ASSESSMENT OF AIRCRAFT'S VERTICAL RESPONSES TO DEVELOP THE ROUGHNESS EVALUATION INDEX FOR AIRPORT PAVEMENT

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AIRPORT PAVEMENT ROUGHNESS

Roughness of airport pavement has long been recognized as the main factor affecting the rideability of aircrafts since rough pavement will induce excess vibrations at aircrafts. In addition, pilots will not be able to read instruments accurately while taking off and it will cause metal fatigue problems for aircraft. The dynamic response of an aircraft to pavement roughness will result in an increase in pavement loading and accelerated pavement deterioration.

Although it is an important subject, unlike highway pavements, not too many studies have been conducted in the past. The main differences regarding the roughness problems of airport and highway pavements are conveyance-related and are listed below. Since there are so many differences, airport and highway pavement roughness studies should be treated as different issues.

- Structures: Aircraft are normally composed of two wings, several engines, one vertical tail, two tail planes, and a cabin body. The aircraft structures are supported by nose and main gears. All the gears are symmetrical to the moving direction only. However, highway vehicles have several sets of tires and suspension systems. Each set can be treated as a quarter-car (QC). That's totally different from aircraft.
- Moving speeds: Aircrafts usually taxi on airport taxiway and apron at speeds less than 20 knots (36 km/hr). While taking off or landing, the speed range is from 0 to almost 200 knots (360 km/hr). Highway vehicles usually maintain constant speeds ranging from 40 to 100 km/hr on the roads. The traveling speed range of aircrafts is larger.
- Dynamics of moving: The design of aircraft structures allow them to take off or land safely and fast while on the runways, and to keep flying while in the sky. For safety concern, the design purpose of highway vehicles is stability traveling at high speeds. The dynamics of their moving are different.

Earlier airport pavement roughness studies can be traced back to 1960's. In 1967, the National Aeronautics and Space Administration (NASA) established an airport pavement roughness evaluation procedure using an aircraft's vertical acceleration at the cockpit, setting the maximum acceptable acceleration to be 0.4 g (*1*). Lee and Scheffel developed a relationship between aircraft gross weight and resonant frequency in 1968 (*2*). The study also showed that aircraft traffic will worsen pavement roughness, and passengers in aircraft of different models on the same pavement will experience different ride quality.

In 1970's, Gerardi et al. conducted a series of studies to develop a rigid-body aircraft model to simulate the vertical acceleration at the pilot's station and at the center of gravity of aircraft, as well as pavement loading at main and nose gears (*3, 4, 5*). That model has degrees of freedom on pitch, roll, vertical and horizontal translation and it was verified with the field data gathered from KC-135, B-52, F-4C, and C-141. The model was further implemented to become the commercialized software, APRas (Airport Pavement Roughness assessment software). APRas is the only airport pavement roughness evaluation software and has been widely accepted internationally.

Although many studies have been conducted to develop the evaluation criteria and procedures of airport pavement roughness, there are still no widely accepted methods to assess airport pavement roughness. Boeing Company has developed an evaluation procedure based on the bump height/length analysis (*6*), but the varying importance of bumps with different wave lengths was not considered. In highway pavement roughness research (*7*), the wave length of pavement profile has been proven to be a factor affecting an automobile's vertical response. The widely-used International Roughness Index (IRI) was developed based on that research outcome. And Transport Canada recently proposed a draft for a Canadian standard of pavement roughness, using the Riding Comfort Index (RCI), based on IRI and RMSVA (Root Mean Square Vertical Acceleration).

Although the IRI has been used in the assessment of airport pavement roughness, its suitability for airport pavement has generally not been discussed, research should be done to compare the vertical acceleration of aircrafts or passenger cars at given pavement profile wave lengths. The objectives of this study are to explore the relationship between an aircraft's vertical acceleration, as well as gear loading, and pavement profile wave lengths. And the development of Airport Pavement Roughness Index (APRI) is also done in this study.

METHODOLOGIES

The commercial software, APRas, was adopted in this study to simulate the vertical acceleration and gear loading of aircrafts. APRas is designed for the assessment of airport pavement roughness with respect to aircraft pilot's station acceleration (PSA), center of gravity acceleration (CGA), main gears pavement loading (MGPL), and nose gears pavement loading (NGPL). Once the pavement profile is input, APRas can simulate the above items at takeoff, landing, and constant speed taxi situation, using the aircraft selected from the embedded database. As mentioned in previous sections, APRas was developed from earlier studies conducted in 1970's (*3*, *4*, *5*). The mathematical models embedded in this software were described in literature and verified with field data. The error of the embedded model is around 10 percent (*5*).

Artificially created pavement profiles were used as the inputs for APRas, and sinusoids with 15 different wave lengths ranging from 0.1 m to 100.0 m, listed in Table 1, were selected. In order to prevent speed variation effects on the simulation outputs, the constant speed taxi simulation module in APRas was adopted in this study. From flight dynamics, it is known that the lift force would be significant at high speeds. That means aircraft's speed is an important factor when performing the simulation. The speed limit of constant speed taxi simulation in APRas is 45 knot. Simulations at higher speeds are required. However, the lift force could dominate the aircraft's vertical responses while taxiing at very high speeds, and very high taxi speed simulations are not necessary. A speed limit of 100 knots was set in a specially-designed version of APRas and used in this research. Ten different taxi speeds, ranging from 10 knots to 100 knots at 10 knots increments, were chosen for the simulations.

Five different aircraft models, 737-200, 737-800, 747-200, 747-400, and MD-11, were simulated in this study. A typical PSA and CGA simulation output with 737-800 aircraft, sinusoids with a wave length of 12.0 m, and a taxi speed of 20 knots, is shown in Figure 1. A steady peak value of PSA and CGA can be found in the figure. Based on this, 3000 simulated peak values with 4 simulation items, 15 sinusoids wave lengths, 10 taxi speeds, and 5 aircraft models, were collected and analyzed in this study. The results are described in the following section.

