metres per second squared, in the k-direction is defined as

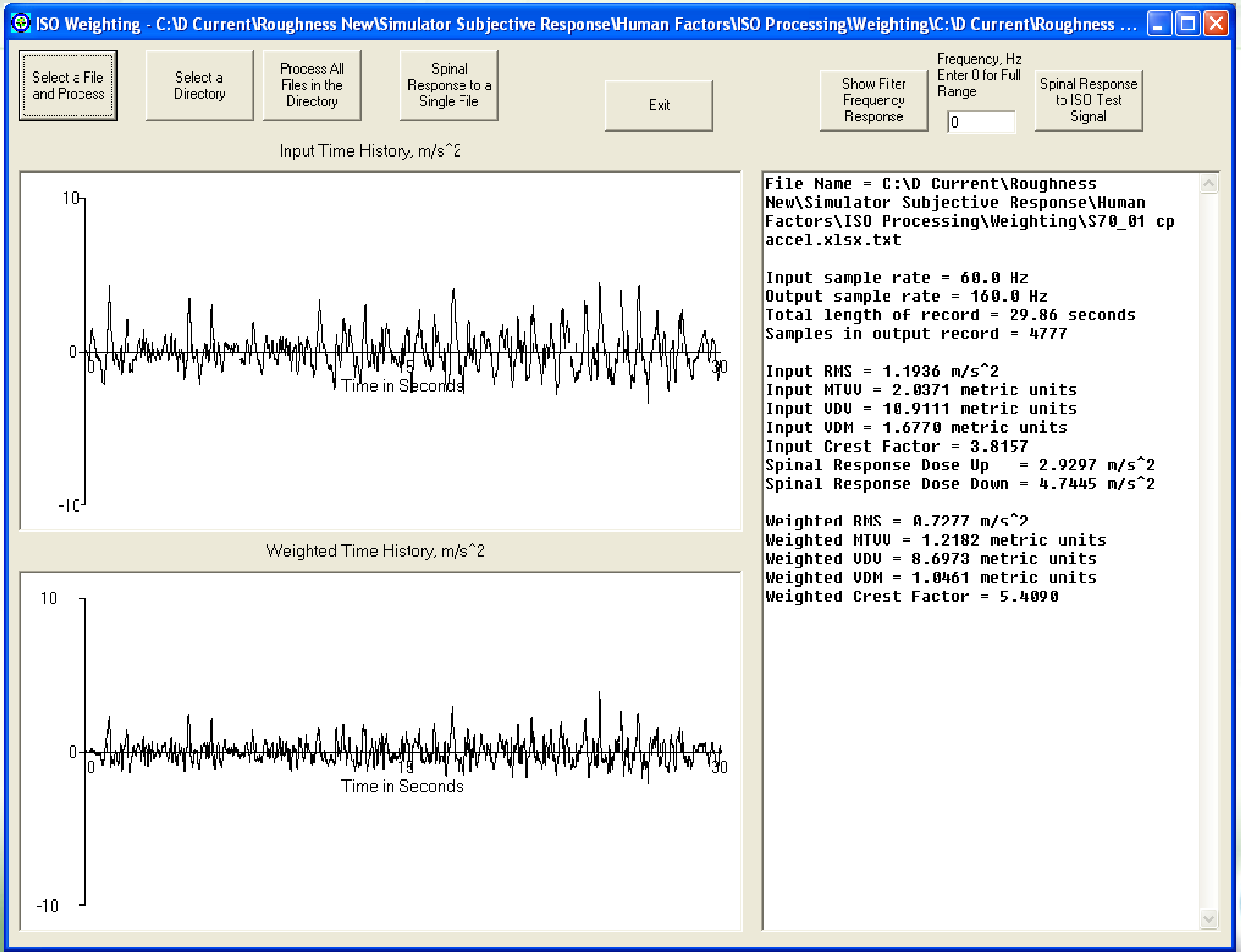
$$D_k = \left[\sum_i A_{ik}^6\right]^{1/6}$$

where

A_{ik} is the i^{th} peak of the response acceleration $a_{lk}(t)$;

$k = x, y$ or z.

