THE IMPACT OF RUNWAY ROUGHNESS IN A HIGH SPEED ABORTED TAKEOFF

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ABSTRACT

A high speed aborted takeoff can be one of the most dangerous operations a pilot has to contend with in commercial aviation. The aircraft is heavy, reaction time is very short, and remaining runway is rapidly approaching zero. When a pilot executes an abort and the remaining runway is short, the pilot must initiate maximum braking effort. This has several serious consequences;

- Hard braking on a heavy aircraft will likely overheat the brakes and main landing gear (MLG) tires. This usually causes damage to the brakes and can blow the fuse plugs in the tires. There is also a potential for fire and MLG structural failure.

- Hard braking "loads up" the nose landing gear (NLG) inducing high vertical and drag loads on the NLG tire and supporting structure. This can cause the NLG tire fuse plugs to blow and possibly fail the NLG drag brace. If the drag brace fails, the NLG will collapse. Dynamic loads caused by runway roughness will contribute significantly to this already serious maneuver.

It's not uncommon for long wavelength roughness to add a 30-40% dynamic load at the MLG and even higher loads at the NLG. These additional loads can make the difference between an incident and an accident with more serious consequences. The rare (but real) high speed aborted takeoff is probably the most important reason to include pavement smoothness as part of an airport's pavement management system. This paper will include simulated results of aborted takeoffs on smooth and rough pavements. It will also include how other factors, such as improperly serviced landing gear struts, can affect aircraft dynamic loads. The paper includes a case history published by the NTSB.

INTRODUCTION

The high speed aborted takeoff is one of the most dangerous procedures that a pilot of a commercial airliner can perform. The aircraft is at its heaviest for that particular flight. Generally, most of the runway is behind you when the decision is made to abort, and at many airports usable overruns are non-existent. Reaction times are minimal, so pilot training is a key factor in proper execution. The high speed aborted takeoff is an emergency operation that calls for maximum braking effort which induces high drag loads in the main landing gear. It can often exceed maximum recommended brake energy usage resulting in hot brakes; a potential fire hazard. Hot brakes can also cause tires to overheat and blow out. Hard braking action induces high nose landing gear (NLG) vertical and drag loads. Large tire deflections can generate heat in the tires causing the fuse plugs to blow out. High drag loads can also fail the nose gear drag brace causing the NLG to collapse. The high speed aborted takeoff is often a primary structural design consideration for the nose and main landing gear struts and their attachment structures. The loading is high for this emergency operation on a perfectly smooth runway. A rough runway will significantly aggravate the situation.

RUNWAY ROUGHNESS DEFINED

Pavement roughness is the undulations in the surface profile that adversely affect the dynamic response of the aircraft that use those pavements. It is not texture. Pavement roughness can be broken into three categories.

1. *Shock* is the result of encountering a sharp change in elevation such as a step bump, a raised slab or spall. These are very short wavelength bumps and dips. Shock loading is typically too fast for the aircraft suspension system to fully absorb the energy. It is transmitted through the structure, is felt by passengers as a jolt and causes a sharp-high frequency loading in the landing gear strut and its supporting structure.

2. *Short wavelength* roughness is undulations in the profile that the suspension system can more readily react to, but does not excite the aircraft as a whole (rigid body modes of vibration). These are wavelengths such as the 16-foot requirement that is specified in the FAA Advisory Circular AC 150/5370 (smoothness specifications for new concrete airport pavements). This type of loading results in strut and tire deflection that will absorb some of the energy. Generally a deflection at the nose gear will not cause a significant deflection at the main gear.

3. *Long wavelength* roughness is undulations in the profile that cause the aircraft to respond as a whole. It excites the aircraft's rigid body modes of vibration predominately in pitch and sometimes roll. It is a coupled response. What happens at the main landing gear will cause a response at the nose gear and vice versa. This type of roughness can be caused by bumps and dips like runway intersections with crowns, rapid changes in grade such as a vertical curve(s), or a dip resulting from pavement settlement or expansion that can occur with time and traffic. This type of roughness causes the highest loading for the longest period of time. It has the biggest impact on aircraft structural fatigue damage and dynamic loading on the pavement itself.

