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A SENSOR-INDEPENDENT GUST HAZARD METRIC

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Abstract

A procedure for calculating an intuitive hazard metric for gust effects on airplanes is described. The hazard metric is for use by pilots and is intended to replace subjective pilot reports (PIREP's) of the turbulence level. The hazard metric is composed of 3 numbers: the first describes the average airplane response to the turbulence, the second describes the positive peak airplane response to the gusts, and the third describes the negative peak airplane response to the gusts. The hazard metric is derived from any time history of vertical gust measurements and is thus independent of the sensor making the gust measurements. The metric is demonstrated for one simulated airplane encountering different types of gusts including those derived from flight data recorder measurements of actual accidents. The simulated airplane responses to the gusts compare favorably with the hazard metric.

Nomenclature

A	non-dimensional gust amplitude, g's
$A_r^{'}$	dimensional gust amplitude over computation interval r, ft/sec
$\overline{A}_r$	non-dimensional gust amplitude over computational interval r, $\frac{A_r^{'}}{w_1}$, g's
$A_+^{'}$	measured gust amplitude in positive direction, ft/sec
$A_-^{'}$	measured gust amplitude in negative direction, ft/sec
$\overline{A}_+$	measured gust amplitude in positive direction, $\frac{A_+^{'}}{w_1}$, g's
$\overline{A}_-$	measured gust amplitude in negative direction, $\frac{A_-^{'}}{w_1}$, g's
$\hat{A}_r$	estimated gust amplitude required to produce 1g acceleration for a computational interval r, g's
$(\overline{A}_+)_r$	maximum measured gust amplitude in positive direction using a computational interval of r seconds (figure 3), g's
$(\overline{A}_-)_r$	minimum measured gust amplitude in negative direction using a computational interval of r seconds (figure 3), g's
$(\hat{A}_+)_r$	maximum estimated gust amplitude in positive direction using a computational interval of r seconds (figure 3), g's
$(\hat{A}_-)_r$	minimum estimated gust amplitude in negative direction using a computational interval of r seconds (figure 3), g's
a_{cg}	change in acceleration at the center of gravity (positive upward), g's
a_{aft}	change in acceleration at the aft passenger cabin (positive upward), g's
σ_n	running standard deviation of a_{cg} over a computational interval of 4 seconds, g's
$\overline{\sigma}_n$	average value of σ_n over reporting interval, g's
$\sigma_{4.0}^{'}$	standard deviation of vertical gust velocity over a 4-second computational interval, fps

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$\sigma_{4.0}$ standard deviation of non-dimensional vertical gust velocity over a 4-seconds computational interval, $\frac{\sigma_{4.0}}{w_1}$, g's

r computation interval (also called rise time), 0.25, 1.0, and 4.0 seconds in example

W airplane weight, lbs

w_g vertical gust velocity (positive upward), fps

ρ density of air, slug/ft^3

V true airspeed, fps

S wing area, ft^2

t time, seconds

$C_{L,\alpha}$ lift curve slope, per radian

w_1 gust amplitude of a step input that will cause a 1g acceleration ($2W/\rho VSC_{L,\alpha}$), fps

HM composite hazard metric, [HM_σ HM_+ HM_-], g's (Read as "' HM_σ ' g's continuous turbulence, with peaks to plus' HM_+ ' g's and minus ' HM_- ' g's")

HM_r hazard metric for peak gusts using a computation interval of r seconds, g's

HM_{peak} peak hazard metrics HM_+ and HM_-, g's

HM_+ component of composite hazard metric due to peak positive gusts, g's

HM_- component of composite hazard metric due to peak negative gusts, g's

HM_σ component of hazard metric for sigma level of turbulence, g's

Introduction

The National Aeronautics and Space Administration has initiated the Aviation Safety Program to reduce the aircraft accident rate by 80% in 10 years. One part of the program is aimed at reducing the injuries and deaths caused by extreme turbulence encounters. Airline experts report and the analysis of Flight Data Recorder (FDR) data indicate that these extreme events are caused by large, discrete gusts in the vertical direction, reference 1. The typical gust encounter that induces serious injuries lasts only a few seconds and is surrounded by relatively calm conditions. The (unbuckled) victim is usually thrown to the ceiling when the airplane momentarily experiences less than 0 g's vertical acceleration. The most severe injuries occur when the acceleration returns to normal positive values and the victim falls back to the floor or, worse yet, on the seat backs or arm rests. Usually the only damage to the airplane is confined to the airplane interior and is caused by the impact of unsecured objects and people with the cabin ceiling and overheads.

One approach to reducing the turbulence accident rate is to develop new or improved turbulence warning and avoidance sensors such as enhanced airborne radars or lidars, reference 2. However, a clearer definition of the turbulence characteristics that cause the accidents is needed so that the new sensor outputs can be made to accurately reflect these characteristics. Past turbulence metrics have had one or more deficiencies. For example, the turbulence metric described in reference 3 is a measure of the eddy dissipation rate, an "average" meteorological parameter unknown to most pilots. The metric described in reference 4 is a running average of the square of the vertical gust velocity. Neither metric is a direct measure of the peaks of dangerous discrete gusts that are of primary interests to pilots, reference 5. In addition, these metrics do not discriminate between positive gusts and the more dangerous negative gusts. Finally, since both are measures of only turbulence characteristics, they need to be multiplied by the appropriate airplane transfer functions to translate them into more useful information for pilots flying different airplanes at different airspeeds in the same turbulence field. This is not to say, however, that the average value of the turbulence is of no interest. For the majority of airline operations in turbulence, the turbulence has a relatively low level and appears to be more or less continuous. Therefore, any metric that is useful in all conditions must reflect the "average" value of continuous turbulence as well as the peaks of the discrete gusts.

The primary purpose of this paper is to define the discrete-gust components of the hazard metric as a function of the first-order, fundamental parameters that determine airplane gust response. A procedure for calculating the numerical values of these components of the hazard metric from measurements of vertical gust velocities is discussed. (The method of measuring these velocities is beyond the scope of this paper). The composite hazard metric, which also includes an average component for continuous turbulence, is intended to replace Pilot Reports (PIREPS) which are subjective, airplane-dependent estimates of turbulence intensity as described in the Aeronautical Information Manual (AIM), reference 6. Since the present metric is based on the characteristics of turbulence that are the root cause of airplane turbulence response, it can be used as the basis for developing sensor-dependent hazard metrics.

