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NEW GENERATION AIRCRAFT DESIGN PROBLEMS RELATIVE TO TURBULENCE STABILITY, AEROELASTIC LOADS, AND GUST ALLEVIATION

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Figure 1 schematically illustrates past history, present status, and future of discrete gusts. Etkin [1] notes that the actual first discrete gust analysis was done in 1915 [2] where the equations and physical concepts related to gust response were derived. In the early 1930's the idea of using an aircraft as a measuring device based on a sharp-edged gust formula was initiated [3]. In the 1930's and 1940's, discrete gust data were collected and analyzed [4]. The present widely used mass parameter gust formula was published in the 1954 timeframe and subsequently resulted in the CAR-4B requirement for gusts [5]. Later the British introduced the idea of tuning a one minus cosine (1-cos) gust [6].

Figure 2 schematically illustrates a secondary line of development. In the early 1930's efforts were started to investigate the idea of gust gradients, and the importance of gradients was recognized. In fact, during this era, a dimensional analysis study showed that gust intensities are related to the cube root of the wavelength [7]. More recently, in the late 1960's, there was a probability analysis which showed that gust gradients and intensities are related and that the cube root type law is valid [8]. Finally, there was a survey that investigated the derived gust velocities of modern jet airplanes [9].

Figures 2 and 3 show there are basically two approaches to the gust analysis: discrete and spectral density. The roles of these two approaches to gust analyses will be discussed later in this presentation. In the early 1930's, von Karman derived the present spectral density characterization of the atmosphere [10], and the idea of using PSD (power spectral density) methods applied to gust analysis was introduced in the early 50's [11]. Again, a period of collecting and analyzing data and refining the approach followed in the 50's and 60's. The result was the FAA Report No. ADS-53 in 1966, which was the first serious attempt at trying to come up with a design criteria for sizing airplane structure based on the PSD gust [12]. Subsequently in 1980, the FAA Appendix G was introduced which requires PSD gust analysis [13]. Some other significant milestones are shown at the bottom of Figure 3. In a paper by Firebaugh [14] an analysis of data was presented which illustrated different conclusions in terms of what some of the gust parameters should be. Also, in the early 1970's the government (DoD) issued a MIL-008861A requirement for PSD type analysis [15].

The present discrete criteria (Figure 4) used by the FAA is based on the mass parameter gust derived in the 1950's [12]. It is a 1-degree-of-freedom analysis which is based on the airplane flying through an idealized 1-cosine gust that is 25 mean aerodynamic chords long. That type of analysis does not

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lend itself to a close-loop method such as would be done for gust alleviating systems or even if it were desired to analyze the effect of SCAS (Stability Control Augmentation System) systems. The criteria specifies design gust velocities based on the data derived in the 1930's and 1940's and, therefore, does not reflect the experience of modern aircraft.

The problem with discrete gust analysis is that it does not really address the question of gradients. Realistic gust gradients are needed if it is desired to evaluate the effects of short-period and dutch roll stability and how the stability of the airplane relates to the airplane response in gust (see Figure 5). Realistic gradients are needed to evaluate the effect of gusts in exciting vibration modes. Finally, realistic gradients are also needed for evaluating close-loop systems or load-alleviating systems. The steeper the gradients through which the airplane flies, the harder it is to design load-alleviating systems that are effective. So, to get a good prediction or analysis, you need to have realistic gradients; that is the main problem with the discrete gust formula.

As shown in Figure 6, the British recognized [6] some of the problems summarized in Figure 5, and in the early 1960's came up with this idea of tuning. In Reference 6 it was stated that realistically the airplane not only plunges but also pitches and it is also known that vibration modes can be excited. The British indicated that these types of parameters should be included in the analysis. At that time, they did not know what the gradients of the gust should be; thus, they required a survey of all possible gradients. Effectively, they were saying that all gradients are equally likely and it is necessary to tune an airplane to find the worst one. The design gust levels, however, were the same design gust velocities that were used by the mass parameter formula and the criteria as originally stated only mentions vertical gust; for some reason no mention of lateral gust was made. The wording of the criteria along with some additional information suggests that the British believe that the main driver in terms of determining the structural gust load should be the discrete gust. The PSD gust is considered secondary and they require it but only as a guide.

Again, the problem is that you do not have realistic gradients. There has been an analysis [10] which indicates that the gradients are, in fact, dependent on the gust intensity and the larger the gust intensity the smaller the gradients as shown in Figure 7. Another problem is that the design gust velocities were not recalibrated to reflect the significant changes in the analysis that the British required. They proposed [8] the original design velocities that were derived based on a simple mass formula parameter, which did not account for vibration modes and pitching of the airplane; they then applied those velocities to the new analysis. An additional problem is that the criteria need to be recalibrated based on the new analysis method.