Table 1.
Simulation Profile Sinusoids Wave Lengths and Corresponding Wave Number

Wave Length (m)	Wave Number (Cycles/m)
0.1	10.000
0.2	5.000
0.5	2.000
1.0	1.000
2.0	0.500
4.0	0.250
6.0	0.170
8.0	0.125
10.0	0.100
12.0	0.083
15.0	0.067
20.0	0.050
25.0	0.040
50.0	0.020
100.0	0.010

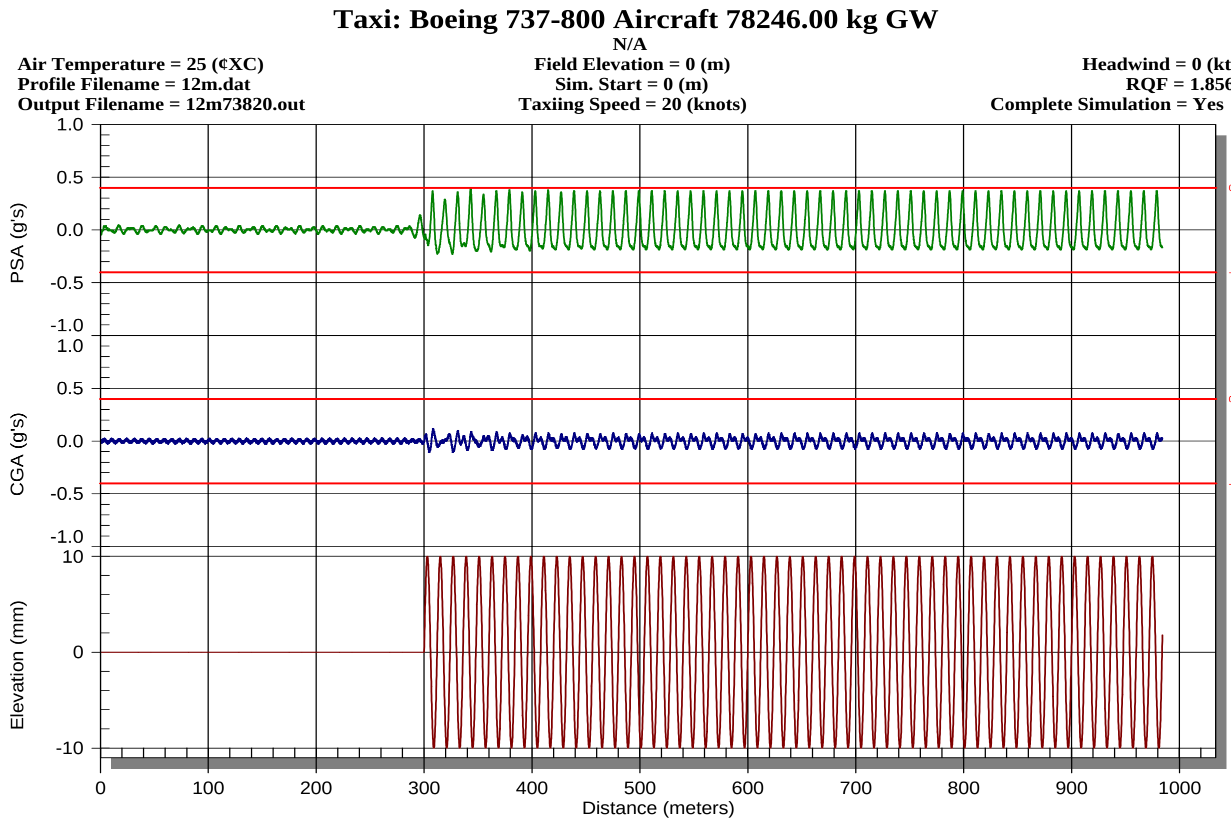

Figure 1. APRas Simulation Output (737-800, 12m Sinusoids Wave Length, 20 knots Speed)

ANALYSIS OF SIMULATION RESULTS

Due to the constraints of paper length, only the simulation outcomes of Boeing 747-400 aircraft are shown from Figure 2 to Figure 5. In each figure, simulation results from 10 different taxi speeds are shown. The y-axis in Figure 2 and 3 indicate the PSA and CGA value in gravity (g) unit. The y-axis in Figure 4 and 5 stand for the ratio between the dynamic pavement loading and static (taxi speed equals to zero) pavement loading. The simulation results from other aircraft are comparable to 737-800's. Other curves are not shown in this paper.

