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Abstract

Positive wavelet analysis is applied to the normal acceleration response of a simple helicopter model to atmospheric turbulence. The method extracts ride quality information about events having a time scale that influences flying qualities. A generalised form of quickness chart is found to be a suitable medium for presenting the results of the wavelet analysis. The SDG model of turbulence is proposed as a useful tool for the validation of the approach and for indicating a viable form for the definition of criteria for helicopter ride quality. The approach develops an analytical framework for extending ride quality studies beyond noise and vibration and into the area where they impinge on the piloting task.

Nomenclature

l	wavelet scale length
t	time
w	normal velocity component, gust intensity
y	peak response
$H, \overline{H}$	gust ramp length, tuned gust ramp length
$\gamma, \overline{\gamma}$	peak response, tuned peak response of SDG family of gusts
a_z	normal acceleration
Q	quickness
$\Delta\phi$	increment in roll angle
$\dot{\phi}_{peak}$	peak roll rate
α, β	turbulence parameters
λ	parameter of SDG analysis
$N_{H,w}$	density of rate of occurrence of gusts
n_y	rate of occurrence of response peaks
$M_{Q,y}$	density of rate of occurrence of response peaks

1. Introduction

Ride qualities and handling qualities are complementary aspects of the overall flying qualities of a helicopter. While handling qualities are concerned with the ease and precision with which piloting tasks can be performed, ride qualities are concerned with the effect of external or extraneous influences on the ride comfort and pilot workload. For the former, enhanced responsiveness is generally a desirable quality but it is undesirable in the context of the latter. Therefore, the objective in improving helicopter flying qualities as a whole is to seek to increase the responsiveness of a helicopter to pilot inputs while at the same time reducing its responsiveness to external effects - with the provisor that in both cases the term responsiveness needs careful and appropriate definition.

Established criteria for the assessment of handling qualities have recently become available through the publication of a set of comprehensive handling qualities requirements for military rotorcraft [1]. As a result, this aspect of flying qualities has received considerable attention [e.g 2,3] while ride quality has been relatively neglected. Existing criteria for ride quality are principally directed towards the areas of noise and vibration and they are briefly discussed in section 2. Discomfort is quantified through a spectral approach to the classification of noise and vibration levels and, as a consequence, the resulting criteria are concerned with a relatively high range of frequencies compared to those encountered in handling qualities.

An important factor in ride quality as it affects pilot workload is the response to gusts present in atmospheric turbulence. Typically, the responses possess significant energy in a fequency range which is intermediate between the high frequency of the disturbances caused by noise or vibration and the low frequency of the long-period helicopter modes. The interaction of these gusts with the airframe and rotating blades is complex and produces both an increase in vibrational disturbance [4] and an intermediate frequency vehicle-response which is composed of discrete events with identifiable structures. The consequent disturbances begin to intrude into the piloting task and impose an additional pilot workload since the responses are intermittent events that require active pilot attention rather than passive toleration as a background of vibrational discomfort.

When seeking to analyse helicopter responses in order to extract ride quality information it is necessary, therefore, to adopt techniques that will encompass both high and low frequency signals and will identify discrete, intermediate frequency, events. The approach taken in a collaborative programme of research between the Defence Research Agency, Bedford, (DRA) and Glasgow Caledonian University (GCU) is to apply wavelet analysis techniques to decompose the response signal into discrete events of different time scales, amplitudes and locations. The method has previously been successfully used to detect features in signals containing a fractal background [e.g 5]. Its application to responses to atmospheric turbulence is described below, in section 3.

For the subsequent post-processing of the event data into a form suitable for expressing criteria for ride quality a type of quickness chart is employed. In handling qualities assessment, quickness charts [1] are employed to represent significant events in the response of a helicopter to pilot inputs during defined manoeuvres. Section 4, below, discusses their additional application to the representation of responses to atmospheric turbulence. Arising from this approach is confirmation that 'quickness' is a generic concept dependent only on the underlying time-scale of the events in the response. The successful development of the use of wavelet analysis and quickness charts in association in order to provide a meaningful representation of the events embedded in a response also brings the potential for the specification of ride quality criteria that are applicable to helicopters in a wide range of flight regimes including cruise, manoeuvring and NOE tasks. In quickness charts therefore there lies a common method of representation for the two aspects of flying qualities

The Statistical Discrete Gust (SDG) model of turbulence [6] may be used to predict the outcomes of the analysis based on the wavelet techniques. The SDG model and its implications are discussed in section 5. The tuning property which is an important outcome of the SDG model predicts particular features of the response quickness charts. These features are illustrated by a simulation study and the concepts are developed in section 6 into a proposed method for expressing ride quality criteria for helicopters encountering atmospheric turbulence.

2. Existing Criteria for Ride Quality.

The objective specification of ride quality or ride comfort criteria is a difficult task since it attempts to place an objective definition onto a quantity which is usually deemed to be entirely subjective. A survey of the existing literature defining ride quality criteria [7] shows that most of the recent research concentrates on defining ride quality using relatively high frequency measurements. Accordingly, present ride quality criteria are based on measurements of noise and/or vibration levels and depend on human subjective recordings for their validation. A summary of two methods for determining ride comfort illustrate the current situation.

The first method is based on a ride quality meter (RQM) developed by NASA to characterise ride comfort based on measurement of interior noise and vibration [8]. The vibration is measured in five axes (vertical, lateral, longitudinal, roll and pitch) and the RQM then combines these into a single vibration discomfort component. Similarly the vehicle noise contribution is computed for noises within six octave bands, having frequencies of 63, 125, 250, 500, 1000 and 2000 Hz. and summed into a single noise component. The two components are then added to provide a total discomfort index for the ride. The key to the NASA approach is the combination of physical units into subjective discomfort units. A notable feature of the NASA discomfort index is that it is possible to identify the relative contribution of the vibration and noise parameters.

The second method [9] used data collected over a number of scheduled flights involving three planes (Nord, Twin Otter and Beech 99) and one helicopter (S-61). Recordings of the six motion variables (yaw rate now included) were made and passengers gave detailed subjective discomfort ratings. Each measure of motion was correlated with comfort to show how relevant each of the physical measures is to comfort. The correlations were used to develop a model based on a point scale of comfort rating. It is worthwhile noting that unlike the NASA approach this latter method includes data from a number of helicopter flights.