In terms of the PSD gust, the basic criteria are based on the von Karman spectra which are defined in Figure 8. In this figure, L is the scale of turbulence and Ω refers to spatial frequency in radians per foot. If the airplane is flying through the turbulence at a particular speed, it can be related to a spectrum defined relative to frequency in Hz. The analysis is a linear one in which the gust varies only in a streamwise direction. The design parameters were developed with a somewhat different philosophy than was used for the discrete gusts. Discrete gust velocities were based on a probability approach where some level of turbulence was chosen such that an encounter was experienced every so many million miles as a basis for the design velocities. The PSD criteria were backed out based on the philosophy of providing equivalent strength to successful airplanes flying in the 1960's. Finally, the present criteria are also characterized by the fact that the various certifying agencies specify different parameters for many of the design parameters. The basic approach is the same but different agencies vary some of the details. Some of these details are significant.

In Figure 9, the PSD analyses are illustrated by two approaches: (1) a mission approach and (2) a design envelope approach. The mission approach seeks to represent the operational characteristics of the airplane in terms of how it is flown, what altitudes and speeds it is flown, what payloads, fuel loadings, and so forth. The design envelope approach is similar to the way other types of loads are computed in that you specify extreme conditions in terms of flying at speeds and altitudes that correspond to the limits of the flight envelope, investigating extreme payloads and fuel loadings, etc. There are various schools of thought within the community in terms of which approach is most desirable, and, in fact, there is a reluctance to really rely on any single approach. The feeling being perhaps that no single approach completely addresses all of the problems related to gust analysis. Presently, both approaches are used. One agency, the military, requires a mission approach; the FAA, however, allows only the use of a design envelope approach.

Presently, there is a question of whether to use discrete or PSD analysis to determine gust design loads. An illustration of these two is presented in Figure 10. The British tend to feel that discrete analysis should be the main thrust. However, the original ADS-53, perhaps reflecting a prejudice in the people who worked on it, indicated that PSD analysis should be the primary means for determining design gust loads [12]. Presently, there is not a specific detailed criteria in terms of how to certify active load-alleviating systems; however, there is an Advisory Circular that is very specific.

Presently, particularly with the FAA [13], both discrete and PSD analyses are required (Figure 11). The discrete mass parameter gust analysis by itself is not adequate since it does not account for dynamic effects. The shaded areas of Figure 11 indicate the parts of the airplane that are likely to be sensitive to dynamic effects. The engine pylons and perhaps wing tips are sensitive to exciting vibration modes which are not predicted by the mass parameter method. The tail is sensitive to dutch roll stability, which again is not accounted for in the mass parameter formula. Finally, the PSD approach has important applications in terms of supporting fatigue and damage tolerance analysis.

The PSD approach is basically a linear approach for analyzing active systems. The problem with approach is how to represent nonlinearities. Figure 12 indicates that you have a control system command and an actual control surface motion which are not necessarily linearly related to the command. An important parameter in PSD mission analysis is the zero crossing of the mean (N_0). The calculation of N_0 involves calculating the spectra of the rate of change of acceleration. A dot indicates a derivative of acceleration. With the streamwise gust model that we have today, the integral of the acceleration rate does not converge. You can get any value you want for N_0 depending on what you choose for the limits of integration.

As mentioned earlier, the vertical tail is particularly sensitive to dutch roll stability (see Figure 13). Modern transports generally have low dutch roll damping and as the damping approaches zero the PSD analysis will predict higher and higher loads on the vertical tail because the analysis assumes resonance at each solution frequency. Therefore, very large vertical tail loads are possible if you have a very low damped dutch roll mode and further assume no pilot interaction in terms of artificially supplying damping and also assume no yaw damper control system.

Historically, as shown in Figure 14, most of the data and criteria is based on using the airplane as a measuring device. The early discrete gust criteria is based on obtaining VG data recorded while flying through turbulence and analyzing that data by using the discrete gust formula. Based on that analysis, deducing what must be the gust velocities that the airplane experienced can be obtained. Then based on that data, coming up with a criteria in terms of design gust values that envelope all the experience or at least the likely experience is possible. The significance here is if it is desired to go the reverse way and re-create extreme acceleration data from the criteria and to change the analysis, it is not possible to get back the original acceleration data. The point to be made is that the criteria and the analysis are tied together and you really should not modify one without modifying the other. The same principle applies for the PSD approach where you are flying through random turbulence. The criteria is derived based on backing out the required design parameters such that the PSD analysis will predict loads consistent with the known strength of successful airplanes. Assume you wish to go the reverse direction using existing criteria but to do something to improve the analysis, if you were to analyze the original airplanes that the criteria was based on, different conclusions would be obtained. One might conclude that the reference airplanes were under-strength or over-strength. Thus, the need to relate the criteria and the analysis is realized. If there is some significant improvement to be made in the analysis, that improvement needs to be related to the criteria.