Theoretical Basis

Previous work, reference 7, has shown that the rise time of discrete gusts as well as their amplitude affects the theoretical severity of a gust encounter. For example, if an airplane gradually encounters a given amplitude gust, its response is much smaller than if the airplane encountered the same amplitude gust in a much shorter period of time. (The rise time is equal to the spatial dimension of the gust divided by the true airspeed of the encountering airplane. In the description of the hazard metric algorithm below, the "computation interval" is equal to the rise time). There is another class of parameters describing the characteristics of the encounter airplane that affects the airplane response, but these parameters are readily available on the data bus of most modern commercial airliners.

Desired Characteristics of Hazard Metric

A measure of the potential gust hazard to airplanes (hazard metric) that is intuitively obvious is needed. For example, a metric similar to the wind direction and magnitude information an airport traffic controller gives to a pilot approaching an airport would be useful. In-flight turbulence could be reported as: "Five knots continuous with peaks to plus 10 knots and minus 15 knots." The value of the continuous turbulence can be a simple running calculation of the standard deviation (sigma) of the vertical gust velocity and is related to ride comfort more than safety. It, therefore, is not the focus of this paper and the NASA's aviation safety program, but is included for completeness. The sigma value of the vertical velocity is closely related to the cube root of the eddy dissipation rate calculated in the in-situ turbulence algorithm described in reference 3. The cube root of the eddy dissipation rate (in meters$^{2/3}$/second) is more meaningful to meteorologists, and the sigma level of the turbulence (in knots or other velocity units) is more meaningful to pilots as a measure of the continuous turbulence and ride comfort.

For the large discrete gusts that cause accidents there may be no consistent relationship between the sigma value of the turbulence and the peak values. The peak values of the gusts are the metrics of interest to pilots from a safety standpoint, reference 5. But for the peak values to be of real value they must also reflect the rise time or the spatial extent of the gusts. In addition, reporting the turbulence levels in knots (or other velocity units) would require the pilot to mentally translate those numbers into a projected response of his airplane at the current airplane configuration and flight condition. Although a similar mental translation is currently required of pilots for the above-mentioned tower-reported wind conditions, a more useful hazard metric would automatically translate the gust velocities into response units such as g's. This translation could be easily accomplished with existing on-board computing capability and parameters already available on the airplane's data bus such as the airplane's weight, airspeed, and altitude. The turbulence could then be displayed to the pilot on his/her console message center as (for example): "Two-tenths g continuous, with peaks to plus five-tenths and minus eight-tenths g's." This is the type of hazard metric described herein. It actually consists of three numbers, HM_{σ}, HM_{+}, and HM_{-}, but will be referred to in the singular.

There is another desired characteristic of the hazard metric that is implicit in the above discussion. That is, the hazard metric is defined over a relatively long period of time and reported at the end of this period. This is desirable from the pilot's standpoint because of his limited capability to process large volumes of data. It is also desirable from the standpoint of data transmitting and receiving bandwidths requirements. That is, the datalink capacities on commercial airliners will limit the frequency that turbulence information can be reported or received. If bandwidth were not a factor, the complete time history of gust velocity measurements could be applied to an airplane-specific, configuration-specific, transfer function on every airplane. This approach would provide a more exact prediction of the airplane's response than the approximate response function incorporated in the present hazard metric.

Algorithm Description

Since this is a description of a sensor-independent hazard metric, it is assumed herein that a time history of the vertical gust velocity is available. The method used to make these measurements is not considered; see reference 2 for example measurements. Only the translation of these assumed gust velocities into a meaningful metric for pilots is discussed. The complete algorithm, shown in figure 1, is described in detail in the following discussion. The first part of the algorithm is the calculation of the sigma component of the hazard metric described by the upper leg of the flow diagram. The sigma level $\sigma_{4.0}(t)$ is calculated for a fixed interval of time. The preliminary suggested computation interval for this calculation is 4 seconds although the exact interval is not important since the values will be averaged later over the much longer reporting interval. The instantaneous sigma levels $\sigma'_{4.0}(t)$ in ft/sec are divided by w_1 to produce the non-dimensional sigma levels $\sigma_{4.0}(t)$, in g's. The first component of the hazard metric for the sigma turbulence is simply the average value of the 4-second running sigma level $\sigma_{4.0}$ over the reporting interval (suggested length of 2 minutes).

$$HM_\sigma = \bar{\sigma}_{4.0} \qquad (1)$$

The second part of the algorithm is the calculation of the peak components of the hazard metric described by the lower leg of the flow diagram. The first step in this leg is the calculation of the incremental gust amplitudes as illustrated in figure 2. The word "incremental" should be emphasized in the preceding sentence. The incremental amplitudes are calculated relative to the instantaneous value of the vertical gust velocity at the beginning of each computation interval. The figure shows calculations at two different measurement times t_1 and t_2. At each measurement, three least squares lines containing 0.25 seconds, 1.0 second, and 4.0 seconds of data are calculated from the w_g values supplied from the turbulence sensor at some given data rate. (For example, 100 samples, second). Only the slope of these lines is of interest since it is only the slope, and not the intercept, that affects the gust response of the airplane. The values of the slopes for each line are kept in separate bins for each computation interval (rise time), r, (0.25 seconds, 1.0 second, and 4.0 seconds in the above example). These three bins contain all the instantaneous values over a fixed interval of time (preliminary suggested reporting interval is 2 minutes). The values in each bin over the 2-minute interval are then multiplied by their respective computation interval (0.25, 1.0, or 4.0 seconds in the example) to produce the incremental gust amplitudes in the units of velocity—see typical incremental gust amplitude $A'_{1.0}(t_1)$ for the measurement at $t = t_1$ in figure 2. The dimensional gust amplitudes $A'_r(t)$ in ft/sec are then divided by w_1, the level of a step-input vertical gust that will produce an acceleration of 1 g, to produce the non-dimensional gust amplitudes $\bar{A}_r(t)$ in g's.