Both of these methods are based on RMS levels of high frequency noise and vibration. The quality of the ride in respect of its influence on pilot workload or task viability is, as a consequence, beyond the scope of these techniques. It is therefore necessary to develop new techniques which are capable of recognising discrete response events of a relatively long time scale.

3. Wavelets and Correlation Surfaces

The analysis method adopted for the current study is illustrated by means of simulated responses to measured turbulence using a linear model of a Lynx helicopter with the reference state corresponding to level flight at 60 kts. The model is obtained via the HELISTAB [10] package which has a facility for isolating the aerodynamic contributions to the linear coefficients of the model. It is therefore a straightforward matter to apply measured turbulence data to this simple model, to which, for the purposes of this investigation, stabilising feedback has been added. The response variable used in this investigation is the normal acceleration of the helicopter. It is an important parameter in ride quality and serves to give an authentic illustration of the technique. Fig.1(a) shows a sample of the vertical component of measured turbulence together with the corresponding response of the normal acceleration a_z. for the linear model. It can be observed that the complexity of the response renders the identification of the amplitude and time-scale of the significant discrete features a task which requires a sophisticated analysis techniques. In order to obtain the required precision and robustness in detecting and extracting discrete events from the response a wavelet technique is adopted. A similar approach has been taken in the analysis of control displacements for workload studies [11]. The positive wavelet approach was developed by Jones in Ref. 5 for the processing of pre-whitened atmospheric turbulence and similar fractal phenomena. The basis of the method is to decompose the given time response into a superposition of positive wavelets of the form

$$y = (\frac{1}{2} + \frac{1}{2}\cos(\frac{2\pi t}{l})); \quad -\frac{l}{2} < t < \frac{l}{2}. \tag{3.1}$$

The fundamental wavelet is illustrated in Fig. 2 . It has unit amplitude, scale l and is located at the origin. It may be stretched by increasing the scale l and located arbitrarily by a simple change of the time, t, origin.

The starting point for the analysis is to correlate the given response, shown in Fig 1(b), with wavelets of different scales and location to produce a correlation matrix. The correlation surface represented by this matrix is shown in Fig. 3 . It possesses extrema, both local maxima and minima, which correspond to discrete features of the wavelet shape embedded in the original response. A scan of the correlation matrix readily locates these extrema and the original signal is decomposed into a list of wavelets of appropriate scale, amplitude and location. The component wavelets may be used to make a reconstruction of the original signal [5] but in the present application the wavelet data must be converted to a form from which ride quality information can be readily deduced. The presentational form chosen in the current work is to display the data using quickness charts. The justification for the use of such charts in areas other than handling qualities is argued in section 4 below.

4. Quickness Charts

Quickness charts are used in ADS 33C to represent events in response data for handling qualities assessment. The calculation of quickness values is illustrated in Fig. 4 for the attitude reponse in a simulation of a helicopter executing a side step manoeuvre [11]. The quickness value is calculated from the formula

$$Q = \frac{\dot{\phi}_{peak}}{\Delta\phi} \qquad (4.1)$$

for the significant increments in roll angle ϕ. These values are then plotted against the increment $\Delta\phi$ on a chart marked with the regions corresponding to varying levels of handling rating in accordance with the procedure described in ADS 33C. and shown in Fig. 5 ($\Delta\phi$ is used here in place of $\Delta\phi_{min}$ since there is little overshoot in the responses of ϕ). Since the manoeuvre is, in essence, a rotation about a single axis the peaks of $\dot{\phi}$ may be identified from the roll rate p response. It is then possible - and is the method normally employed in direct, automatic, processing of the responses - to integrate the pulses of p in order to obtain the increments of ϕ.

The dimensions of quickness, the vertical axis on the quickness chart, are those of frequency and the horizontal axis is the magnitude of the increments of the helicopter's roll angle. The horizontal axis is chosen this way since the amplitude of the discrete changes of roll angle is the key performance parameter in the assessment of handling qualities of the sidestep manoeuvre. Padfield [e.g.12] has argued that underlying the use of quickness parameters is a general principle that matches, in relation to responsiveness, high frequency and small displacements with low frequency and large displacements. Contours of equal 'responsiveness', following the argument above, resemble hyperbolae and responsiveness increases the further away the contour is from the axes (Fig. 6) . For handling qualities, the need is for enhancement of responsiveness to pilot input therefore one would expect that desirable handling qualities would indeed correspond to increasing responsiveness. On a quickness chart, therefore, the level of handling qualities improves as the regions move away from the axes. As indicated earlier, responsiveness is undesirable when considered in relation to the effect of turbulence on ride quality so it is to be expected that in any application of quickness charts the ride quality will deteriorate as the regions move away from the axes. However, the first step is to specify which variables are to be represented on the quickness chart. In the present work, as indicated above, attention has been focussed on the normal acceleration of the helicopter as the prime parameter determining ride quality, and the quickness values have been calculated by identifying discrete pulses of normal acceleration. The quickness value for such an event is calculated from

$$Q = \frac{a_{z_{peak}}}{\Delta w} \qquad (4.2)$$

where

$$w = \int_t a_z dt \qquad (4.3)$$

and the integral is taken over the duration of the pulse in a_z. A similar approach has been taken by Thomson and Bradley [11] where pulses in the lateral cyclic control have been used to quantify workload in a sidestep manoeuvre. The calculation of quickness values from a response typified by Fig.1(b) presents a significantly greater problem than a response arising from handling qualities studies such as Fig. 4. The latter has a small number of discrete events of significant amplitude and they have similar duration. As a result the pulses are easily identified by inspection or simple processing, for example, by detecting changes of sign of the response in order to isolate pulses. The response to turbulence is a combination of a large number of discrete events of different durations corresponding to the frequency content of the response. Direct processing of the results is therefore inappropriate and special techniques are called for in order to extract the variety of discrete pulse-events of which the response is composed. For the response to turbulence, the quickness chart is prepared from the wavelets which comprise the response and have been extracted by the analysis software. For each detected wavelet in the compiled list, a quickness value is calculated. The wavelet form eqn. (3.1) gives a quickness value which reduces to

$$Q = \frac{2}{l} \qquad (4.4)$$

It should not be surprising that the quickness value depends soley on the scale l of the associated wavelet. It is clear that cast in terms of a wavelet approach the quickness measures the time-scale (by its inverse) of a discrete event and thus provides a generic measure which is independent choice of the horizontal axis. It is therefore possible to seek to attach to this axis a suitable measure for ride quality and the current study has focussed on the peak normal acceleration $a_{z_{peak}}$, the value of which is available for each component wavelet from an examination of the correlation matrix. The quickness chart so produced is of the generic type described by Padfield with axes corresponding to frequency and amplitude both increasing in the direction of general undesirability in terms of the quality of the ride.