VISUAL BASIC COMPUTER PROGRAM FOR ISO COMPUTATIONS



DECEMBER 2010: SIMULATOR DATA COLLECTION #4

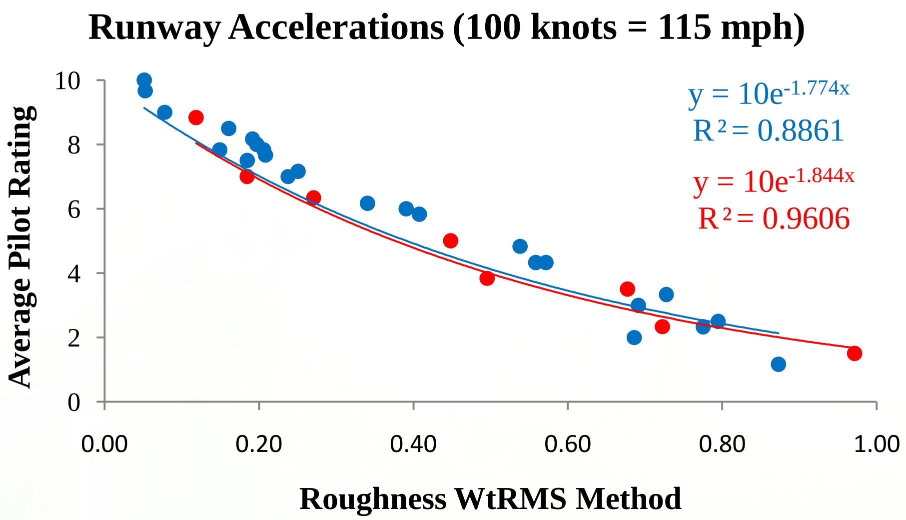
- 3 Pilots – 2 Sessions (64 Scenarios Each).
- 128 Scenarios Total.
- 32 Runway and 32 Taxiway:
  - 24 Real World profiles.
  - 8 Generic profiles (sum of random amplitude sine waves).

SIMULATOR DATA COLLECTION #4 (continued)

- 4 objective cockpit acceleration index methods (ISO 2631)
  - WtRMS Weighted RMS
  - WtMTVV Weighted Maximum Transient Vibration Value
  - WtVDV Weighted Vibration Dose Value
  - DK Acceleration Dose
- Analysis:
  - Part I: Mathematical model of rating versus acceleration index.
  - Part 2: Correlation (strength and direction of relationship).

RUNWAY ANALYSIS

- Real World (n=24) and Generic (n=8) were compared for Runways

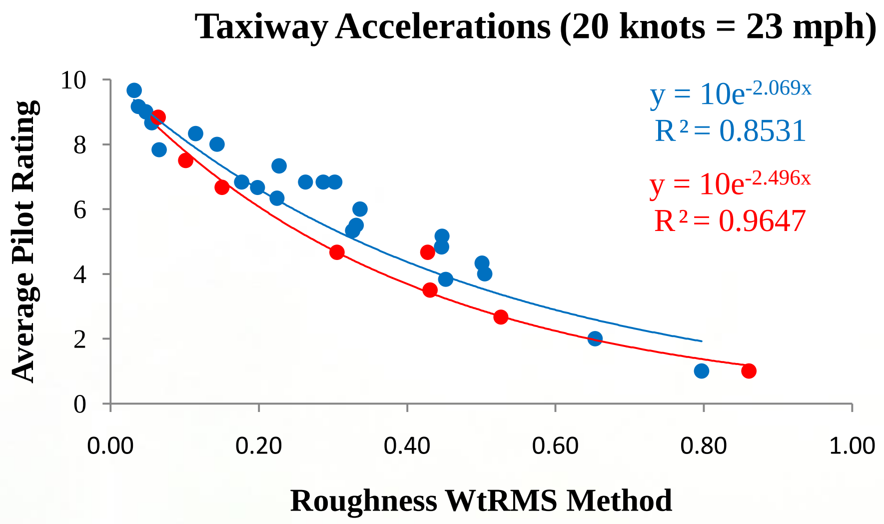


- R^2 was also computed for other roughness methods:

WtMTVV	.9089	.9204
WtDVM	.9310	.9396
DK	.9139	.9549

TAXIWAY ANALYSIS

- Real World (n=24) and Generic (n=8) were compared for Taxiways



- R^2 was also computed for other roughness methods:

WtMTVV	.8931	.8868
WtDVM	.9242	.9686
DK	.8512	.9223

PHASE II STUDIES

- Preliminary Study Late 2011
  - Panel Size - 12 pilots
  - 4 Simulator sessions, 3 pilots per session
  - Each pilot will rate 80 roughness profiles (20 each real-world and generic taxiways and runways)

- Full Study Early 2012
  - Panel size - 36 pilots
  - 12 Simulator sessions, 3 pilots per session
  - Each pilot will rate 80 roughness profiles (20 each real-world and generic taxiways and runways)

FUTURE WORK

- Run supplementary panel rating tests on the FAA's A330/340 full-motion simulator.
- Develop a methodology for computing cockpit acceleration on measured profiles using the aircraft simulation models in ProFAA and converting to a roughness index based on the simulator panel rating test results.
- Develop roughness index criteria for triggering activities such as pavement resurfacing.

FUTURE WORK (continued)

- Measure aircraft response to roughness using the FAA’s Boeing 727-100 ground testing aircraft for comparison with the 737 simulator and ProFAA simulation models.

MORE INFORMATION

- http://www.aiporttech.tc.faa.gov
- gordon.hayhoe@faa.gov or albert.larkin@faa.gov for copies of the computer programs.