The basic goal of the criteria is to successfully extrapolate the experience of past airplanes. Illustrated in Figure 15 are old airplanes that are considered to be satisfactory from the structural point of view, are economically viable, and now you have some new airplane which needs to have the same characteristics. The new airplane should be structurally safe and economically viable. The analysis and the criteria primarily are ways of extrapolating the successful experience of old airplanes to new airplanes. The important question is how well the analysis and criteria predict the relative characteristics between the old and new so that significant changes are accounted for in the new design relative to the old design.

Generally, the criteria need to be integrated with modern analysis (Figure 16). Modern analysis refers to a method that accounts for dutch roll and short-period stability, and vibration modes along with the need to define realistic gust gradients. If those changes are made, then the design criteria should be reviewed in terms of what should be the design gust levels and also perhaps incorporate any experience we have with modern aircraft along with historic data from the 1930's and 1940's.

The main message is the need for standardization of approach and concensus in terms of what the approach should be (Figure 17). Some think PSD by itself is sufficient for determining design gust loads. There are other schools of thought that suggest if you have a realistic discrete gust approach, you do not need PSD gust for determining design loads. Is there something unique that the PSD gust analysis offers that is not part of the discrete gust analysis? Variations in the way mission and design envelope approaches to PSD gust are treated in criteria should be resolved.

There are various data, proposals, and interpretations of data in terms of how the scale of turbulence varies with altitude (Figure 18). Another question concerns the calculation of the zero crossing count, which is important in the mission analysis. As discussed earlier, the integral of the acceleration rate spectra does not converge; thus, we need to have a criteria that defines what the cutoff frequency is so that everyone is consistent. Another issue which is left up to the individual is whether one should analyze vertical gusts and lateral gusts independently or whether they should be combined.

Should there be some minimum standards concerning mission segments when the mission PSD approach is used (Figure 19)? In the extreme case you could define the mission as a single segment altitude, speed, and weight configuration. Or you could have many segments. Is there some minimum standards that could be imposed? Since the structures and controls disciplines are separate, there tends to evolve a separate description of the atmosphere that is used by controls engineers in terms of how they evaluate control system performance in turbulence versus the criteria the structural engineer uses in sizing the structure.

Shown on the top of Figure 20 is the formula that is used in the mission analysis for computing the crossings with positive slope of any load level L. As shown, it is a function of the N_0 mentioned earlier. P1 and P2 are the proportion of time in storm and non-storm turbulence, and b_1 and b_2 relate to the intensity of the storm and non-storm turbulence. If you change values for the scale of turbulence or cutoff frequency, the P's and b's should be recalibrated. This is true because the P's and b's were backed out to match flight experience, so the analysis and data are related. If the P's and b's are changed, you could conceivably come up with a different exceedance curve as indicated by the solid and dashed lines. The philosophy in the past has been to set the design crossing level (N_{DL}) to be consistent with known levels of limit load. The limit load is a known number that corresponds to the known strength of a previous airplane that has been successful. Now what would happen if you change the analysis to reflect a different exceedance curve? Y should back out a different N_{DL} as opposed to saying that the crossing exceedance relationship is different and therefore the design load level is now x percent bigger.

Relative to future airplanes that are going to be flying at higher altitudes than present aircraft: Probably we need to think about what should be the gust criteria at altitudes above 50,000 feet (Figure 21). The other question relates to the streamwise gust model. A lot of information indicates that at least at low altitudes the scale of turbulence is relatively small so that three-dimensional effects may be important at low altitudes. b/L is the span to scale of turbulence rates. There is perhaps some value for that parameter where you could say that three-dimensional effects are important and other values where three-dimensional effects can be neglected.

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QUESTION: Warren Campbell (BDM Corporation). One thing that you didn't address was what importance you place on the shape of your probability density distributions. I noticed that when you showed that exceedance curve, part of that exceedance curve was based on the assumption of the Gaussian distribution.

ANSWER: That is true.

CAMPBELL: Do you have any feel for the importance of probability distributions?

ANSWER: I guess I don't. As long as the distribution which, in turn, relates to that exceedance curve is a tool to back out the design values not an end in itself, I don't think it is terribly important but I don't really know.

CAMPBELL: One other question. When you design an aircraft, pardon my ignorance, do you consider fatigue in the PSD part.

ANSWER: Yes.

QUESTION: Bob Heffley (Manudyne Systems). From the standpoint of the designer, can you comment on how the pilot in the loop needs to be accounted for and what the implications are on the analysis methods that you describe, i.e., for both the discrete gust and power spectral density.