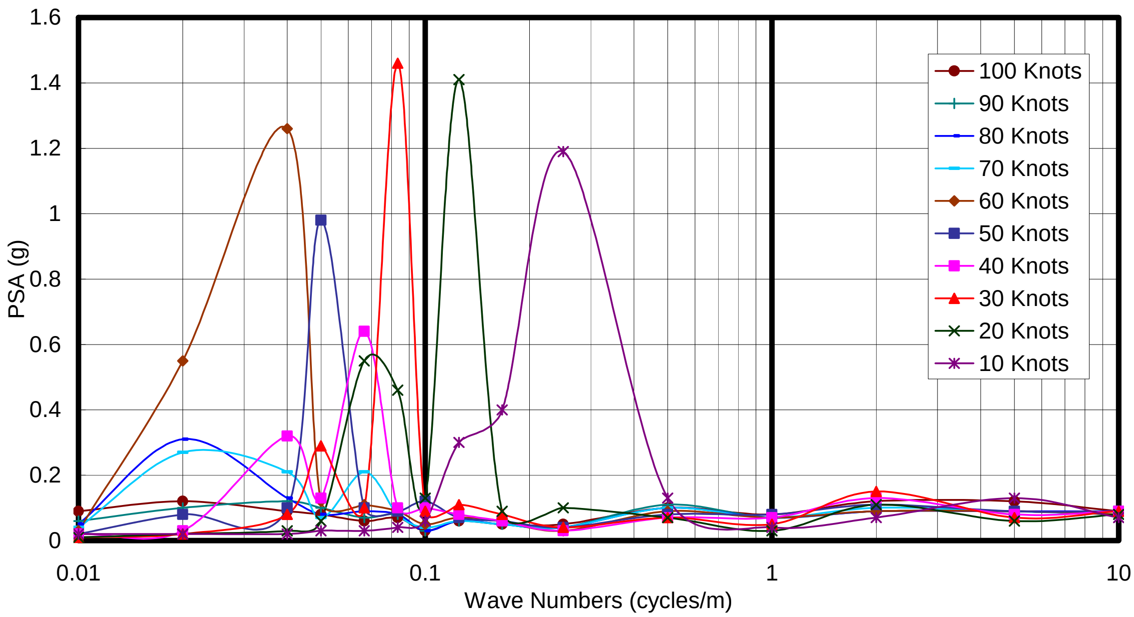

Figure 2. Relationship between PSA and Profile Wave Number for 747-400

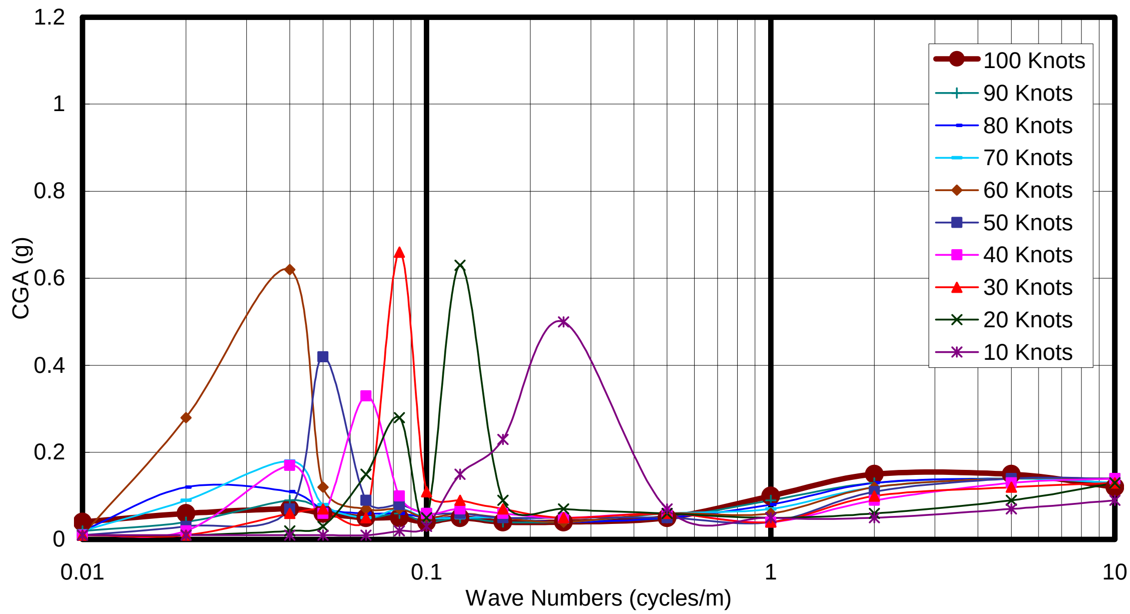

Figure 3. Relationship between CGA and Profile Wave Number for 747-400

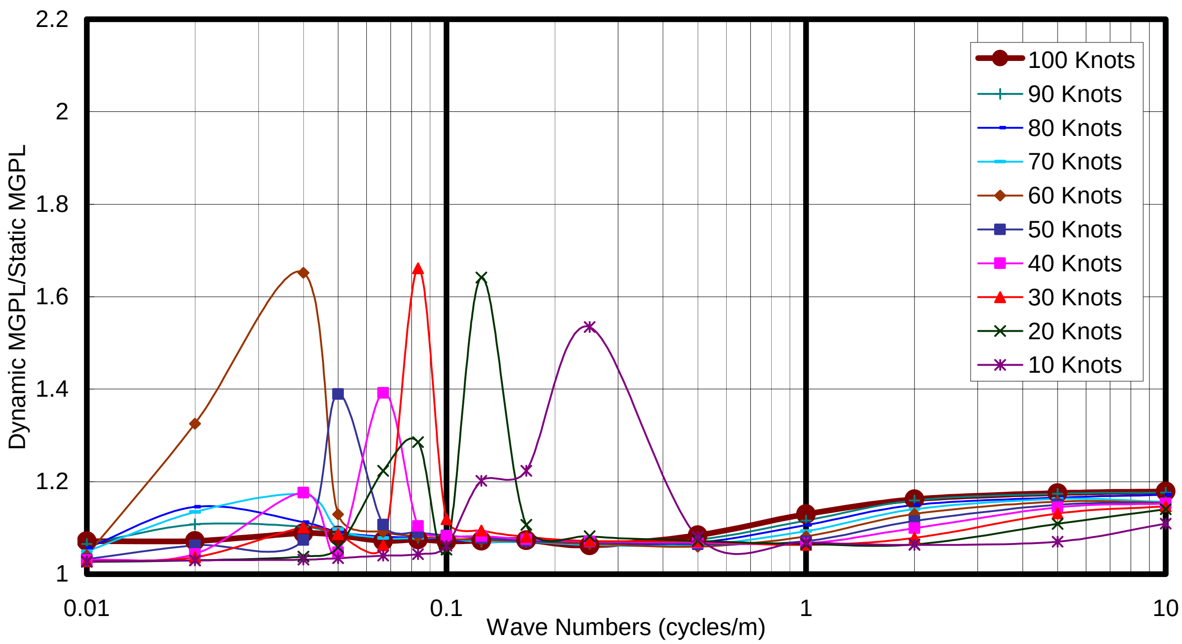

Figure 4. Relationship between Relative MGPL and Profile Wave Number for 747-400

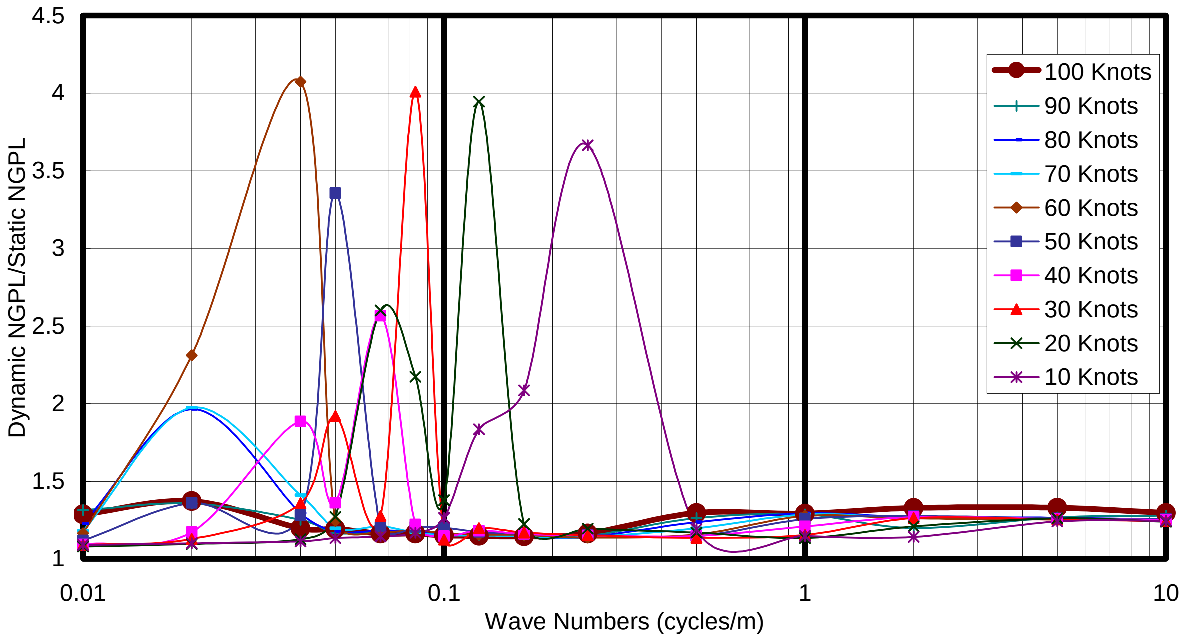

Figure 5. Relationship between Relative NGPL and Profile Wave Number for 747-400

From the figures, it can be found that the wave numbers for peak acceleration/loading decreased as the taxi speed increased, indicating that aircraft at high speeds are sensitive to long wave length profiles, i.e. wide bumps. At speeds higher than 60 knots, the acceleration and loading curves' peaks are not as obvious as those at speeds less than 60 knots. It is because of the influences of the lift force, aircrafts' vertical accelerations and gear loadings are more affected by lift force rather than the roughness of pavement. Generally speaking, PSA values are higher than CGA values, indicating that at the pilots' station in the cockpit, more sensitivity is evident to the pavement roughness than in the general passengers' cabin area, and they are all greater than the 0.4 g threshold. The peak value of PSA at speeds less than 60 knots are higher than 1.0 g. A second resonant peak occurs at PSA and CGA simulations. It can be found in Figure 4 and Figure 5 that the peak value of relative NGPL are higher than relative MGPL, which implies that pavement roughness has a greater influence on nose gear loading than on main gear loading.

For normal taxiing of moving aircraft, the speed is usually around 10 to 20 knots. It can be found from the figures that the wave numbers of peak acceleration/loading in this range are about 0.1 to 0.3 cycles /m, which are 3.3 to 10.0 m in wave length. For speeds higher than 20 knots, the critical wave number is between 0.02 to 0.1 cycles /m, which are larger than 10.0 m in wave length. It can be concluded that profile wave lengths between 3.3 to 10.0 m should be minimized from airport taxiway and apron pavement, and wave lengths between 10.0 to 50.0 m should not occur along an airport runway pavement.

DEVELOPEMENT OF NEW EVALUATION INDEX OF AIRPORT PAVEMENT