The wavelet techniques developed at DRA and employed at GCU provide a reliable and consistent method of extracting quickness data. With the availability of such tools, quickness charts can provide an objective measure of ride quality by quantifying the rate of occurrence of pulses of different amplitudes and quickness values. The calculated quickness values are shown in Fig. 7. It can be seen that the response contains events possessing a wide range of quickness values and that the dynamics of the system appear to have little influence on the distribution of points.

The analysis techniques have been discussed for a response to a sample of measured atmospheric turbulence but the process may also be applied to an appropriate analytic formulation of atmospheric turbulence. In particular, the SDG model has a close association with wavelet concepts and it is a useful validation exercise to examine this model and derive predictions for the general appearance and special features of the quickness chart.

5. The Statistical Discrete Gust (SDG) Model of Turbulence

The SDG model of turbulence is a stochastic representation where atmospheric turbulence is composed of discrete gusts of different amplitudes and spatial scales. The relationship between the scale of a gust and the mean amplitude of gusts of that scale defines the spectral properties of the turbulence. The SDG model is therefore compositional in nature and its discrete formulation makes it appropriate to the current application.

The starting point is to consider a discrete ramp gust as a basic element from which atmospheric turbulence is made up. This is illustrated in Fig. 8 which shows a gust rising to its maximum intensity w over a distance (ramp-length) H. In many applications, and of interest in the current study, the ramp gust represents an increment in the vertical velocity component of turbulence. The SDG model of turbulence considers an aggregation of such gusts in the following way. The number of discrete gusts per unit distance in the ramp length range $(H,\ H+dH)$ with gust intensity greater than w is taken to be $N_{H,w}\,dH$ where

$$N_{H,w} = (\alpha / H^2)\ \exp(-w / (1.15\beta H^{1/3})) \quad (5.1)$$

This distribution is illustrated in Fig. 9. Jones [6] notes several important features that this relationship incorporates:

(a) The distribution for fixed H is exponential and therefore non-Gaussian.

(b) The H^{-2} factor gives self similarity.

(c) α is a constant defining the mean rate of occurrence of gusts.

(d) The $H^{1/3}$ factor is related to the '-5/3' exponent of the power spectrum.

The numerical constant 1.15 merely simplifies some subsequent formulae and β measures the overall amplitude of the gusts.

The second element of the SDG approach is the powerful result which follows from the application of the turbulence model to the response of a linear system. It can be shown that the number, n_y, of peaks of the response whose magnitude exceeds y is given asymptotically by

$$n_y = (\alpha / \lambda\overline{H})\ \exp\ (\ -\ y / (\beta\,\gamma(\overline{H}))) \quad (5.2)$$

where the quantities $\overline{H}$, $\gamma(\overline{H})$, and λ are derived according to the following discussion.

Fig. 8 illustrates the response of a linear system to a discrete gust of intensity w and ramp-length H. The response is considered to have a single dominant peak of magnitude γ. When the ramp-length, H, is varied and the intensity w is made proportional to $H^{1/3}$, it is found that for many practical systems there is an optimum value for H that maximises the peak response γ. This situation is illustrated in Fig. 10; the optimum (or tuned) value of H is denoted $\overline{H}$ and the corresponding value of γ is $\gamma(\overline{H})$. The constant λ employed above is related to the curvature of the graph of γ at the optimum point. Values for $\overline{H}$, $\gamma(\overline{H})$ and λ may be determined by straightforward analysis and then used in the formula for n_y, above, either to validate the model through the use of direct turbulence measurements or to make response predictions. It is clear that the graph of $\ln(n_y \lambda \overline{H})$ against $y / \gamma(\overline{H})$ should be a straight line with $\ln(\alpha)$ and $-1/\beta$, which are parameters in the original turbulence model, as intercept and slope. Thus such graphs characterise the original turbulence and should be independent of the system employed in generating the responses.

Physically, the result indicates that only those gusts close to the tuned ramp-length cause significantly large resulting peaks in response. The statistics of the original SDG model dictate this crucial tuning property. The method may be extended to encompass systems which have more than one significant peak in response and to apply to systems which exhibit non-linearity, but the fundamental tuning property is retained. Using the SDG model, the statistical properties of the turbulence may be related to the features present in the response. One of the strengths of the method is that subsequent developments have not changed the original concept or the validity of its predictions.

In the current work the linear system is the helicopter model described in section 3, and the ramp lengths are measured in time rather than distance so that the scale length l is used in place of ramp length H. A typical response in normal acceleration, a_z, to a ramp gust is shown in Fig. 11 and the associated tuning curve is shown in Fig. 12. It can be seen that the system tunes to a ramp length corresponding to 1.8 seconds.

The reason for the use of the wavelet analysis method is to decompose a response into its component events of different scales whereas the asymptotic result, eqn (5.2), above refers to the aggregation of all such responses. Therefore, in the present work one must take a step back from that result and consider the contribution to n_y arising from discrete gusts distributed over the range of scales, l.

$$n_y = \int_0^\infty (\alpha / l^2) \exp(-y / (\beta \gamma(l))) dl \tag{5.3}$$

In terms of the quickness, Q, rather than the scale, l, this becomes upon using (4.4):

$$n_y = \int_0^\infty \tfrac{1}{2} \alpha \exp(-y / (\beta \gamma)) dQ. \tag{5.4}$$

The density $M_{Q,y}$, the number of peaks in response exceeding y per unit of Q, is therefore:

$$M_{Q,y} = \tfrac{1}{2} \alpha \exp(-y / (\beta \gamma)), \tag{5.5}$$

where it should be noted $M_{Q,y}$ is a density with respect to Q only. Contours of $M_{Q,y}$ may be displayed on the response quickness charts from

$$y = \beta \gamma(Q) \log(\alpha / (2 M_{Q,y})) \tag{5.6}$$

which are illustrated in Fig. 13. The direct appearance of the tuning curve, γ, should be noted. The consequence of this result is that the SDG method may be used to predict the quickness response of a system in a direct way and may be used as an initial design exercise which can be validated when measured data is available from flight or more sophisticated simulations.