ANSWER: I guess in terms of the pilot the implications center on how he would respond to turbulence and how he would interact with it. Presently, the analysis generally doesn't account for that. You either do an open loop analysis in which you assume the pilot has no interaction at all or a closed loop analysis which again assumes the pilot isn't doing anything but the active system is doing all the feedback. I know in the controls area there are various pilot models that attempt to simulate delays and gains to represent the pilot as if he were a control law. I am not sure if there is a universal agreement as to what is a good pilot model. I guess it could be included if it could be represented as a control law, but right now they're not.

QUESTION: John Houbolt (NASA Langley). Richard, that was a nice rundown. I'd like to make this observation though. I wish I had a half hour to get up and give a follow-up talk to what you just said and place a lot of your notions in a little bit different context and from a little bit different perspective. There are a number of things that could be slanted differently than what you have done there. Let me just mention two of them. One of them is the power spectral density approach. You can do everything with that that you can do with the discrete gust approach but more and in a much rational way. So you can cover everything that the discrete gust approach has in it automatically in the power spectral density approach. And now the second thing I'd like to comment on is your comments on N_0, the zero crossing problem. If you do it right there is no problem getting N_0 correctly. It will converge very nicely and very rapidly. The reason I mention this is that this is one of the problems that we have at a conference of this sort. It's a heck of a time to disseminate certain pieces of information. Ten years ago I told people how to calculate N_0 in a proper way. That still hasn't gotten around the community and there is a reason for that. There is probably only one person in this audience, namely you, that is familiar with the N_0 problem and it is a difficult problem of getting this information around to the various people, because there is very little interest in it, but indeed if you do it properly, there is no problem whatsoever in calculating N_0. I think the sort of thing we need to take up in this conference is how do we get some of this information out of the group in a better way than we have presently been doing. This is an observation, not a question.

QUESTION: Jack Ehernberger (NASA Ames). Can you amplify briefly on your comment for a future requirment of more data characteristics above 50,000. Is that related to a specific inadequacy of previous data sets or some new unique design concepts?

ANSWER: Yes, I would think in terms of the discrete gust, the design gust velocities are functions of altitude and, as I remember, the discrete gust is only defined in military and civil regulations up to 50,000 feet. At the cruise speed, it is 50 ft/sec, up to 20,000 feet, and then it linearly reduces to some value at 50,000 feet. I'm raising the question that above 50,000 feet what do you do? Should structural analysts continue to allow it to linearly reduce to zero or assume a different function? I was thinking of what I had seen in the news about some of these hypersonic airplanes that are going to be flying at the edge of the atmosphere.

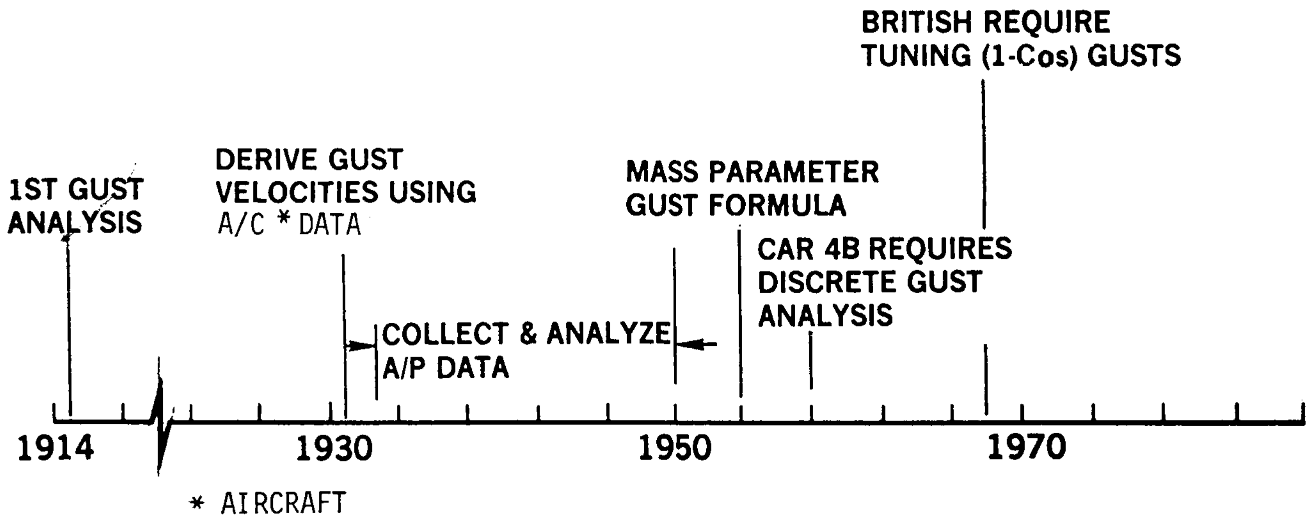


Figure 1. Development history of discrete-type gust description.