While all three of these can have an adverse effect on the aircraft's performance in a high speed aborted takeoff, type 3 is the most significant, primarily because of the length of time (low frequency) the dynamic loading is induced into the structure. Type 1 and 2 can result in "wheel hop" if the roughness is severe enough. Wheel hop causes the tire to momentarily lose contact with the surface which reduces braking ability.

RUNWAY ROUGHNESS EFFECTS ON NORMAL AIRCRAFT OPERATIONS

The primary reason for constructing and maintaining a smooth airport pavement is *to minimize the surface irregularities that influence aircraft response during taxi, takeoff and landing*. Surface characteristics, including the elevation profile, can change with time and traffic, and it is important to track these changes as part of the pavement management program.

During takeoff, when the aircraft is on the ground for 30 seconds or so, ride comfort, which most people associate with roughness, is really not the most important issue. The important issues with regard to pavement roughness are connected to aircraft and pavement performance.

- Aircraft Useful Life: Even though the aircraft is on the ground during takeoff and landing for only 30 seconds, it is half of the Ground-Air-Ground (GAG) fatigue cycle. Many commercial aircraft are designed for 20,000 GAG cycles. The useful life of the aircraft is reduced when operations are on rough surfaces. The margin for overloads is small. It costs airlines more to operate and maintain their aircraft on rough runways. Rough runways reduce the useful life of the aircraft.

- Pavement Useful Life: When an aircraft encounters a bump, it will rebound with a dynamic load. Dynamic loads of 30-40% are not uncommon. This dynamic loading will hammer the pavement in the same general location again and again and it is this area that is most likely to fail first. Maintaining a smooth pavement will extend the useful life of the pavement.

- Stopping Distance: It takes more distance to stop an aircraft on a rough runway than on a smooth runway. When an aircraft has vertical motion caused by bumps, the normal load on the main landing gear (MLG) varies, and therefore, the braking force varies. In addition, the antiskid system may give false information about the speed because of the changing tire diameter. Finally, roughness can affect a pilot's ability to maintain steady brake pressure.


Courtesy F. Seggie

Figure 1. Example of Runway Roughness.

It is important to recognize that multiple bumps and dips in succession have a very non-linear effect on aircraft response. Just as the aircraft is rebounding from one bump, another is encountered. The struts are already deflected from the first bump, so that there is little stroke remaining to absorb the second bump. Struts are non-linear. The more they are deflected, the stiffer they get. Consequently, the load going into the aircraft structure is non-linear.

RUNWAY ROUGHNESS EFFECTS IN A HIGH SPEED ABORT

In a normal takeoff, the pilot is not committed to takeoff until V1 (the takeoff decision point) is reached. A pilot has the option to abort the takeoff at any time up to that point. He is required to compute required runway length prior to takeoff such that, at or below V1, he has enough runway to get the aircraft stopped. When computing the required runway length before takeoff, the RCR (runway condition reading) is included in the computation. His calculations also include headwind and density altitude effects, as well as the gross weight and cg of the aircraft. His calculations do not include the extra stopping distance required due to pavement roughness.

As an example, let's say you're traveling at 100 knots, you get an engine malfunction light and decide that an abort is the best option. You have very little runway remaining to get stopped. This requires a maximum braking effort. The aircraft will pitch forward on the NLG compressing the tires and the strut (Figure 2). The compressed tires will heat up and possibly blow the fuse plugs. Secondly, in an abort, there is a risk of fracturing the NLG drag brace, which would cause the NLG to collapse. Finally, a high speed aborted takeoff can overheat the brakes, often causing the MLG tires to blow out and/or create a fire hazard.

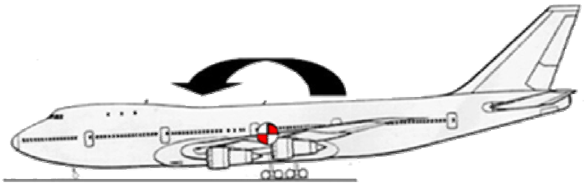

Figure 2. Aircraft Undergoing Maximum Braking as in a High Speed Aborted Takeoff.