6. Comparisons and Criteria

The quickness charts prepared from the response to measured turbulence, Fig 7, are not directly comparable with the contours of quickness density typified by Fig. 13. It is, however, a simple matter to convert the data to the required form, as shown in Fig 14. There are a number of factors which affect the validity of any comparison between the predictions of the SDG model and the results of the wavelet analysis. The primary reason for any discrepancy is the difference between the shape of the response to a ramp input and the shape of the elementary wavelet - in this example the difference between Fig. 2 and Fig. 11. It can be seen that the scales differ significantly and this will distort the position of the contours on the quickness density chart.

Note that it is the contours from the SDG approach which must be adjusted since, here, the assertion is that the pulses in normal acceleration defined by the wavelet shape are the events that properly contribute to the quality of ride.

The contours of quickness density obtained from the response to measured trubulence are repeated in Fig. 15 where illustrative boundaries for acceptable ride quality criteria are also marked. They too are expressed in terms of the density of the number of exceedances of peaks in response. At present, of course, the regions shown are speculative. Nevertheless Figs. 14 & 15 show the value of the current analysis. They bring together specified criteria, predictions from an established model and results from measured turbulence. Physically meaningful quantities are displayed on these charts: time-scales of responses and the rates of occurrence of their peaks. At this stage the missing element is to match the criteria to the experiences of the real world by analysis of data from piloted simulations and flight tests.

7. Conclusions

This paper has described the progress made at GCU and DRA into the application of wavelet techniques for the extraction of ride quality information from responses. In parallel with the wavelet studies has evolved a proposed new way of defining ride quality criteria. The use of a generalised quickness chart to display responses and criteria is a method which has both physical relevance and precise, formal, interpretation. A major advantage is that the method is closely related to that used for evaluation of handling qualities so that there is a potential mechanism for investigating quantitatively the interactions between handling and ride quality.

In summary, the following points can be made:

(i) Wavelet analysis has been successfully applied to the normal acceleration response of a simple helicopter model to atmospheric turbulence.

(ii) Generalised quickness charts have been found to be a suitable medium for presenting the results of the wavelet analysis.

(iii) The SDG model of turbulence is a useful tool for the validation of the approach and for indicating a viable form for the definition of criteria for helicopter ride quality.

(iv) The whole approach has been successful in developing an analytical framework for extending ride quality studies beyond noise and vibration and into the area where it impinges on the piloting task.

Future items of work include simulation studies involving more sophisticated helicopter simulation models and a more detailed SDG analysis to allow for the variation in profile of the responses to ramp gusts. The pressing need is for a programme of piloted flight simulation in order to draw, with authority, the regions on the quickness density charts where appropriate levels of ride quality lie.

8. Acknowledgement

The simulation data for the side step manoeuvre was provided by Dr D. G. Thomson of Glasgow University.

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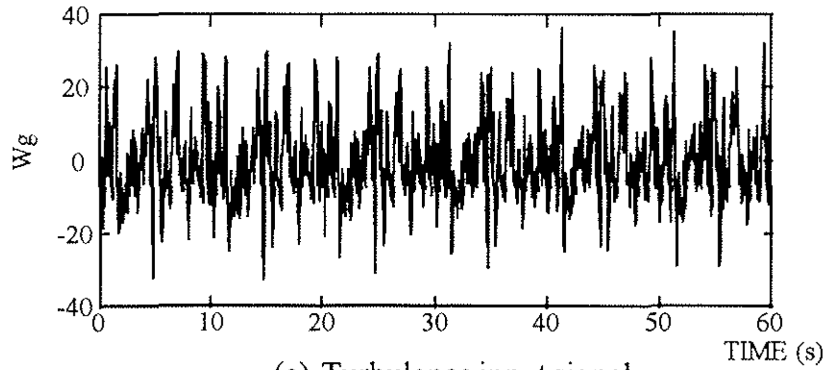
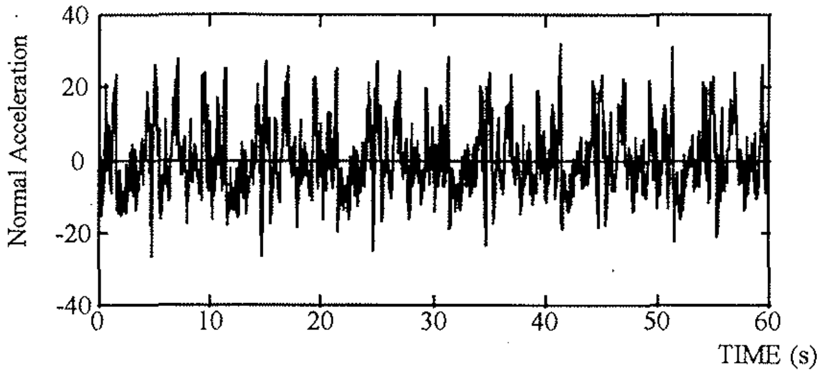


(a) Turbulence input signal



(b) Response to turbulence

Figure 1

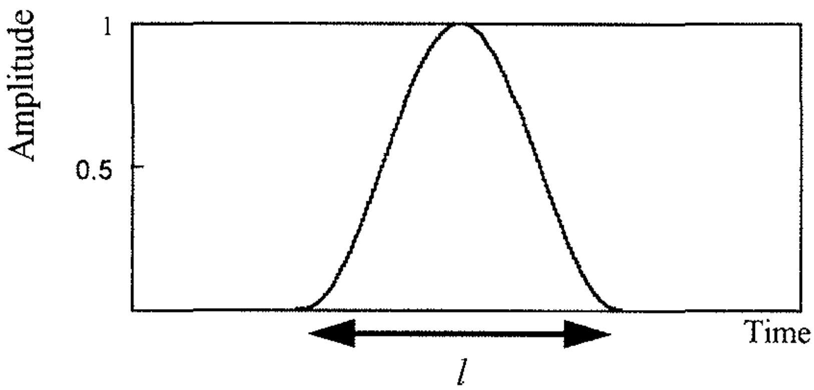


Figure 2: Fundamental wavelet, scale l.