The next step in the calculations for peak hazard metric components is to scale the non-dimensional gust amplitudes $\bar{A}_r(t)$ to approximate the airplane response to different gust rise times. The result of this calculation is $HM_r(t)$, the estimate of airplane response due to gusts with lengths corresponding to r = 0.25, 1.0, and 4.0 seconds. The equation used was

$$HM_r = \bar{A}_r(t) / \hat{A}_r \qquad (2)$$

where

$$\hat{A}_r = 1 + r \quad \text{with r = 0.25, 1.0, and 4.0.} \qquad (3)$$

The equation for $\hat{A}_r$ is an approximation for the 1-g acceleration contour presented in figure 11 of reference 7. Further research may be needed to define a more representative equation for the whole commercial fleet.

The last step in the process is to determine the maximum and minimum values of HM_r to produce the peak hazard metric components, HM_+ and HM_-.

$$HM_+ = (HM_r)_{\max} \quad \text{and}$$
$$HM_- = (HM_r)_{\min} \qquad (4)$$

It should be noted that the dimensional sigma level $\sigma'_{4.0}(t)$ and the gust amplitudes $A'_r(t\ )$ may be useful to meteorologists for producing various weather products. However, the emphasis here is on a hazard metric for pilots for use in the cockpit in place of current PIREP's.

A graphical depiction of the logic involved in calculating the peak components of the hazard metric is presented in figure 3 for an assumed example. As can be seen from figure 3, the lines of constant +/- 1 g acceleration (corresponding to equation (3)) reflect the fundamental characteristic that larger gust amplitudes are required to produce the same acceleration level for longer rise times. The figure also illustrates the logic for calculating values of the peak hazard metric components HM_+ and HM_-.

For the present example of three rise times, the 6 peak non-dimensional gust amplitudes in the reporting interval can be compared with their corresponding values on the lines of constant +/- 1 g acceleration. The positive gust amplitude that is largest relative to its corresponding value on the +1g line will be the "reported" positive peak hazard metric component. A similar interpretation can be applied to the negative peak component. Of course, these operations are actually carried out in the algorithm by equations (1) thru (3) for HM_+ and HM_-. In the example shown in figure 3, $(\overline{A}_+)_{1.0}$ is the largest relative positive gust, and $(\overline{A}_-)_{4.0}$ is the largest relative negative gust.

For this paper, a distinction is made between positive and negative gusts since negative gusts are considered more dangerous because they can cause people to rise off the floor or their seats. However, further research may indicate that only the largest absolute peak hazard metric (or only the negative hazard metric) is needed. The sigma hazard metric component will probably be necessary no matter which peak hazard metric component is used.

The three rise times used in this paper correspond to different spatial dimensions of the turbulence depending on the true airspeed of the airplane. For a typical cruise speed of 800 ft/sec, the corresponding spatial dimensions are 200 ft, 800ft, and 3200 ft. The present values of rise time are preliminary and further research may be needed to establish final values. In addition, more than three different values of rise time could be used for finer rise time resolution or a wider range of rise times.

Simulated Cases

Sample calculations were made to illustrate the application of the hazard metric using the preliminary values of the defining parameters. The one exception to the suggested preliminary values is the 2-minute reporting interval because the data did not exist for that length of time. In these calculations, various gust shapes were used as input to the longitudinal math model for the140,000 lb transport airplane described in reference 7. The simulated airplane responses to these gust shapes were then recorded and the maximum and minimum accelerations at the center of gravity were determined. The hazard metric was, on the other hand, calculated solely from the input gust shapes and the gust parameter w_1 as described above. The results of these calculations are shown in the following figures. The simulations were run using a time increment of .01 seconds. The effect of the values of the time increment on the comparison was not investigated.

Discrete Gust Example The results of the calculations for a gust profile derived from the flight recorder measurements of an actual accident are presented in figure 4. The gust profile is representative of a discrete gust that causes accidents. The 4-second running sigma calculation of the vertical gust velocity, $\sigma'_{4.0}$, begins with a relatively large value because it includes the first 4 seconds of the data in figure 4. When $\sigma'_{4.0}$ is non-dimensionalized by w_1 and then averaged over the 14 seconds of available data, the sigma hazard metric component is about twice the averaged simulated c.g. acceleration (1.18 g's compared to 0.62 g's), figure 5. Thus, the sigma hazard metric component does not correlate well with the simulated response for a discrete gust. This result was expected since the sigma hazard metric component is designed for low-level continuous turbulence and not discrete gusts. In addition, it should be remembered that for this example, the averaging time for HM_σ was only 14 seconds rather than the suggested 2 minutes for an operational algorithm. If 2 minutes of flight data were available, the averaged values $\overline{\sigma}_n$ and HM_σ would probably be much smaller than in this calculation because of the apparent limited spatial extent of this particular discrete gust. In fact, if the averaging interval (reporting interval) were much longer, $\overline{\sigma}_n$ and HM_σ would approach zero even though there are very dangerous peaks in the gust. These peaks are captured by the peak hazard metric components described next.

The dimensional gust amplitudes, A''s, for the peak components of the hazard metric are also presented in figure 4. The largest (absolute) dimensional gust amplitude for this discrete gust is for the 4-second rise time. However, the calculations shown in figure 5 indicate that when the amplitudes are adjusted for the response characteristics of the airplane (using equation (3)), the resulting hazard metric for the 1.0-second rise time has the largest values (+1.29 g's and −2.50 g's). These values compare reasonably well to the largest simulated accelerations at the center of gravity of 1.73 g's and −1.87 g's. Although the comparison might be improved by using different rise times, the comparison for other gust profiles might be degraded. A large variety of gust shapes must be examined to see which rise times, etc give the best overall correlation. Continuous Turbulence Example

Continuous Turbulence It is instructive to examine the characteristics of the 3 hazard metric components for continuous turbulence. The dimensional parameters for Dryden turbulence (sigma level = 30 fps and characteristics scale length of 1750 feet) are shown in figure 6. The 4-second running sigma level, $\sigma'_{4.0}$ is relatively constant as it should be for continuous turbulence. In addition, the sigma hazard metric component, HM_σ, compares favorably with the averaged sigma simulated acceleration, $\overline{\sigma}_n$, (1.47 g's and 1.29 g's respectively in figure 7). This result was expected since the sigma hazard metric component was designed for continuous turbulence such as this.