What factors determine the impact of pavement roughness and how much it aggravates the emergency situation?

- The level of roughness,
- The speed when the abort was initiated,
- The amount of runway remaining,
- The takeoff weight compared to its maximum design takeoff weight,
- The friction of the runway surface (including wet and contaminate runways).

What are the possible consequences that a rough runway would introduce?

- Since more stopping distance is required on a rough runway, the aircraft could overrun the end of the runway even though the computed stopping distance was sufficient. This is one reason why some major airports have installed an EMAS (Engineered Material Arresting System) at the ends of some runways.

- Hard braking will cause the aircraft to pitch over, loading up the NLG strut and tires. The tires will heat up and possibly blow the NLG fuse plugs. High vertical loading on the NLG will also impose a high drag load. A sufficient drag load could fail the NLG drag brace. Failure of the NLG drag brace will result in the NLG collapsing. This is aggravated if the NLG strut and drag brace have been in service for a long time and have accumulated fatigue damage. In addition, strut under-servicing may cause premature strut bottoming that will send a shock into the aircraft strut, and put an even higher load on the structure.

- The excessive heat generated by the MLG brakes could cause the MLG tires to blow the fuse plugs. In fact, this was a primary reason for development of tires with fuse plugs. They're designed to prevent a catastrophic tire blow out which could throw shrapnel into hydraulic lines and fuel cells. The high speed aborted takeoff is a (if not the) primary consideration in computing the design braking capacity for an aircraft. Most commercial aircraft have sensors that inform the pilot of brake temperature. He may not take off if the brakes have exceeded a certain temperature during taxi; the reason being that he could not get the aircraft stopped in a high speed abort. The sensors also help decide weather an emergency should be declared after an abort has been performed. Some military aircraft do not have brake temperature sensors, and rely on the flight engineer to compute brake temperature. When an aborted takeoff happens, it often requires that the brakes be inspected/replaced because of heat damage. It is also possible that one of the MLG drag braces could fail, causing it to collapse. Under-serviced struts will aggravate the situation. Drag brace failure of the MLG is probably not as likely as the NLG, but is aggravated on an aging aircraft that has accumulated a lot of ground-air-ground cycles.

High speed aborted takeoffs are rare when one considers the amount of takeoffs made daily. When they do occur, the damage is usually limited to hot brakes and blown fuse plugs on the tires. The exception is when the aircraft overruns the end of the runway. Then, severe damage can occur to the structure unless an EMAS is in place.

The following are two case histories of high speed aborted takeoffs. Runway roughness was not discussed in the incident reports because of little or no information about the profiles of the runways. However, one can be assured that any roughness would have contributed to the problem. These examples are typical of the damage that can be incurred in a high speed aborted takeoff.

1. <u>B-1B, Ellsworth AFB SD, Nov 23, 2004:</u> The aircraft aborted the takeoff at 139 knots when a "hatch warning light" illuminated. The crew was successful in getting the aircraft stopped on the runway. The crew reported hot brakes and declared a ground emergency. A fire in the left MLG wheel well caused substantial heat and fire damage resulting in $962,000 in repair costs.

2. Boeing 737-500 Denver International Runway 7-25, August 7, 2004: The aircraft was instructed by the tower to abort the takeoff because of another suspected aircraft on the runway. The pilot aborted and was able to taxi to the deicing pad for a 90 minute cool down. The aircraft sustained deflation on four MLG tires and brake damage to four MLG brakes.