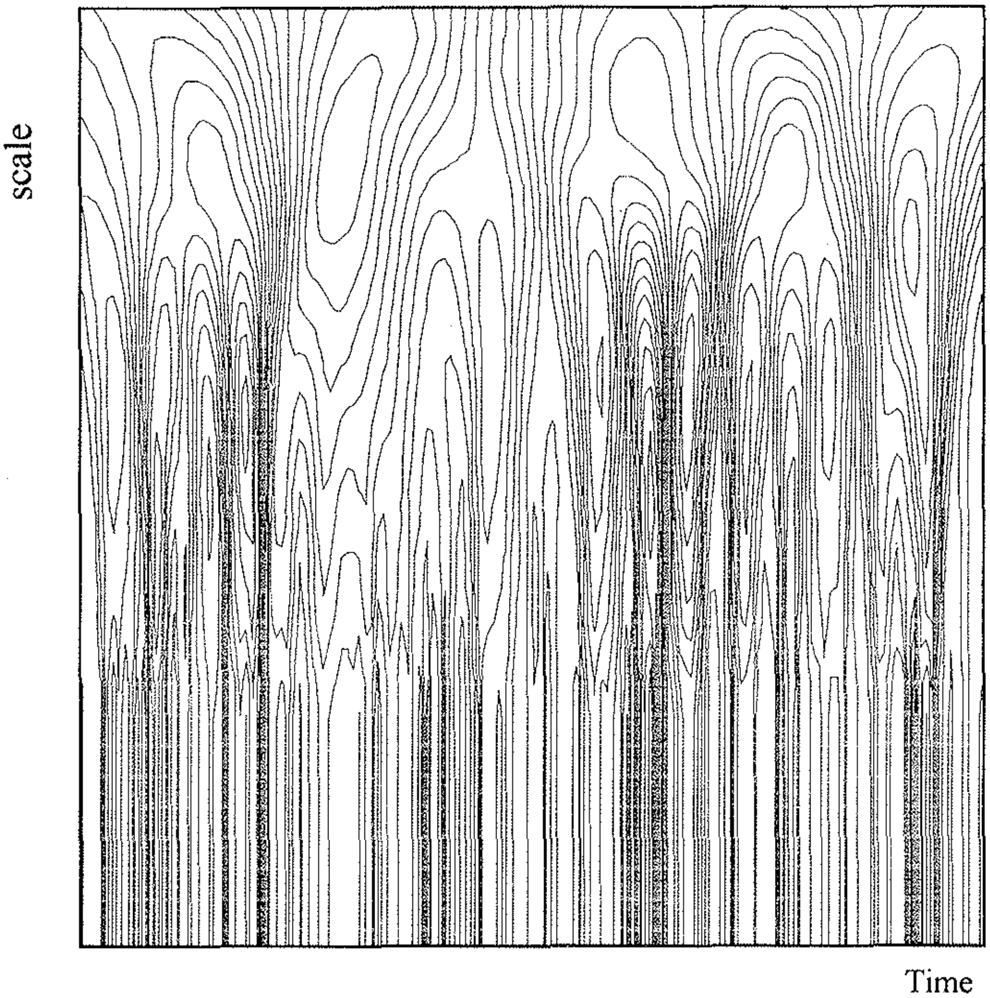


Figure 3: Part of correlation surface for normal acceleration.

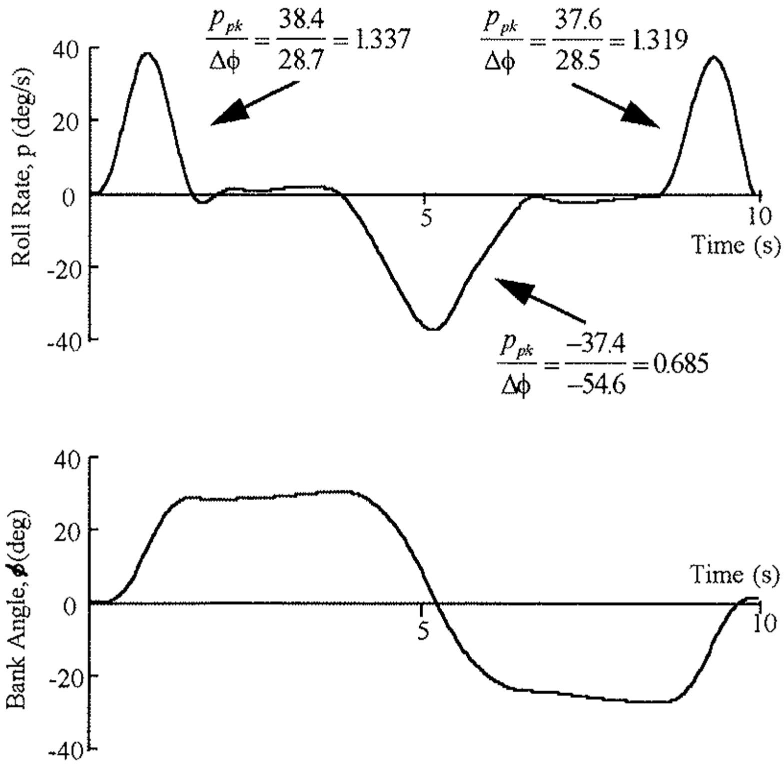


Figure 4: Calculation of roll quickness from inverse simulation of a rapid sidestep MTE.