The 3 peak amplitude traces ($A'_{.25}$, $A'_{1.0}$, $A'_{4.0}$ in figure 6) show that this part of the algorithm effectively filters the gust velocities with the longer rise times corresponding to longer filter time constants. For this turbulence, the peaks of the incremental gust amplitudes are practically equal for rise times of 0.25 seconds and 1.0 seconds while the gust amplitudes for the 4.0-second rise time are much smaller. When the dimensional amplitudes are adjusted for the airplane response, the peak hazard metric components for the 0.25-second rise time are the largest, figure 7, rather than those for the 1.0-second rise time for the discrete gust example. This result reflects the high frequency content of the Dryden turbulence. The final values for the peak hazard metric components are +4.71 g's and –3.09 g's. These values do not compare as favorably with the simulated peak c.g. accelerations (2.59 g's and –3.26 g's) as did the previous values for the discrete gusts. However, more examples are needed to draw firm conclusions. Another noticeable difference in the calculations in figure 7 is the high frequency (3 Hz) response in the acceleration at the aft cabin location. This response is due to the first-fuselage-bending mode being excited by the high frequency components of the Dryden turbulence. The present hazard metric does not account for structural responses, but as shown in reference 3 high frequency accelerations are not likely to cause passenger injuries.

Collected Results: Twelve additional gust wave shapes were investigated in addition to the two examples shown above. That is, mountain rotor wave shapes with 4 different amplitudes and gust lengths were simulated using the expression described in reference 7. Two additional discrete gusts from actual airplane accidents were simulated, as were four 1-cosine gusts, and two additional Dryden turbulence fields with different sigma levels and scale lengths. The results of these calculations are summarized in figures 8-10. The agreement between the peak hazard metric components, figure 8, is acceptable for most of the gust shapes with the poorest agreement for the continuous Dryden turbulence as expected. Generally, the largest disagreement is in a conservative direction; that is, the peak hazard metric over-predicts the actual accelerations.

Although the hazard metric presented here was designed to predict the acceleration at the center of gravity, a comparison of the peak hazard metric components and the acceleration at the aft passenger cabin are compared in figure 9. The biggest difference between figures 8 and 9 is that the simulated accelerations in the aft cabin, $(a_{aft})_{peak}$, are shifted to larger absolute values especially for the Dryden turbulence. This result is to be expected since the airplane's rigid-body pitching motion and the structural response tend to increase the acceleration at the aft cabin compared to the acceleration at the center of gravity. But as mentioned earlier, the high-frequency accelerations due to the structural mode are not as likely to cause passenger injuries as are the lower rigid-body accelerations, reference 7.

The sigma component of the hazard metric is compared to the simulated sigma acceleration at the center of gravity in figure 10. As expected the agreement is good for the Dryden turbulence but poor for the discrete gusts. This result is the opposite of the result shown in figure 8. Thus, these two figures show that the sigma component and the peak components complement each other for different types of turbulence. It should be emphasized that the above data are for simulated airplane responses. As shown in reference 7, the actual airplane response in the NTSB-reported data were sometimes much larger than the simulated responses. The reason for this discrepancy was most probably due to either transients when the auto-pilot disconnected or out-of-phase inputs by the pilot. No hazard metric will probably ever be able to predict the response of every pilot to an unexpected turbulence upset.

Concluding Remarks

A quantitative hazard metric for airplane turbulence response has been described. The metric is intuitively and is intended to replace the subjective, airplane-dependent Pilot Reports (PIREPS) in current use. A procedure for calculating the metric has been described and demonstrated using preliminary values for the fixed parameters defining the metric. The metric has been applied to simulated discrete and continuous gust encounters and has been shown to give reasonable results. That is, the discrete gusts are adequately described by the "peak" components of the hazard metric, and continuous turbulence is adequately described by the "sigma" component of the hazard metric.

The fixed parameters defining the hazard metric need to be more thoroughly checked before the hazard metric is operational. The metric should also be compared to actual airplane responses (rather than simulated responses as was done here) for several encounters of real turbulence by instrumented airplanes. The correlation is expected to be useable for most modern transport airplanes. The defining parameters of the final hazard metric will be a compromise for different gust shapes/flight conditions/airplanes/etc.

The parameters that need to be optimized/ascertained are:

(1) The number of rise times in the "peak" hazard metric component calculations (3 in above example)
(2) The values of the rise times over which the peak gust amplitudes are calculated (0.25, 1.0, and 4.0 in above example).
(3) The best relationship between gust amplitude and rise time for adjusting the dimensional gust amplitudes of airplane response (equation (3)).
(4) The time interval over which the metrics are averaged and reported (2 minutes preliminary suggested value).
(5) The number of peak hazard metric values that need to be reported. That is, whether both positive and negative hazard metric components need to be reported (as in above example) or is the largest absolute metric or the negative metric sufficient.
(6) The effect of spatial or temporal resolution (data rate) of the vertical gust measurements.