A standard evaluation methodology and roughness index is desirable to adequately describe the roughness of an airport pavement. The suitability of widely-accepted highway roughness evaluation index, the International Roughness Index (IRI), for airport pavement and the development for a new dedicated airport pavement roughness evaluation index using Wavelet theory are described in this section.

Suitability of IRI for Airport Pavement Roughness Evaluation

International Roughness Index was calculated from the quarter-car filter at a simulated speed of 80 km/hr with “golden car” parameters using pavement profile as input (*8*). “Golden car” is a set of parameters for the referenced quarter-car computerized response system. IRI’s suitability can be evaluated through comparing the wave number responses of quarter-car filter with “golden car” parameters at different simulated speeds (Figure 6) with previous figures of APRas simulation outputs. If they exhibit similar shapes, we can say both IRI and aircraft’s responses are sensitive to the same pavement wave length range and the suitability is high. The bolded curve in Figure 6 indicates the standard IRI wave number responses simulated at a speed of 80 km/hr. Comparing Figure 6 and previous figures of APRas simulation outputs, it is clear that an aircraft’s vertical acceleration and pavement loading responses with respect to wave number are not identical to wave number responses of IRI.

It is noticeable that the most significant difference between airport and highway pavement roughness evaluation lies in the wide range of aircraft speeds and the dedicated simulation speed of quarter-car filter adopted in IRI. In Figure 6, it can be found that the curve shapes of quarter-car filter are similar at different simulation speeds, and the curves shift left as the simulation speed increases. The trend of the curve shifts is identical to that of APRas simulation results. However, the curves of the same simulation speed in APRas outcomes and quarter-car filter cannot be matched. And the curves shapes of quarter-car filter are different from the APRas simulation outcomes. Since a good airport pavement roughness evaluation index whose wave number responses should match aircraft’s vertical responses, it can be concluded that IRI is not suitable for evaluating airport pavement roughness.