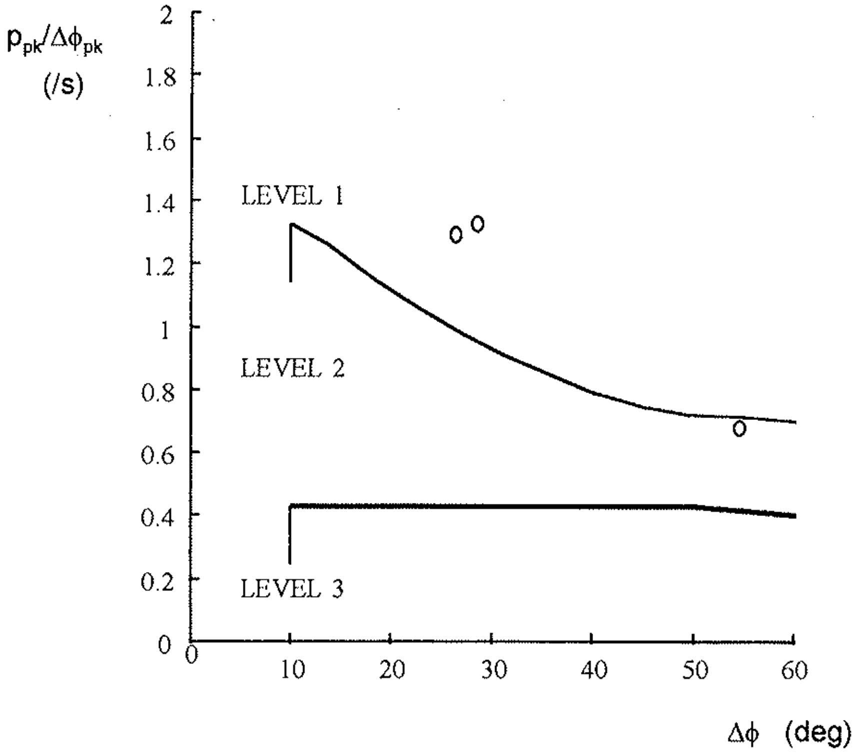


Figure 5: Roll quickness chart from inverse simulation of a rapid sidestep MTE.

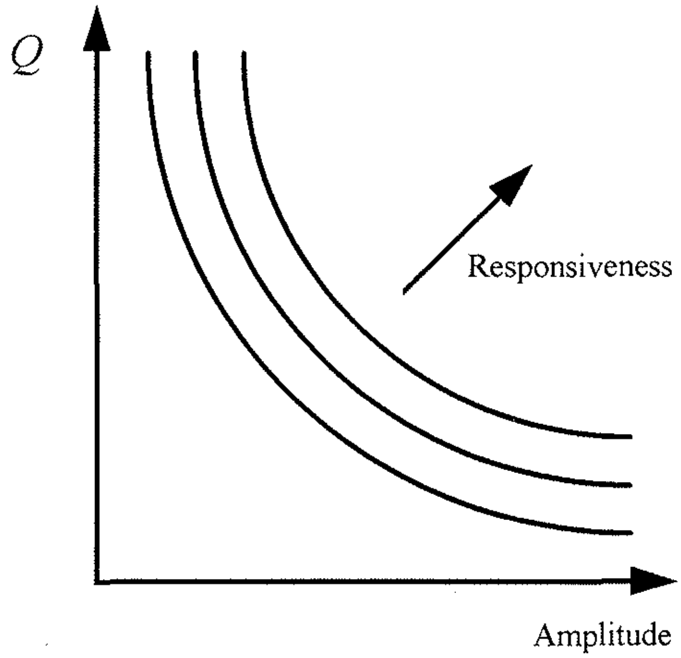


Figure 6: Contours of equal responsiveness.

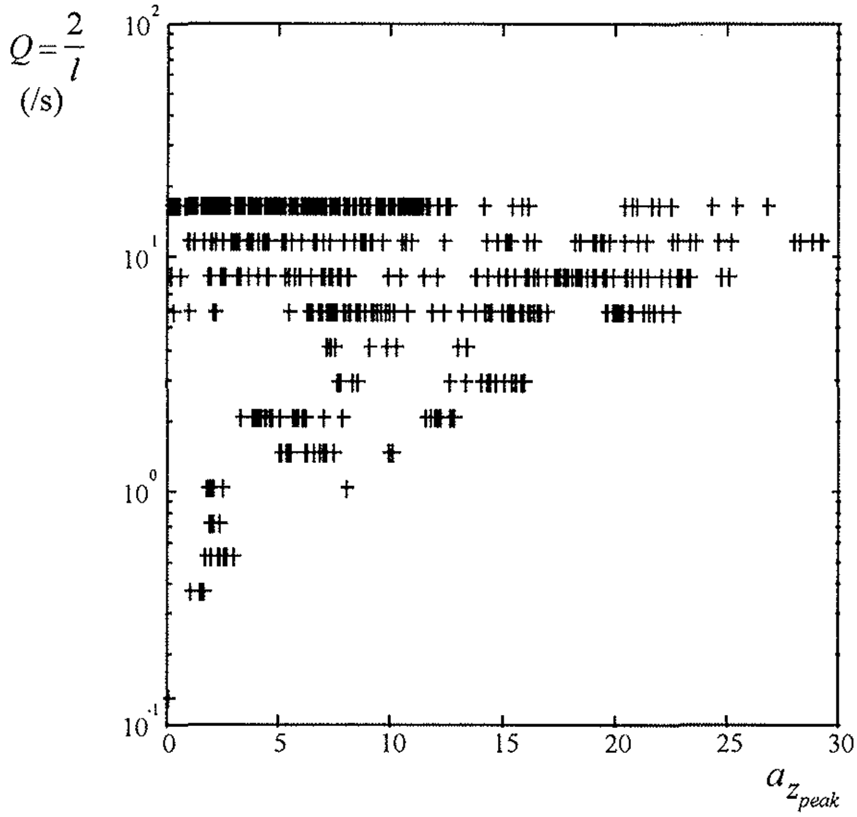


Figure 7: Quickness chart for response.

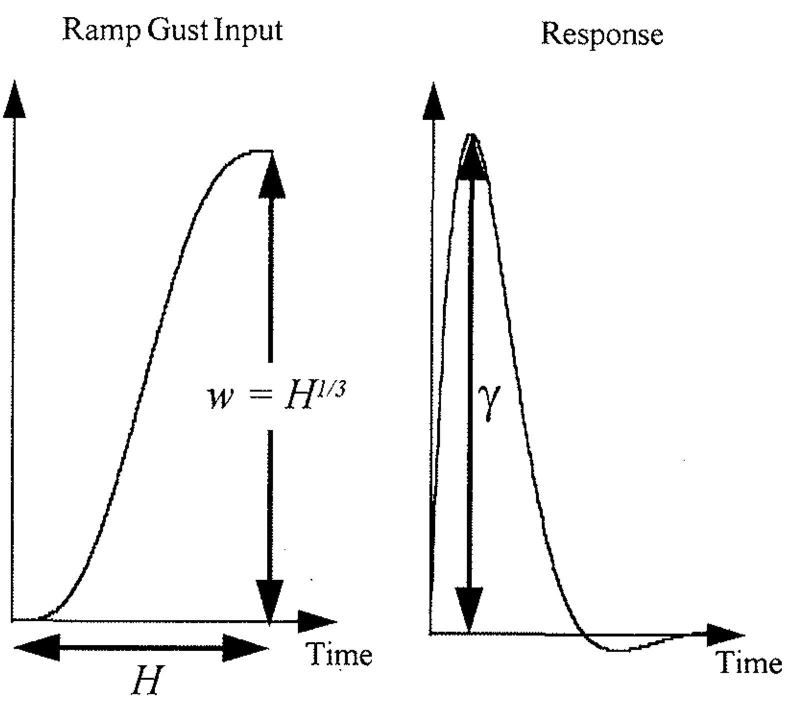


Figure 8: Ramp gust input with single peak response.