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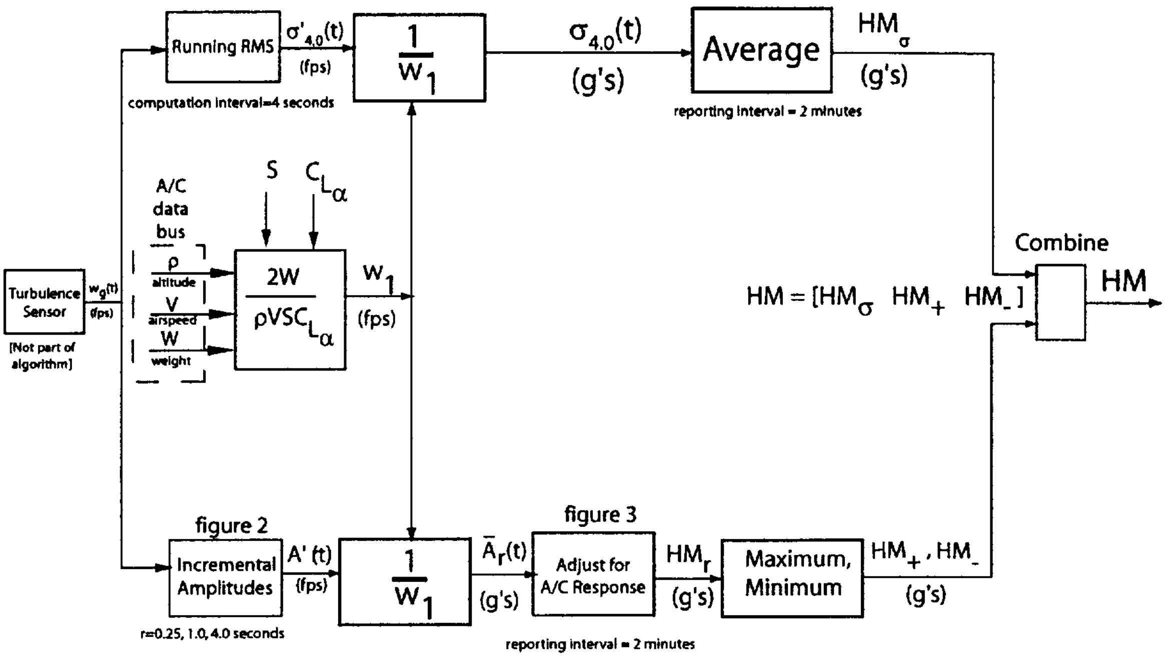

Figure 1. Flow diagram of hazard metric calculation.

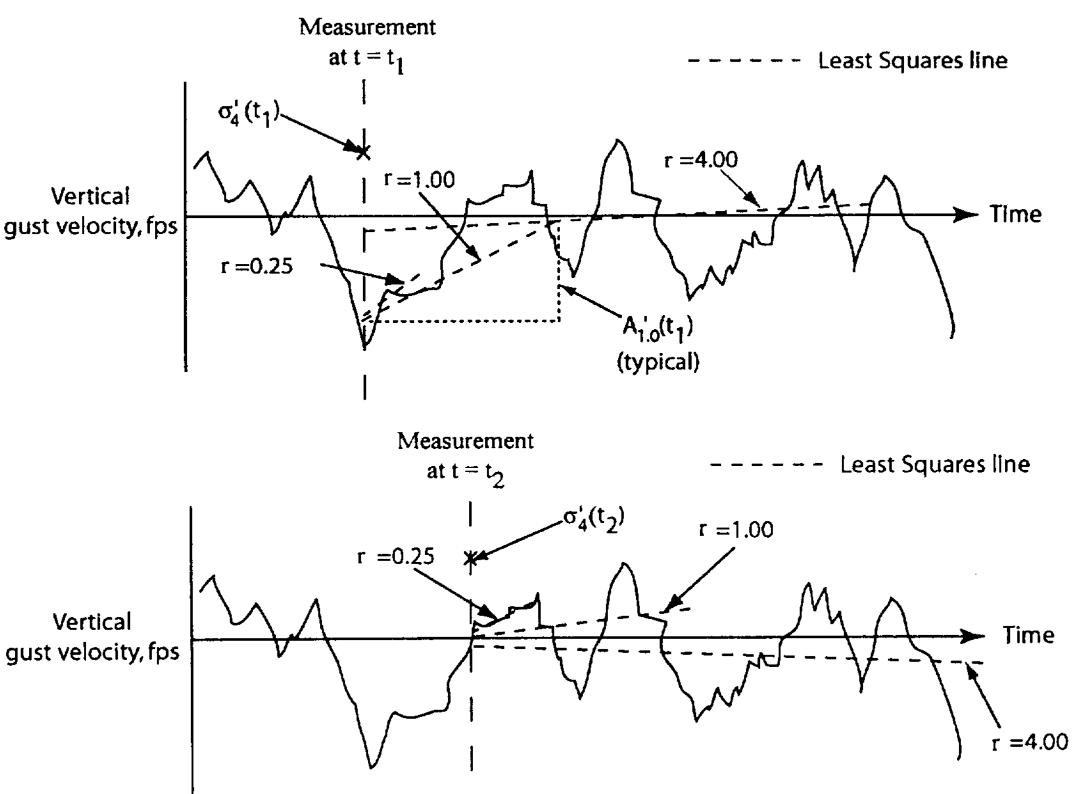

Figure 2. Illustration of incremental, dimensional gust amplitude calculations.

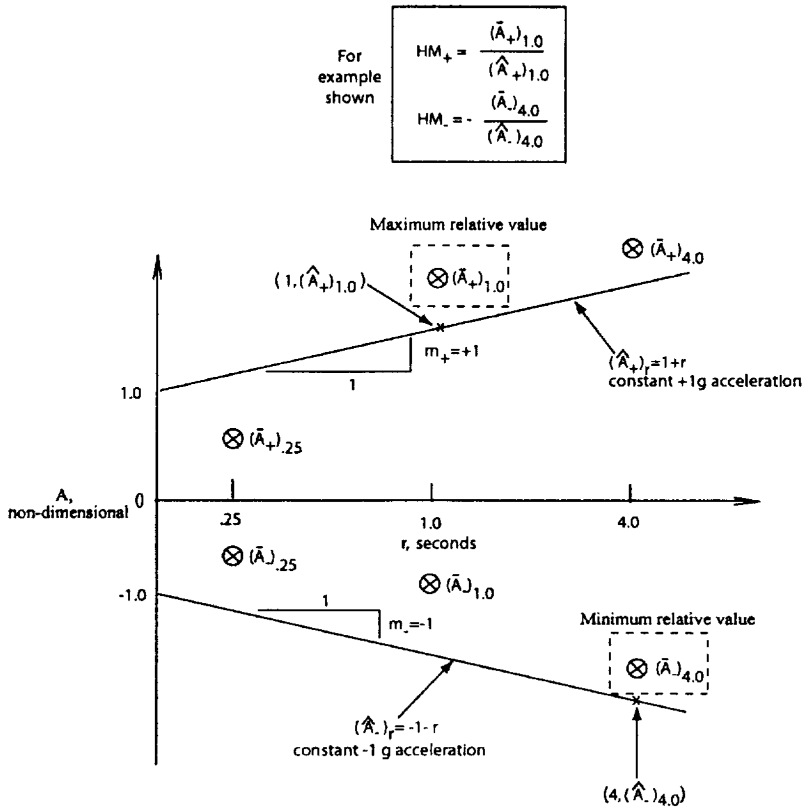

Figure 3. Graphical depiction of the terms involved in the peak values of the hazard metric.