AIRCRAFT STRUCTURAL DESIGN CONSIDERATIONS

The design of a typical passenger and cargo type aircraft often uses the Military Specification 8862A series for landing gear design. Mil Spec 8862A (ground handling loads) says that the MLG shall carry 2 times the maximum expected static load, and the NLG shall carry 3 times the maximum expected static load. The aborted takeoff and nose gear "slap down" operations influence the higher load factor on the NLG design. The maximum load on the main landing gear is calculated using the maximum design takeoff gross weight with the most aft center of gravity. The maximum load on the nose landing gear is calculated using the maximum design takeoff gross weight with the most forward center of gravity. It should be pointed out that the 2w and 3w load factors are "design values". The gear is designed to withstand these loads. A factor of safety of 1.5 is generally used on aircraft structure. This means that the "ultimate load", the point at which failure may occur, will be 1.5 times the 2w and 3w discussed above.

When a maximum braking effort is applied, the aircraft will pitch forward on the nose landing gear (NLG) compressing the tires and the NLG strut. When very little tire deflection or strut stroke is remaining to absorb runway roughness, most of that energy is transmitted to the aircraft structure. It is very non-linear as can be seen in the typical load stroke curve shown in Figure 3. The spring rate while undergoing hard braking is much stiffer than that at static load. Consequently, loads will increase non-linearly in the strut, drag brace and supporting structure. Figure 3 also illustrates the importance of proper strut servicing; it is most important to prevent under-servicing, because the load-stroke curve becomes even stiffer.

Some airports have installed arrestor beds (EMAS) at the ends of their runways to safely capture an aircraft in a high speed abort or when landing long. Runway roughness will impact the effectiveness of the system by altering the aircraft's initial conditions upon entering the EMAS. The NLG is a vulnerable structure when entering the EMAS material. If the NLG is undergoing additional loading because of roughness, the drag brace may fail, where it would not have on a smooth runway.

AIRCRAFT RESPONSE TO RUNWAY ROUGHNESS

The level of runway roughness on most commercial runways in the United States is mild and produces acceptable aircraft response during normal takeoff and landing operations. A high speed aborted takeoff is not a normal operation. Mild bumps and dips during normal operations can be significant during a high speed abort for several reasons. One, the NLG is highly loaded as described above, and two, because the bumps and dips that are at the ends of the runways are not normally encountered under these loading conditions. There are no official criteria that specify when a runway has become too rough. In many cases it is pilot and passenger complaints

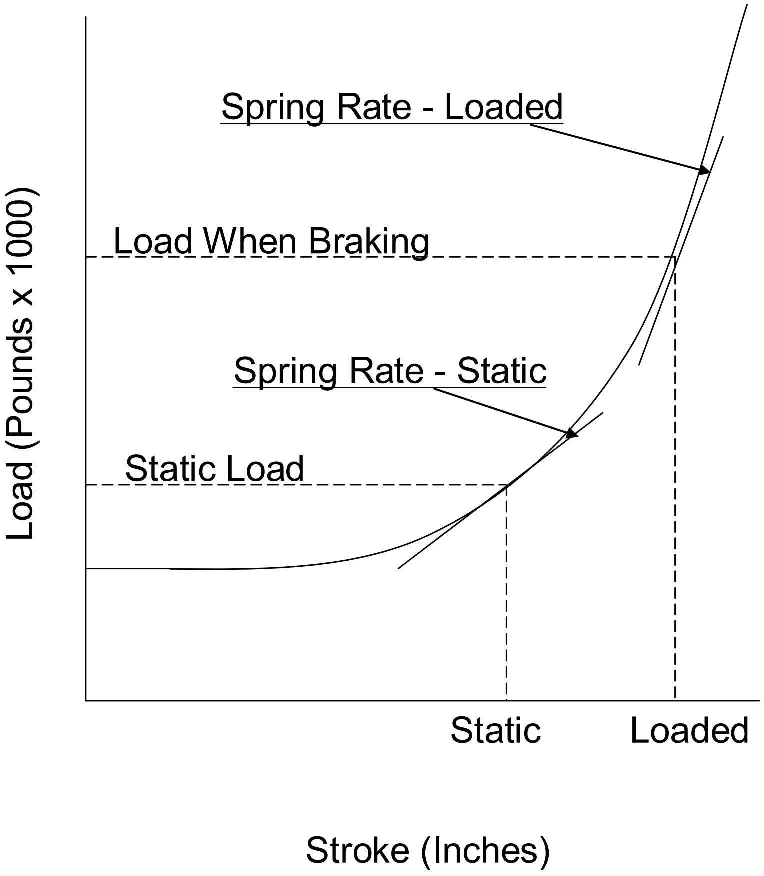

Figure 3. Typical Nose Landing Gear Load-Stroke Curve.