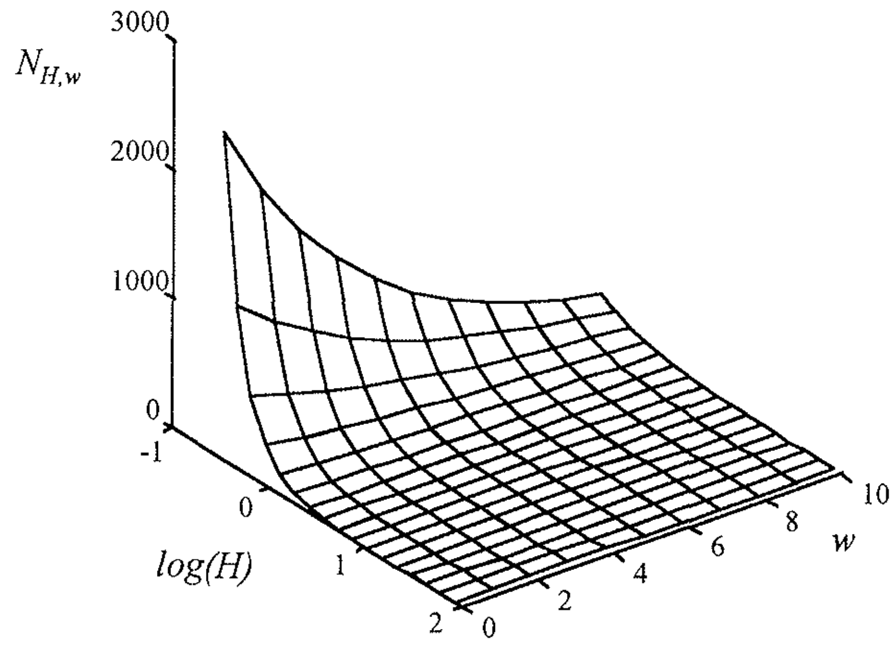


Figure 9: Number of gusts of ramp length H exceeding intensity w (SDG model).

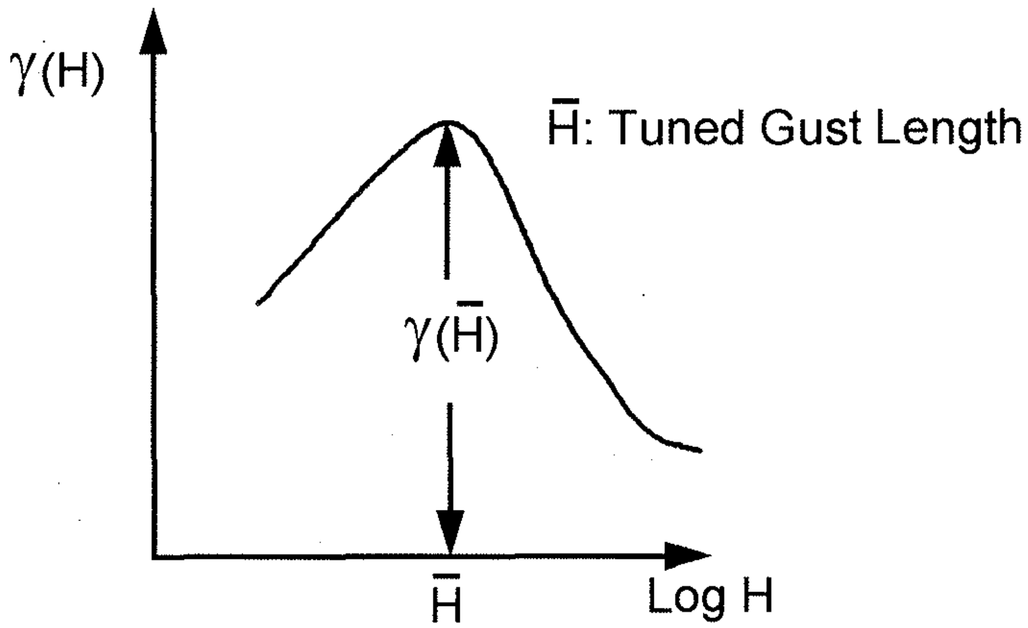


Figure 10: Discrete gust response function.

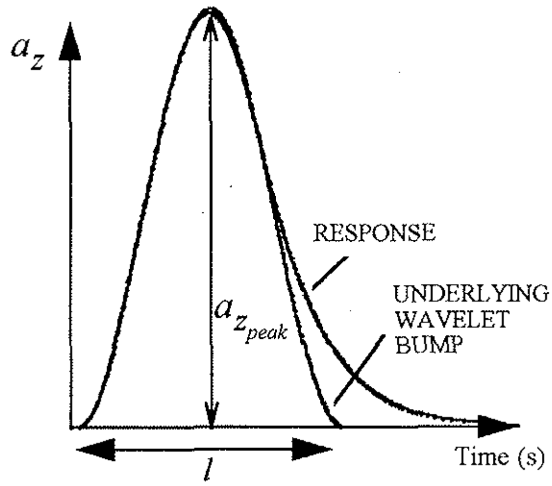


Figure 11: Response event of a_z and its wavelet component described in terms of its scale and peak value.