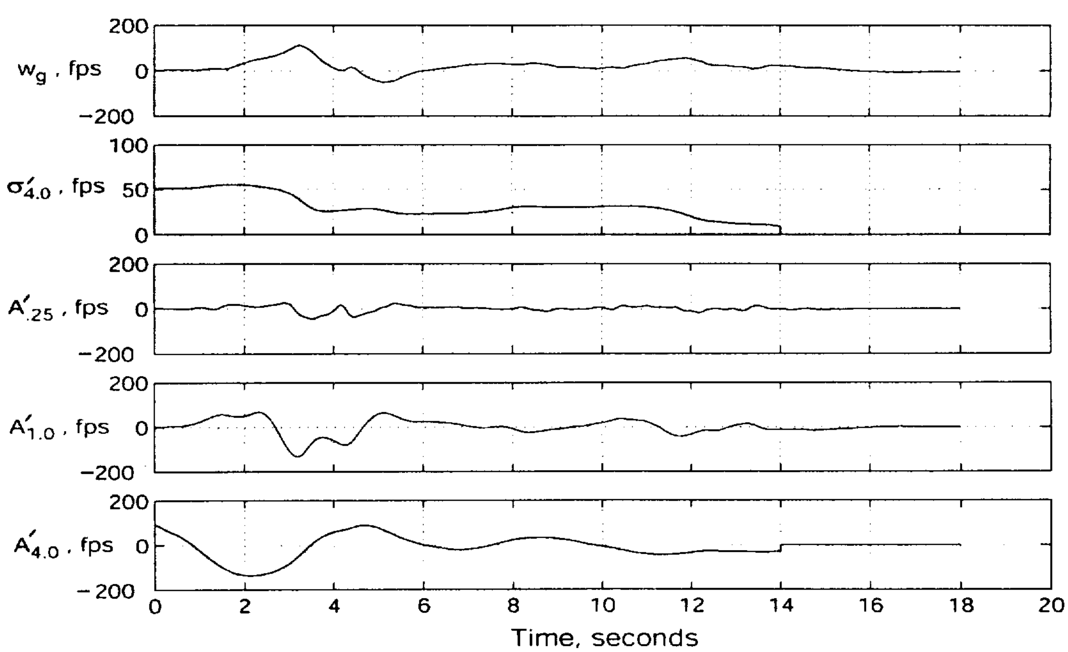

Figure 4. Incremental, dimensional gust amplitudes and running SIGMA for a discrete gust

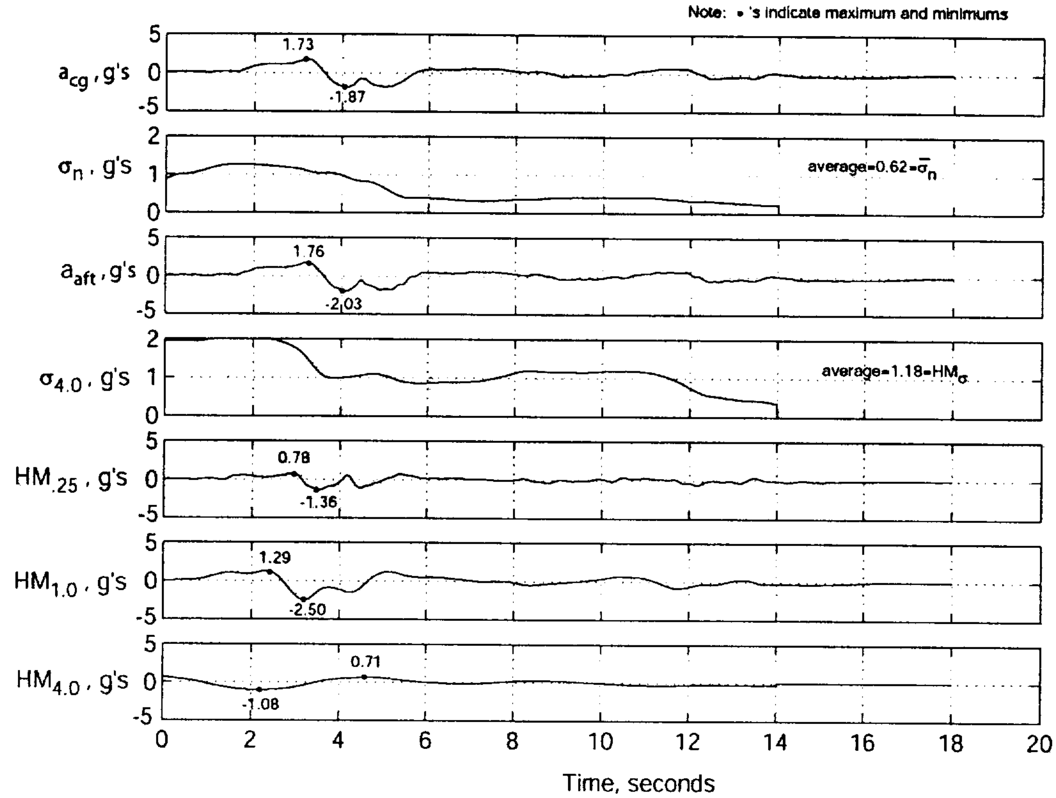

Figure 5. Hazard metrics components for a discrete gust.