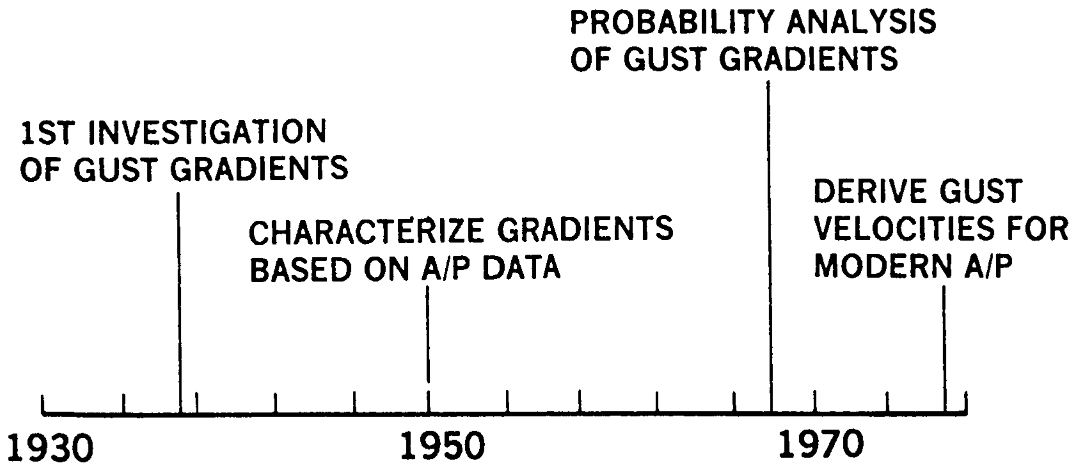


Figure 2. Time frame for gust gradient analysis development.

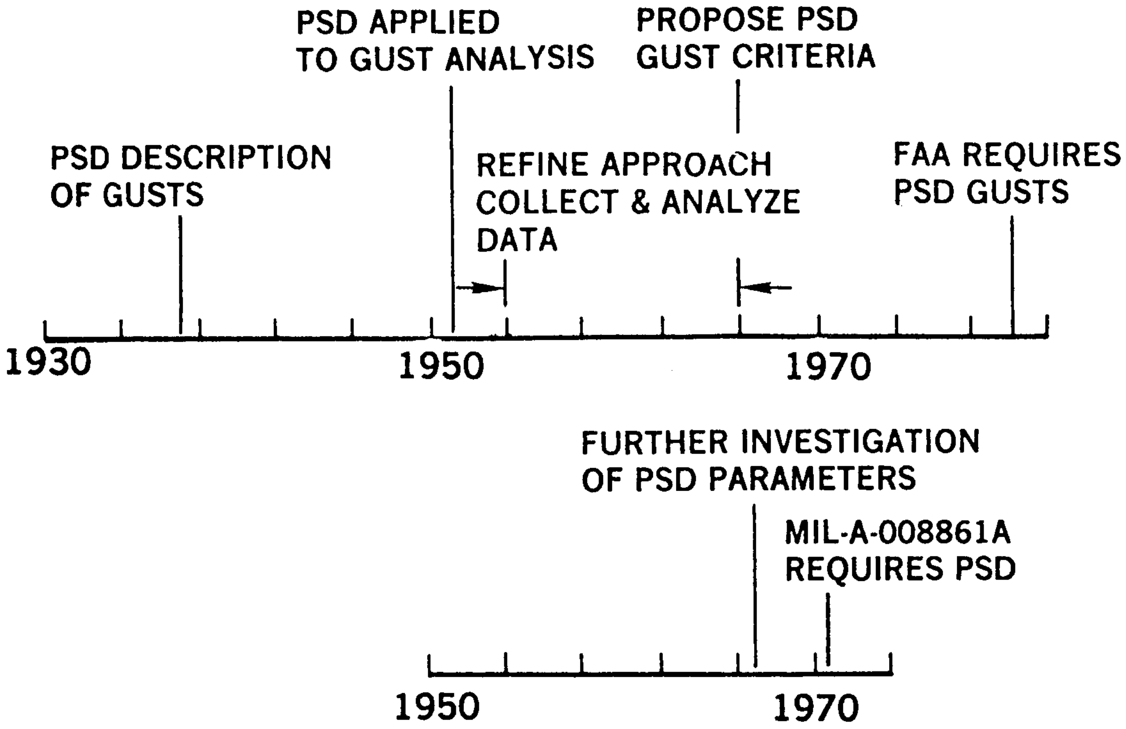
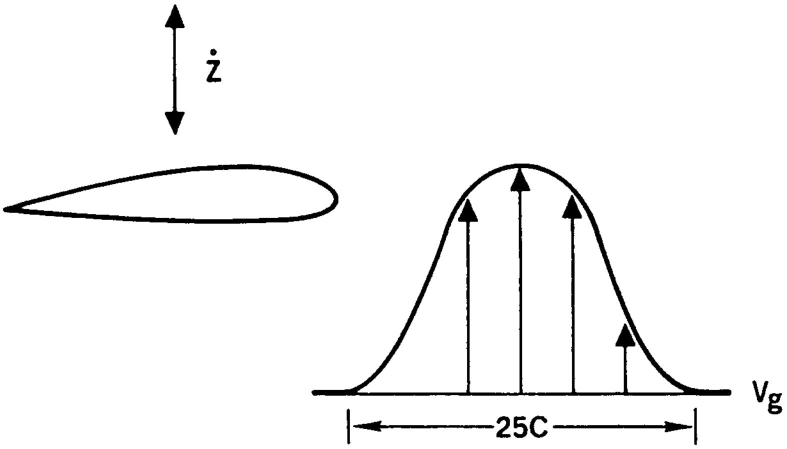