that alert airport owners that roughness may be an issue. However, in recent years, some airports have taken the proactive approach of adding runway roughness assessment to their pavement management programs. When conducting these smoothness assessments, it is important to consider the high speed aborted takeoff and bumps and dips at the runway ends.

Figure 4 is a 100-foot straightedge assessment of three runways currently in use in the United States. Two are roughness extremes and the third is typical of most airport pavements. The plot shows the maximum deviation anywhere along that straightedge as it moves down the runway. The top trace is a runway that causes many pilot complaints. The middle trace is a runway that is typical of those runways that have been in use for several years. The lower plot is a new, very smooth concrete runway. Figures 5, 6 and 7 show the response of a Boeing 737-800 approximation to the smooth, average and rough runways during a normal takeoff. The top trace is the vertical acceleration at the pilot's station. The middle trace is the vertical acceleration at the aircraft's center of gravity. The accelerations are banded by a band of +/- .4g. This criterion defines "the threshold of discomfort" as published in Volume III of the Shock and Vibration Information Handbook, Chapter 44, "Effects of Shock and Vibration on Man" by D. E. Goldman and H. E Von Gierke [1]. Additionally, this level of unwanted aircraft response is a threshold at which aircraft fatigue damage begins to occur with dynamic loading. This .4g level has become accepted by many in the industry as a standard for when an airport pavement is approaching the *rough* category. This is not a hard and fast rule, but is an indicator that if exceeded, it would be advisable to examine that section of pavement in more detail. The bottom trace is the runway profile as it is encountered by the main landing gear. The differences in response are significant. An aborted takeoff would produce even higher responses, which would vary depending on the speed and runway location where the abort was initiated.

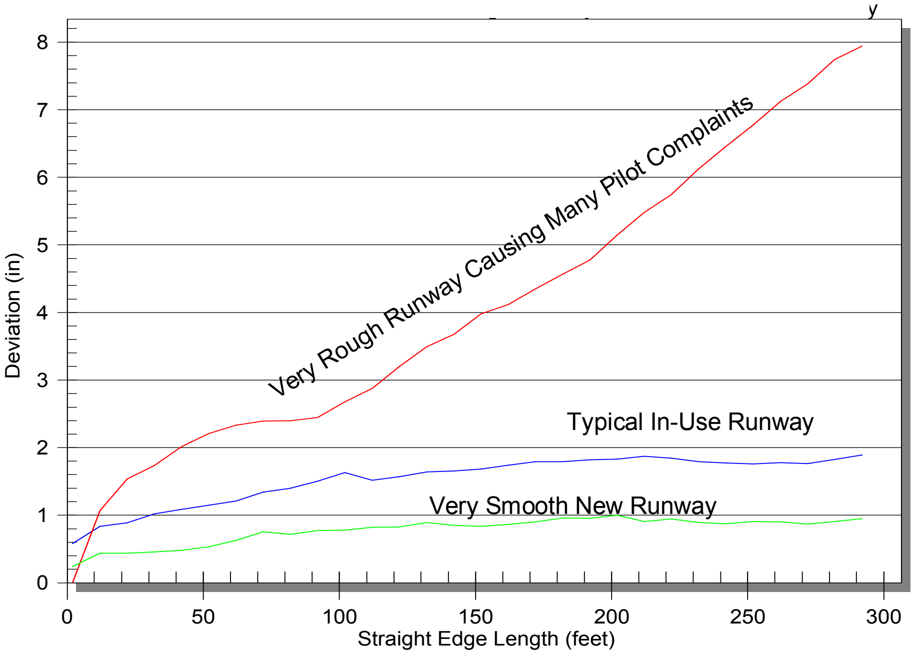

Figure 4. 100-Foot Straightedge Assessment of a Smooth, Average and Rough Runway Profile.