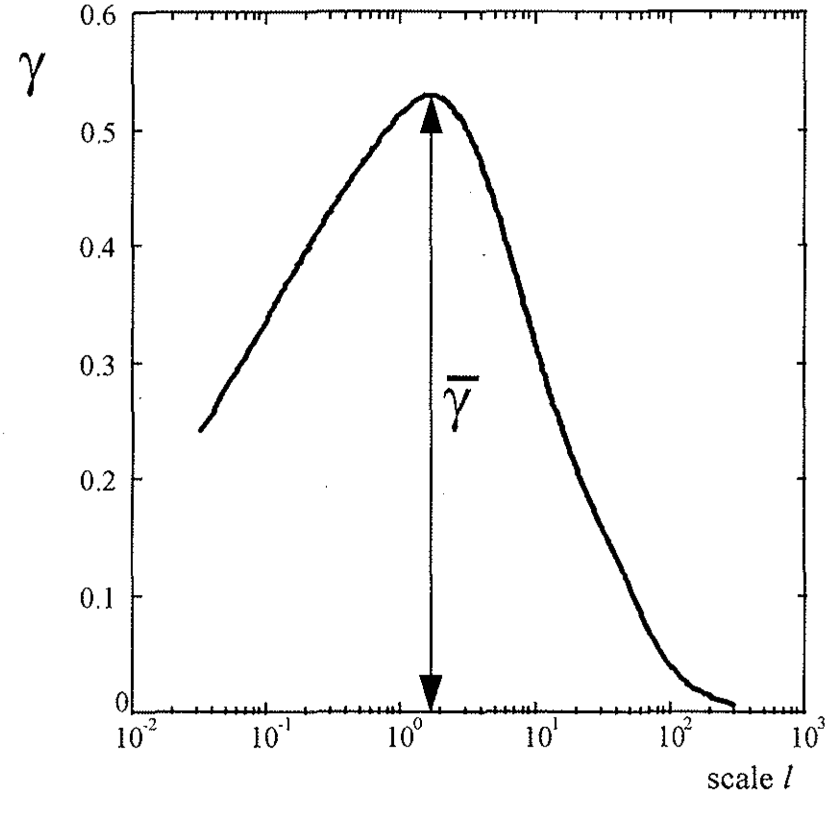


Figure 12: Tuning curve for linear Lynx.

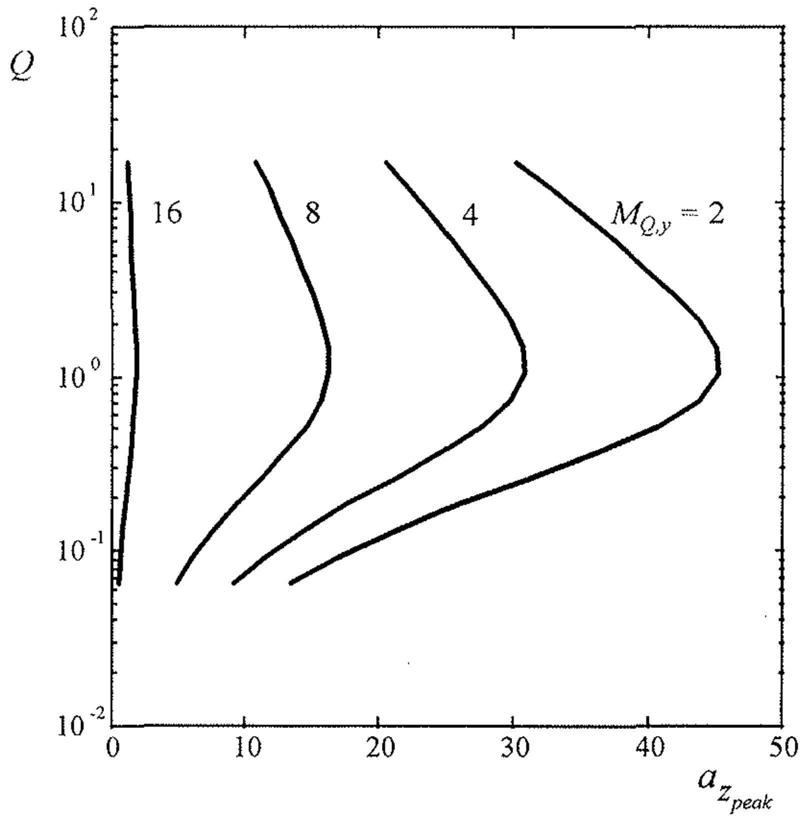


Figure 13: Contours of predicted response density.

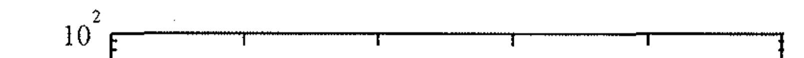


Figure 14: Contours of measured and predicted response density.

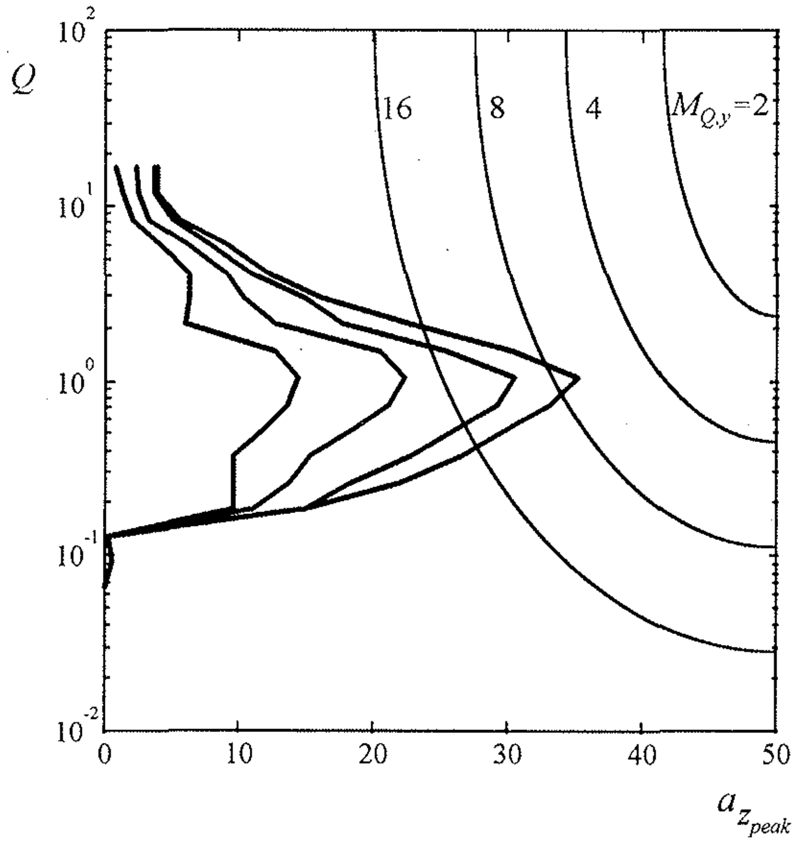


Figure 15: Contours of measured response density with illustrated criteria.