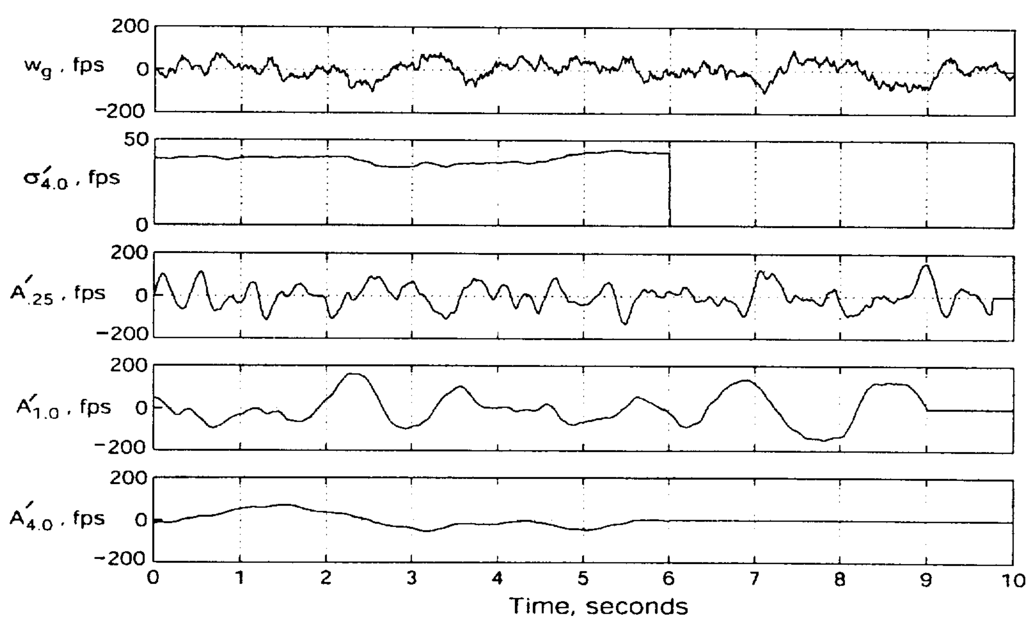

Figure 6. Incremental gust amplitudes and running SIGMA for Dryden turbulence.

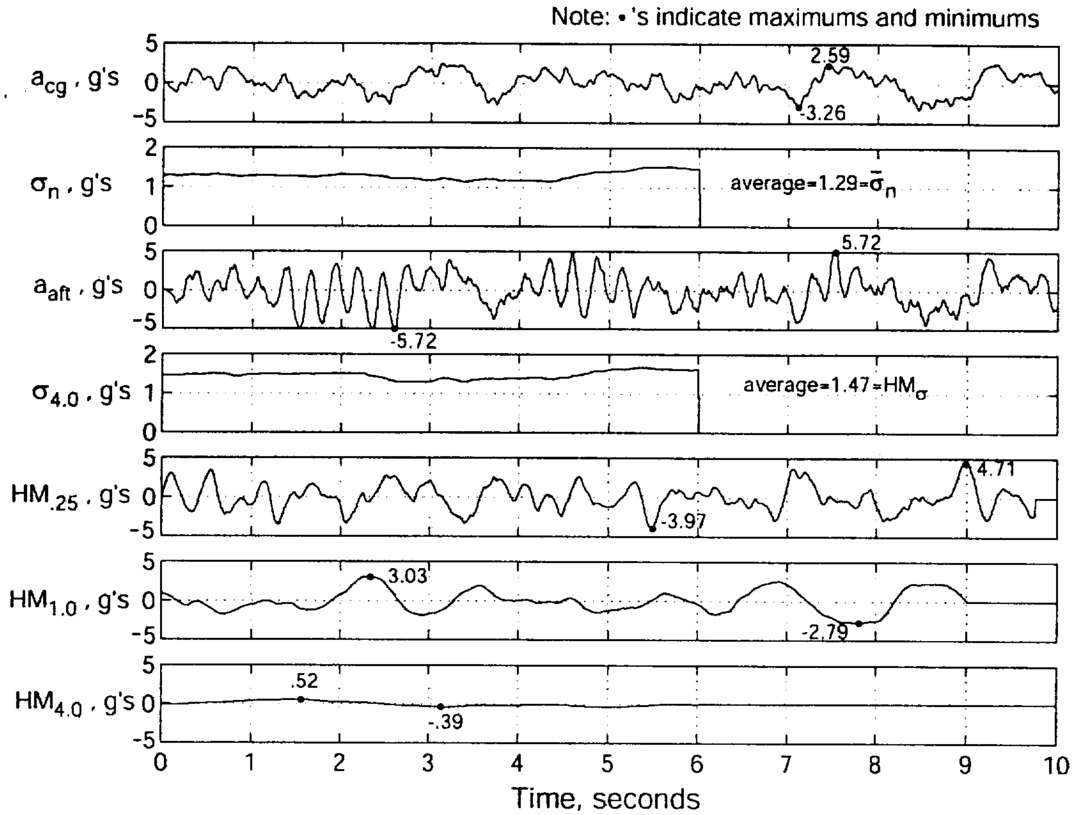

Figure 7. Hazard metric components for Dryden turbulence

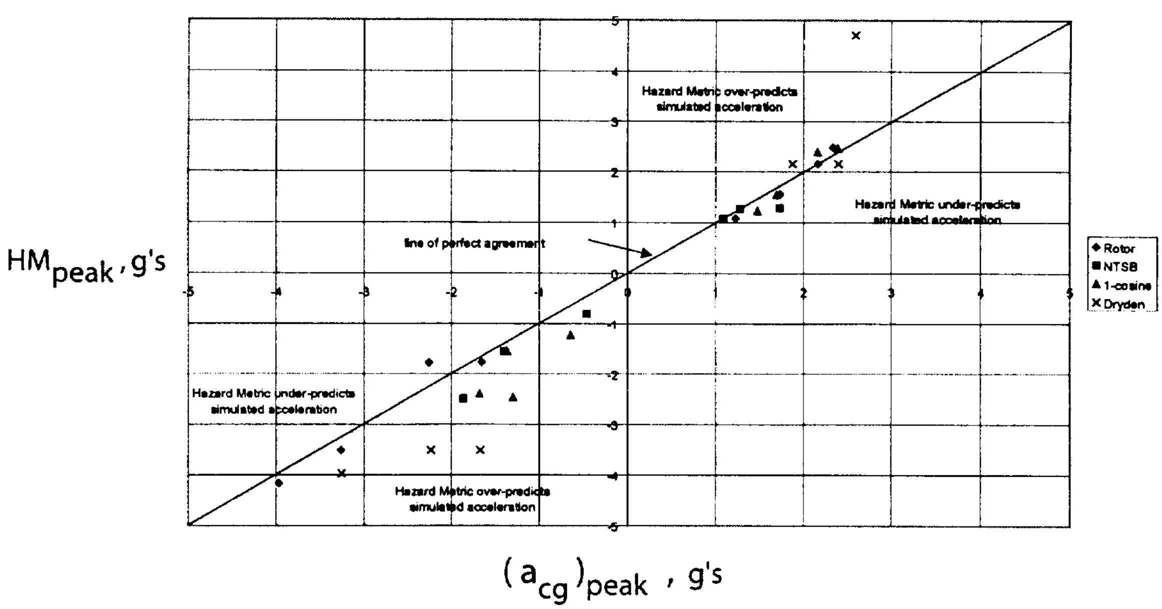

Figure 8. Comparison of the peak hazard metric components with simulated accelerations at the center of gravity