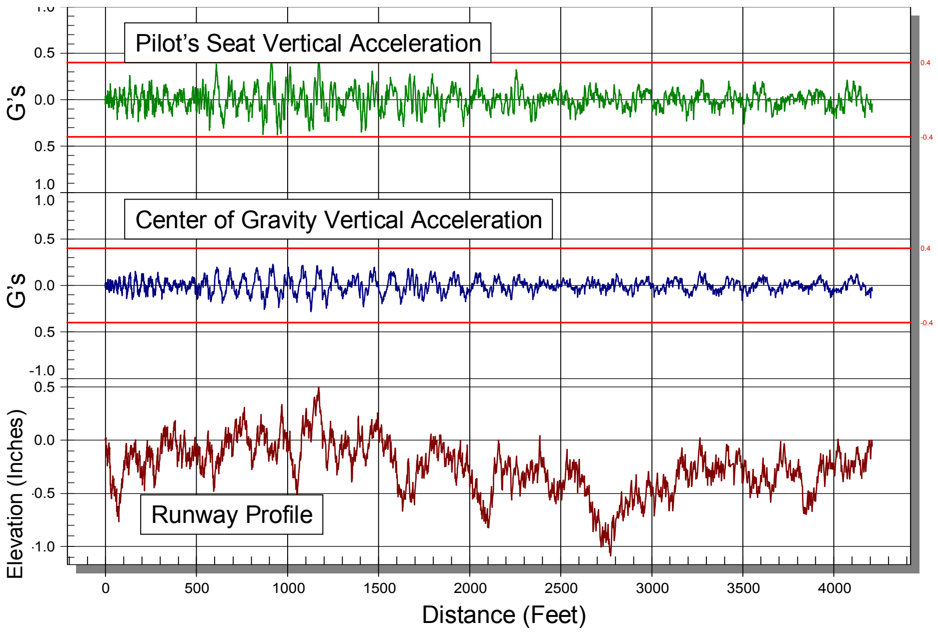

Figure 5. Simulation of Boeing 737-800 Takeoff on a Very Smooth Runway.

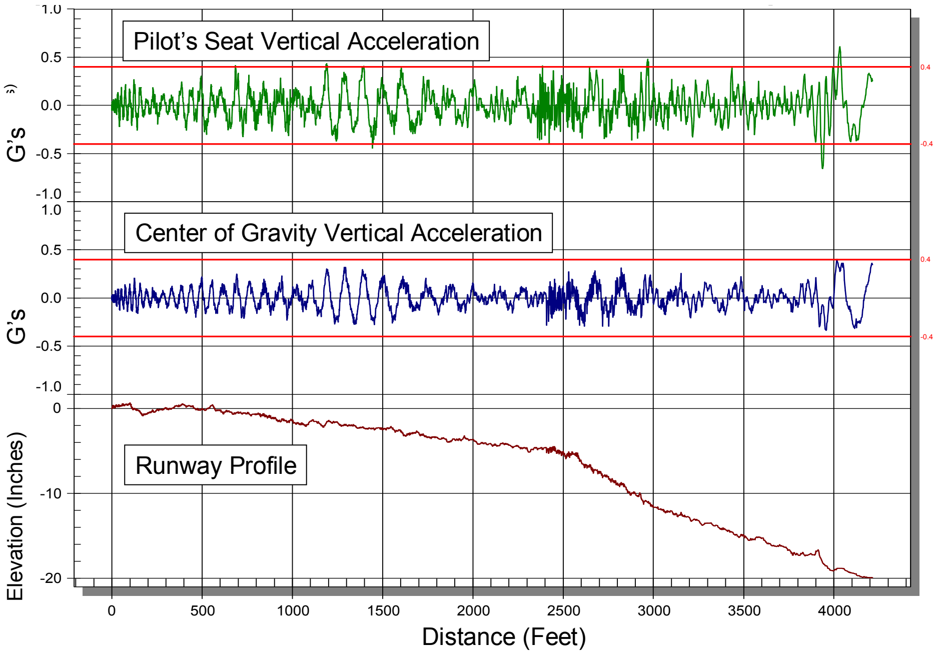

Figure 6. Simulation of Boeing 737-800 Takeoff on a Typical In-Use Runway.