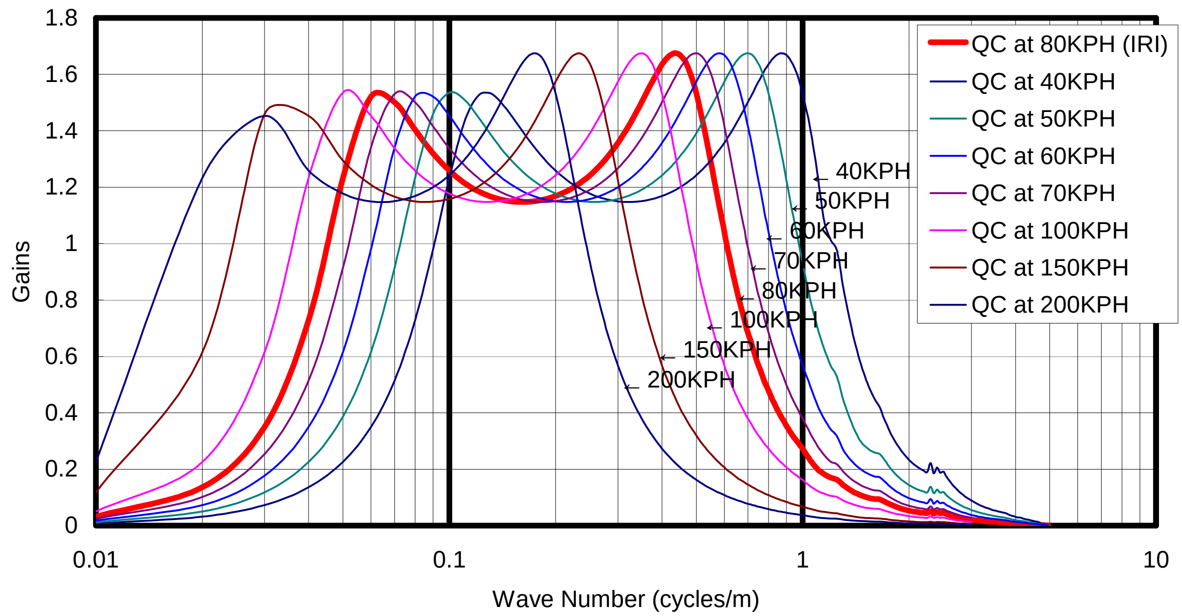

Figure 6. Wave Number Responses of Quarter-Car Filter at Different Simulated Speed

Practicability Discussion of Airport Pavement Roughness Index using Wavelet Theory

Since a quarter-car filter is not suitable for the evaluation of airport pavement roughness, new methodologies should be considered to develop a new index. It is clear from the APRas simulation results that an aircraft's vertical responses are sensitive to the wave length of pavement profiles. So the new methodologies must be capable of identifying wave forms of different wave lengths in the pavement profiles. And signal analysis techniques can be applied to develop the index.

The most well-known of signal analysis techniques is Fourier analysis, which breaks down a signal into constituent sinusoids of different frequencies/wave lengths. However, Fourier analysis has a serious drawback. In transforming to the frequency domain, time information is lost. When looking at a Fourier transform of a signal, it is impossible to tell when a particular event took place. When we treat pavement profiles as a signal and apply Fourier analysis on it, it means the location information of rough section of the analyzed pavement is gone. This methodology cannot satisfy pavement management system's needs. A newly-developed technique, Wavelet Theory, which can analyze the frequencies/wave lengths information without losing the time information, may be suitable for this application.

The advantage of using Wavelet Theory to develop the new evaluation index is its ability in identifying the amplitudes and locations of wave forms with dedicated wave length. Using the specified wavelet function, the input pavement profile can be deconstructed into different wave forms of different wave lengths. Once the weight coefficients of wave forms of different wave lengths are determined, the pavement profiles can be reconstructed by the weighted wave forms to establish the Airport Pavement Roughness Index (APRI).

Choosing of Suitable Wavelet Function for Deconstruction of Pavement Profiles

The deconstruction of a pavement profile into wave forms of different wave lengths by Wavelet Theory can be illustrated in Figure 7. A pavement profile can be deconstructed into a “detail” (high-frequency part) and an “approximation” (low-frequency part). The “approximation” of that original pavement profile can be further deconstructed into a detail and an approximation. The whole process can be iterated, so that one pavement profile is broken down into many lower resolution components. This is called the wavelet decomposition tree.

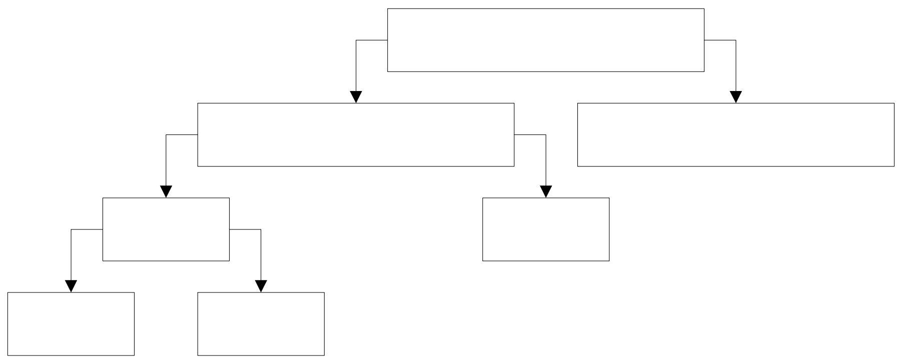

Figure 7. Wavelet Decomposition Tree

Before conducting the wavelet decomposition process, a suitable wavelet function must be chosen. A common way to find the appropriate wavelet function is to evaluate the root-mean-square error (RMS error) of the synthesized pavement profile (summarization of all details and approximations) by different wavelet function with respect to the original profile. Twenty-one different wavelet functions from Daubechies family, Symlets family, and Coiflets of different orders with thirteen different pavement profiles as the input were assessed in this study. The evaluation results are shown in Figure 8.

From the figures, it can be found that the range of RMS error of different wavelet functions is between $1x10^{-7}$ to $1x10^{-16}$. The least RMS error occurs while using order 3 Daubechies (Daub3) wavelet function to achieve the deconstruction. And Daub3 wavelet function is chosen in this study to develop APRI. Given that the central frequency of Daub3 is 0.8 Hz and the recording interval of pavement profile is 0.25m, the highpass cut-off wave numbers at different levels of wavelet deconstruction is shown in Table 2.