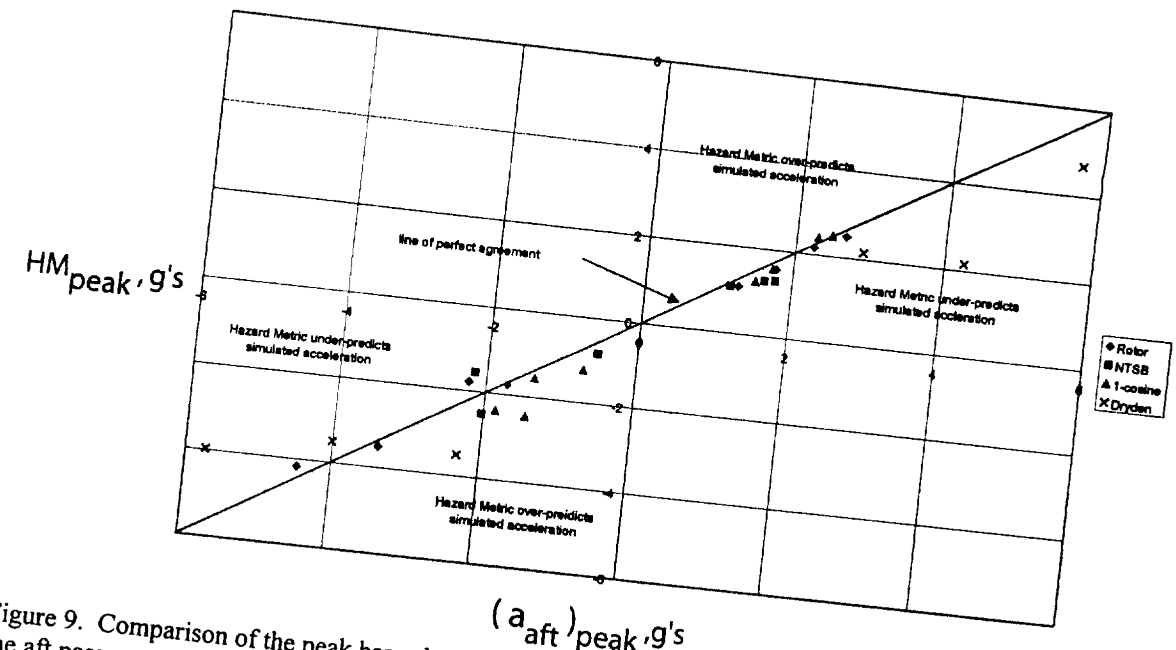

Figure 9. Comparison of the peak hazard metric components with the simulated accelerations at the aft passenger cabin.

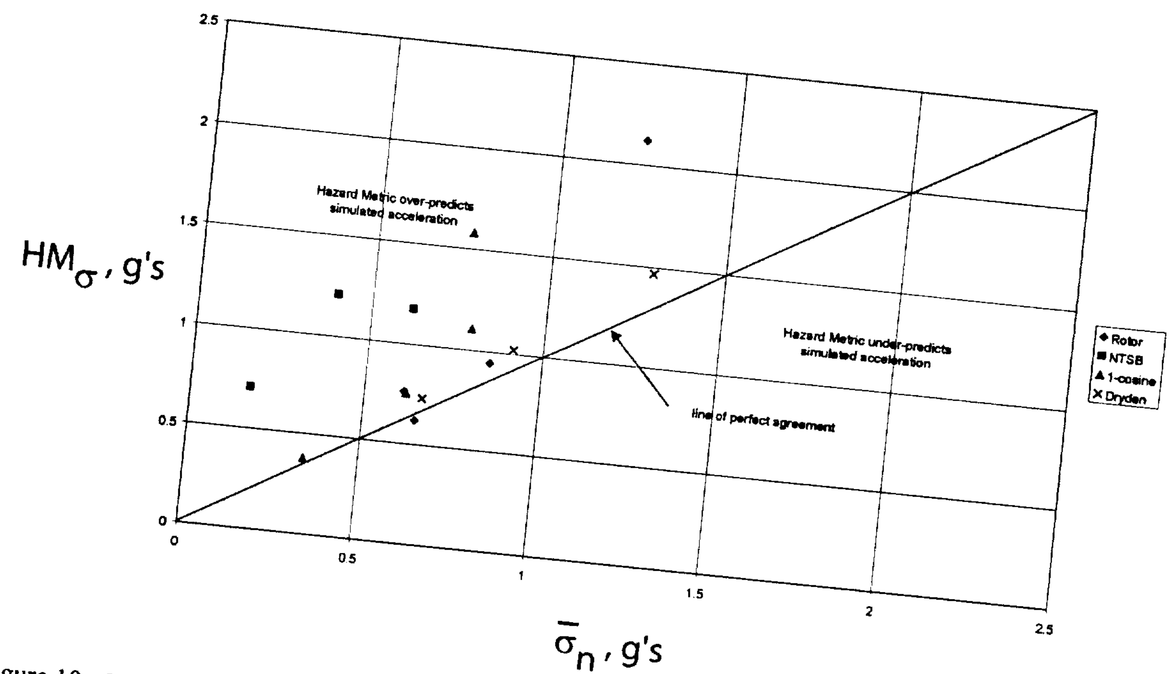

Figure 10. Sigma component of hazard metric for various types of turbulence.