Figure 3. PSD gust history.



- **BASED ON 1 DOF ANALYSIS**
- **BASED ON METHODOLOGY AND DATA 30-50 YEARS OLD**
- **DOES NOT PERMIT CLOSED-LOOP ANALYSIS**
- **DOES NOT REFLECT MODERN AIRCRAFT**

Figure 4. Discrete gust--present criteria.

REALISTIC GUST GRADIENTS

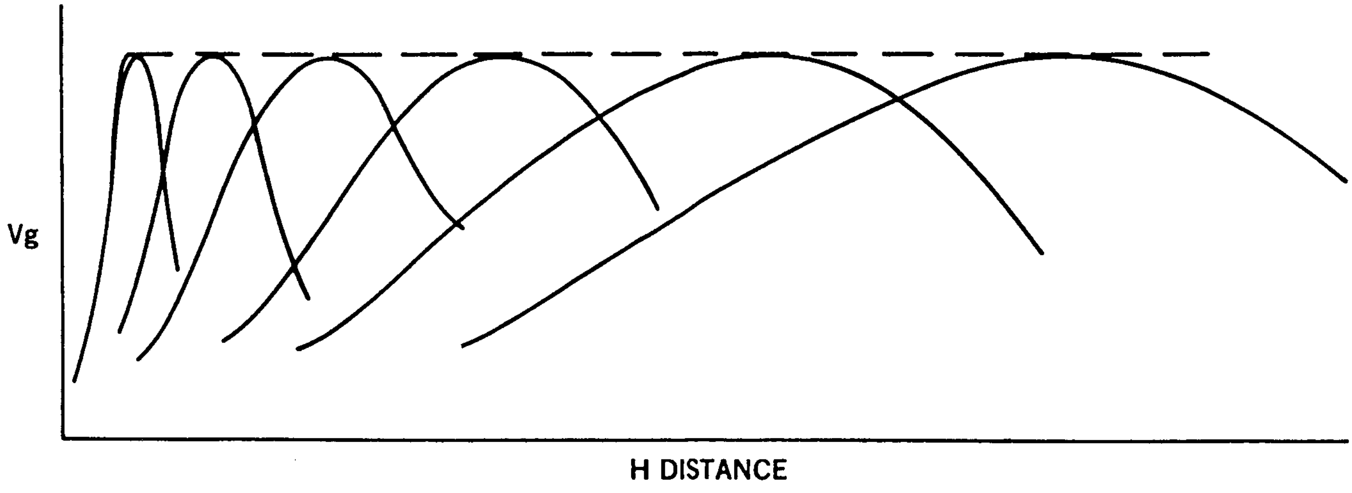
NEEDED TO EVALUATE A/P STABILITY

NEEDED TO EVALUATE VIBRATION MODES

NEEDED TO EVALUATE GLA SYSTEMS

Figure 5. Discrete gust--problems.