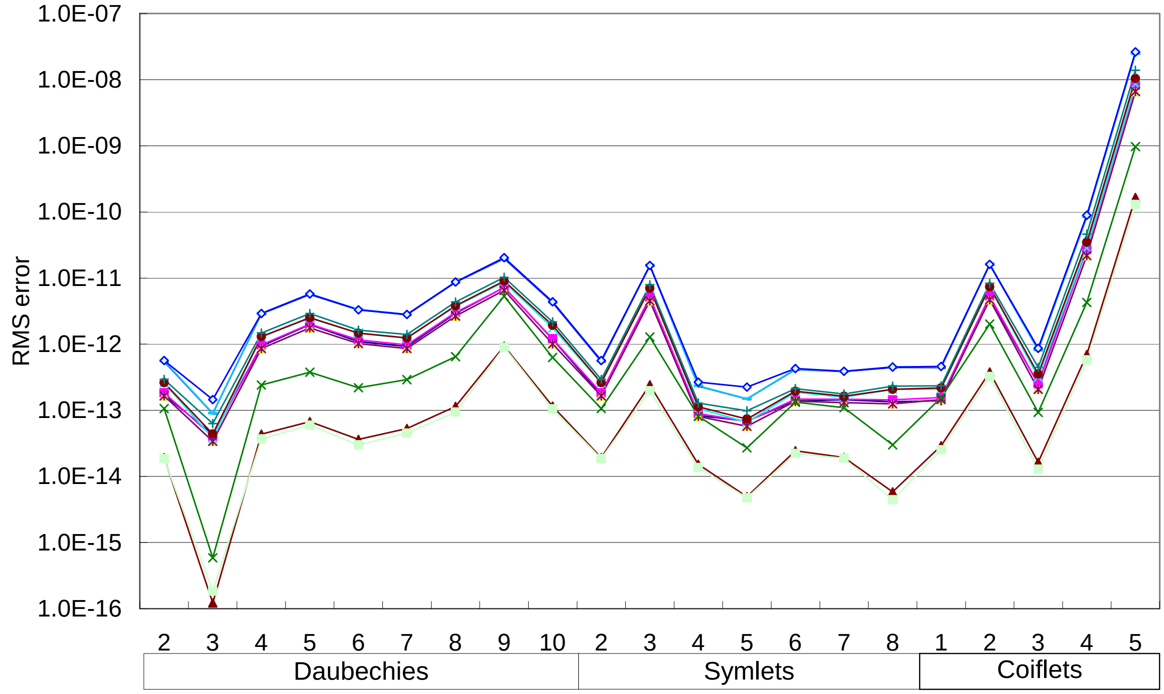

Figure 8. RMS Error of Applying Different Wavelet Functions on Pavement Profiles

Table 2.
Highpass Cut-off Wave Numbers and Lengths at Different Levels of Wavelet deconstruction

Level	Highpass Cut-off Wave Number (Cycles/m)	Corresponding Wave Length (m)
1	3.2	0.3125
2	1.6	0.625
3	0.8	1.25
4	0.4	2.5
5	0.2	5
6	0.1	10
7	0.05	20
8	0.025	40
9	0.0125	80

Determination of Weight Coefficients and Calculation for APRI

The next step after choosing Dau3 as the wavelet function in APRI would be the determination of weight coefficients of different pavement profiles with different wave numbers. The determination is based on the simulation outcome described in previous sections. All the simulated PSA, CGA, relative MGPL, and relative NGPL were converted into its “gain” value. The gain value for each simulated item is calculated by Eq. (1):

$$\text{gain} = \frac{\text{simulation output}}{\text{Max. value of all simulation outputs}} \times 2.0 \tag{1}$$