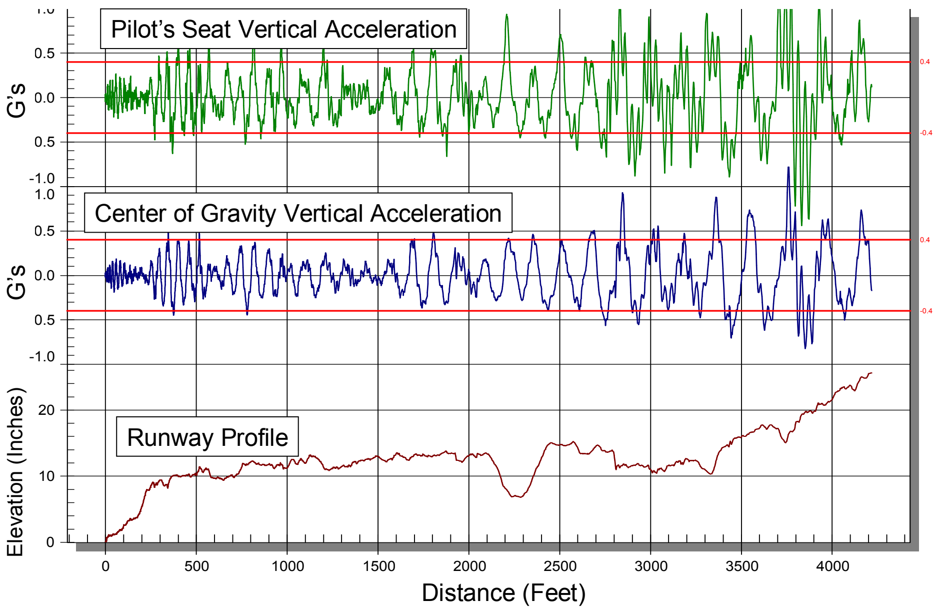

Figure 7. Simulation of Boeing 737-800 Takeoff on a Very Rough Runway.

CONCLUSIONS

The impact of runway roughness in a high speed aborted takeoff presents a technical gap in the air transport industry. There is a need to quantify the effect of roughness on required stopping distance. There is also a need to quantify the impact of runway roughness on the dynamic loads induced into the aircraft. If a "roughness index" of some sort could be measured and assigned to a runway, the index could be used to compute a more accurate V1, and therefore minimize the chance of overrunning the runway in a high speed abort

More importantly, there is a need to establish upper limits of allowable runway roughness. An official criterion defining when a runway has become too rough would minimize the impact of roughness in a high speed abort. In addition, by maintaining pavements in this manner, the useful life of the pavement and the aircraft that use those pavements would be extended.

The importance of proper landing gear strut servicing is often underestimated. It is especially important not to under-service the struts. Under-servicing increases loads going into the aircraft structure non-linearly. It is important during normal taxi, takeoff and landing operations and especially important in a high speed aborted takeoff.

A high speed aborted takeoff is one of the riskiest maneuvers that can be performed by a commercial or military pilot. This is especially true for large aircraft that require a lot of runway for takeoff and have a lot of mass to get stopped. This emergency operation is risky on smooth runways and with aircraft systems operating perfectly. Runway roughness, under-serviced struts, or aging aircraft that have accumulated fatigue damage, degrades the situation even further. These conditions could make the difference weather an aircraft overruns the end of the runway or damages critical aircraft components such as tires, a drag brace, or brake assembly. In either case, an incident becomes an accident.

REFERENCES

1. Goldman, D.E., and Von Gierke, H.E., “Effects of Shock and Vibration on Man,” in *Shock and Vibration Handbook*, C. M. Harris, ed., New York, McGraw-Hill, 1988.