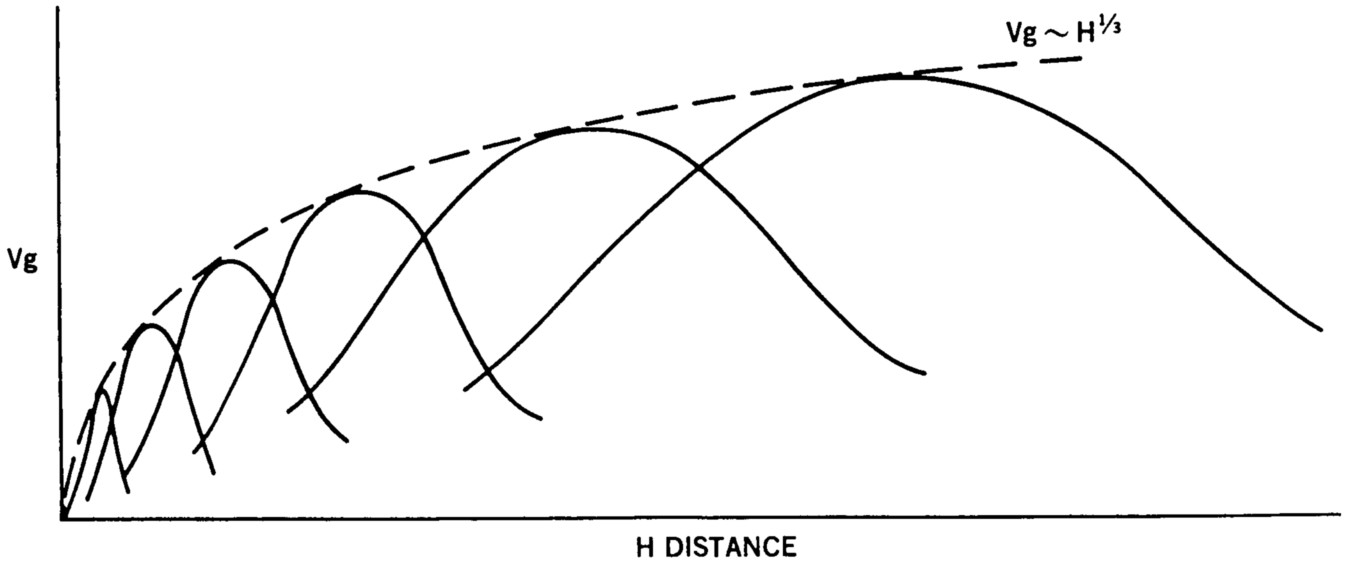
- REQUIRE MODERN METHODS TO "TUNE" 1 - Cos GUSTS



- USES MASS PARAMETER DERIVED GUST VELOCITIES
- "TUNING" SPECIFIED ONLY FOR VERTICAL GUSTS
- PSD GUSTS REQUIRED AS "GUIDE"

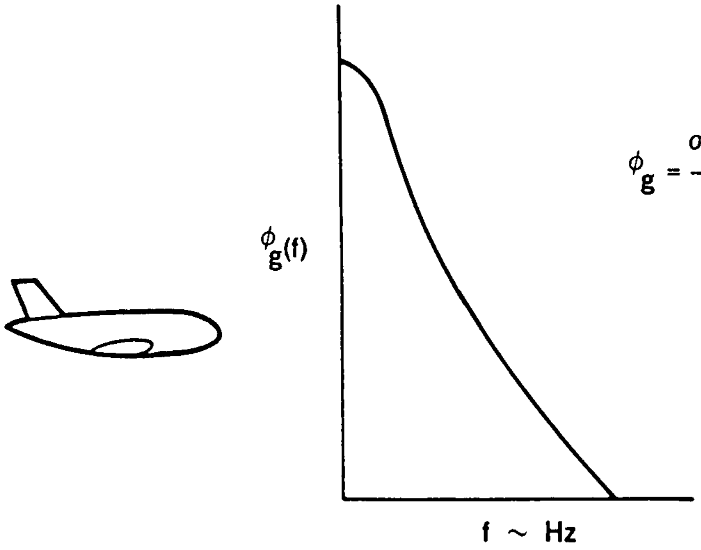
Figure 6. British discrete gust--present.

- "TUNING" DOES NOT PRODUCE REALISTIC GRADIENTS



- DESIGN VELOCITIES WERE NOT RECALIBRATED

Figure 7. British discrete gust--problems.



$$\phi_g = \frac{\sigma_g^2 L}{\pi}\left\{\frac{1 + 8/3\,(1.339L\,\Omega)^2}{[1 + (1.339L\,\Omega)^2]^{11/6}}\right\}$$

- LINEAR ANALYSIS OF STREAMWISE GUSTS
- STRENGTH EQUIVALENT TO 1960s AIRCRAFT
- VARIETY OF GUST CHARACTERIZATIONS

Figure 8. PSD gust--present criteria.