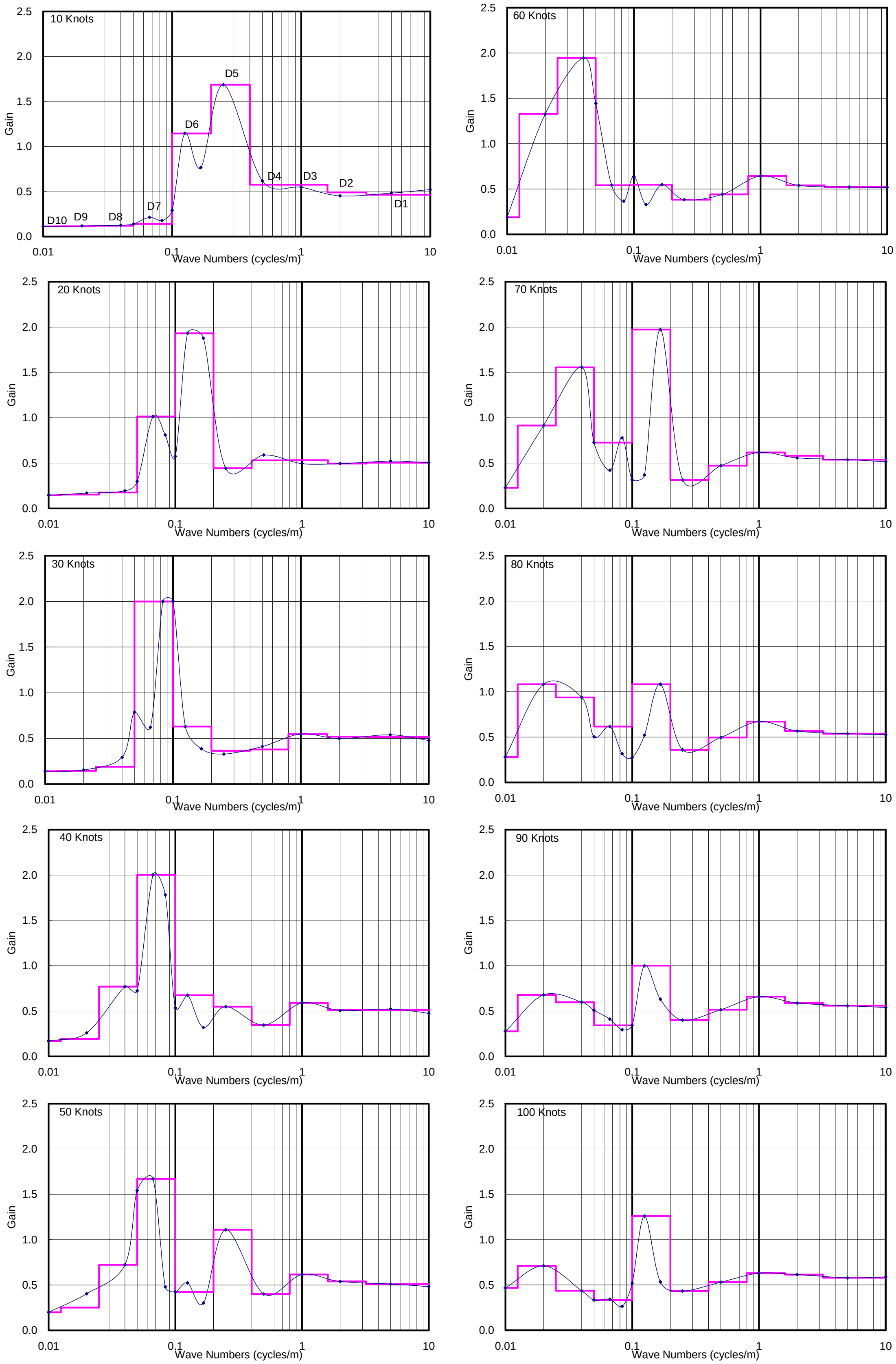

Figure 9. Weight Coefficients for Ten Different Aircraft Taxi Speeds

The overall gain value of a specific wave number is the maximum value of the gain values of the four simulated items at that profile wave number. The overall gain values at different profile wave numbers with different taxi speeds are shown in Figure 9 as blue lines. The purple lines in the figure represent the simplified shape of corresponding blue lines. And the gain values of purple lines are treated as the weight coefficients of the deconstructed pavement profile at different levels. The Airport Pavement Roughness Index at taxi speed s (APRI_s) can be calculated by Eq. (2) with a unit of m/km.

$$\mathrm{APRI}_s = \frac{1}{L}\sum_{n=1}^{9} C_{n,s} D_n \tag{2}$$

Where:

L : Average length of APRI, unit: kilometer;

D_n : Detail wave form after applying Wavelet Transform at level *n*, unit: meter;

$C_{n,s}$: The weight coefficient of level *n* detail at speed *s*.

A computer program is developed in this study to perform the deconstruction and calculation of APRI. The computer output showing a profile with its nine levels details (D_n) using Daub3 function is shown in Figure 10.

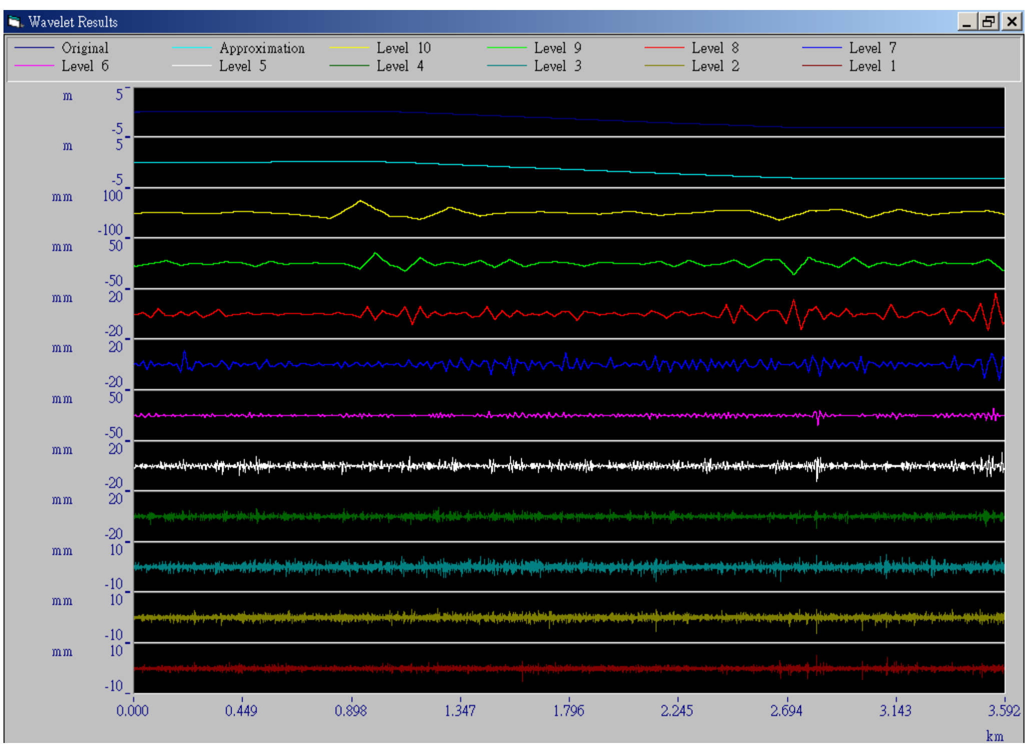

Figure 10. Computer Output of a Profile with a 10 Level Wavelet Decomposition Using Daub3

Comparison between $APRI_s$, IRI and Aircraft's Vertical Responses

The Airport Pavement Roughness Index at taxi speed s can be calculated by Eq. (2) described in previous section. In this section, a 3660 m long real airport runway pavement profile was analyzed. APRas was also used in simulating Boeing 737-800 aircraft's vertical responses while taxiing at a constant speed of 20 knots on this pavement. The simulation results are shown in Figure 11. The APRI at a taxi speed of 20 knots ($APRI_{20}$) and International Roughness Index of this profile is determined and averaged every 100 m. The analyzed results can be seen in Figure 12.

It can be seen from Figure 11 that significant peaks of both vertical accelerations and pavement loadings can be found at about 1500 m from the runway threshold. In Figure 12, a peak can also be found at the same section of pavement for $APRI_{20}$ while IRI at this section remains flat. $APRI_{20}$ does have better correlation with aircrafts vertical responses than IRI.

However, as mentioned in the first section of this paper, the moving speeds of aircrafts vary from 0 to 200 knots. Evaluating the airport pavement roughness by APRI with only one taxi speed is not suitable. Further studies should be done.

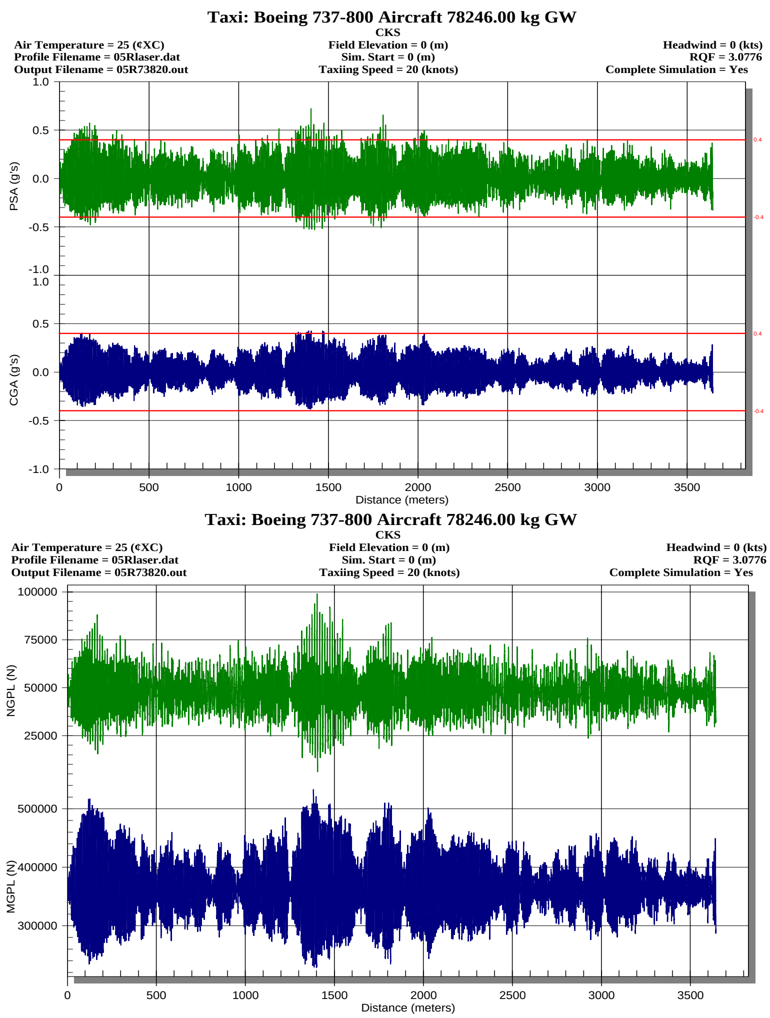

Figure 11. Vertical Responses of a Real Runway Profile for 737-800 at a taxi speed of 20 Knots

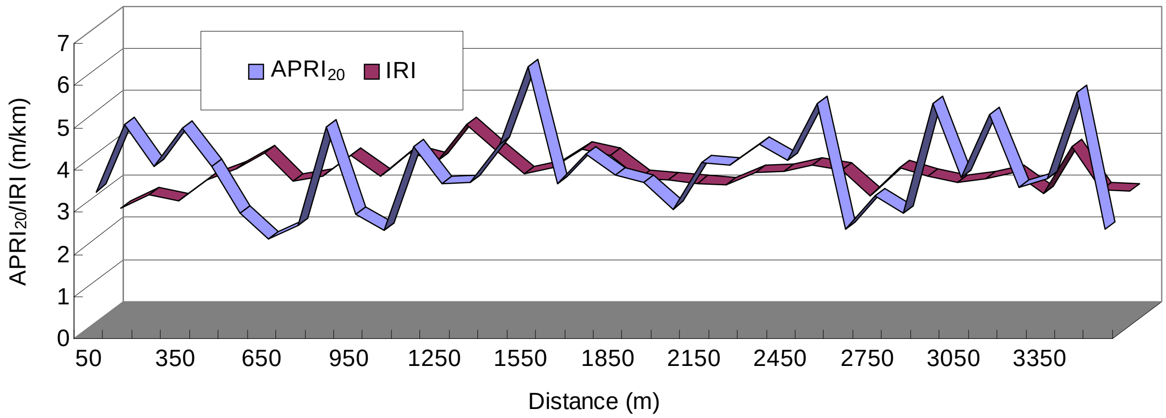

Figure 12. $APRI_{20}$ and IRI Results of the Same Runway Profile

CONCLUSIONS AND RECOMMENDATIONS

The main objectives of this study are to explore the relationship between an aircraft's vertical acceleration, as well as gear loading, and pavement profile wave length. The development of the prototype of Airport Pavement Roughness Index (APRI) is also done. The following conclusions and recommendations can be made,

1. The occurring wave length of aircraft's peak vertical acceleration and loading increases as the taxi speed increases. And pavement roughness has a greater influence on nose gear loading than on main gear loading.

2. The pilots' station in the cockpit is more sensitive to pavement roughness than in passengers' area in the cabin, implying that airport pavement roughness is more a flight safety-related issue than a passenger's comfort-related issue.

3. Pavement profiles having wave length between 3.3 to 10.0 m should be prevented from airport apron and taxiway pavements, and profiles of wave length between 10.0 m to 50.0 m must be prevented from airport runway pavement.

4. The widely-used highway pavement roughness evaluation index, IRI, is not suitable for the assessment of airport pavement roughness. A new index should be developed.

5. The methodology of adopting Wavelet Theory to establish the Airport Pavement Roughness Index at different taxi speeds has been established, as well as the weight coefficients at different taxi speeds. And Daub3 wavelet function is found to be the most appropriate one while processing pavement profiles by Wavelet Theory.

6. $APRI_{20}$ of a real airport pavement profile is calculated. And it does have better correlation with aircrafts vertical responses than IRI.

7. More studies should be conducted to develop a general APRI. The situation that aircrafts moving at a wide range of speeds in airport pavements should be accounted.

8. Studies on the pavement maintenance threshold of APRI shall also proceed, as well as the development of airport pavement roughness evaluation procedures.

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