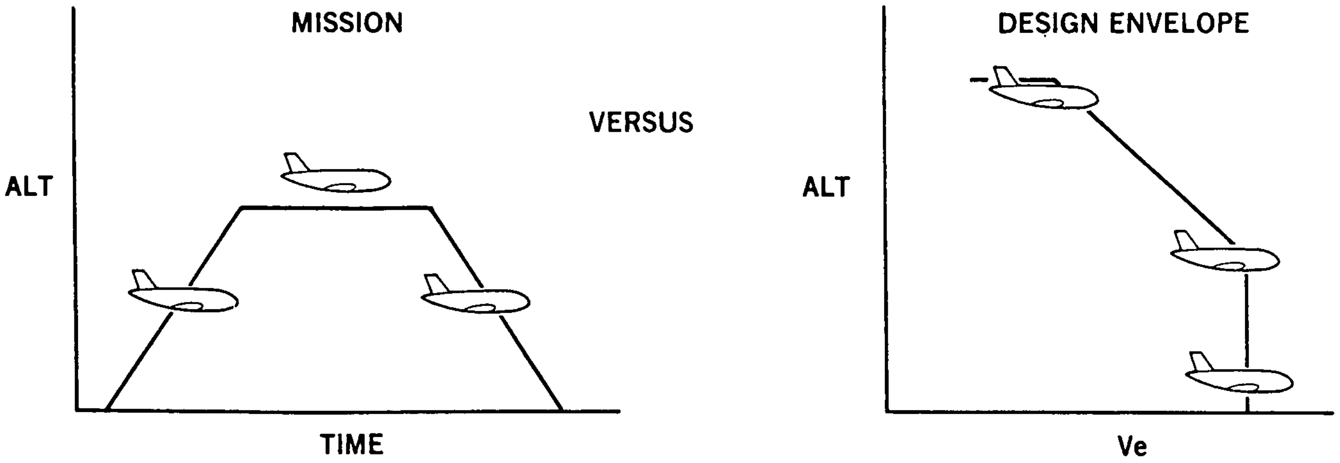
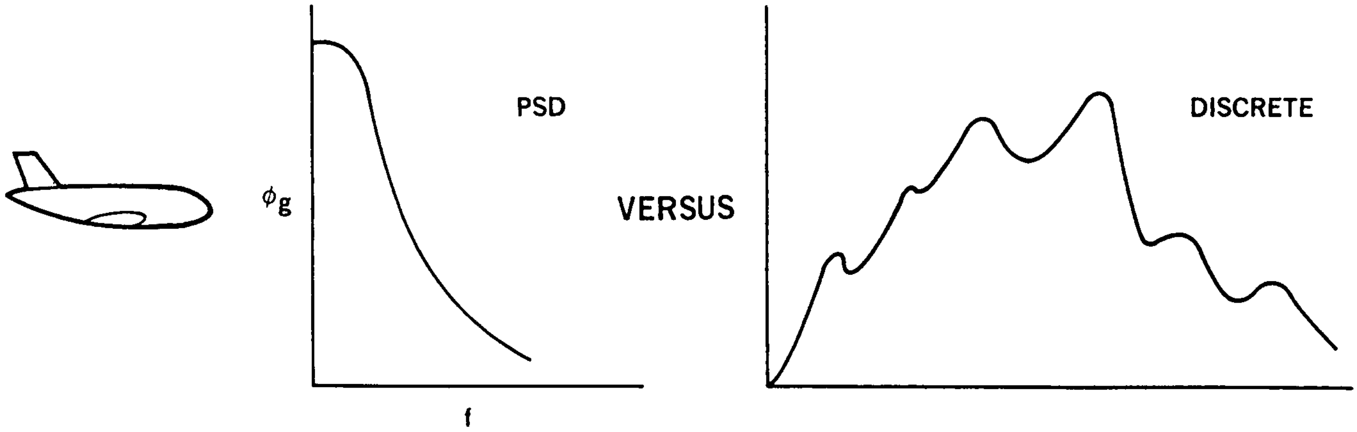


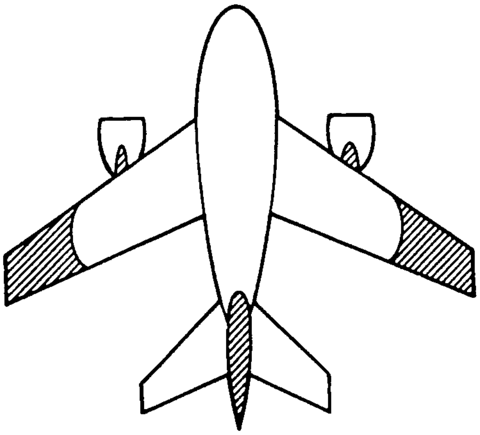
Figure 9. PSD gust--present criteria.



- **FAA ADVISORY CIRCULAR ON ACTIVE CONTROLS FOR LOAD ALLEVIATION**

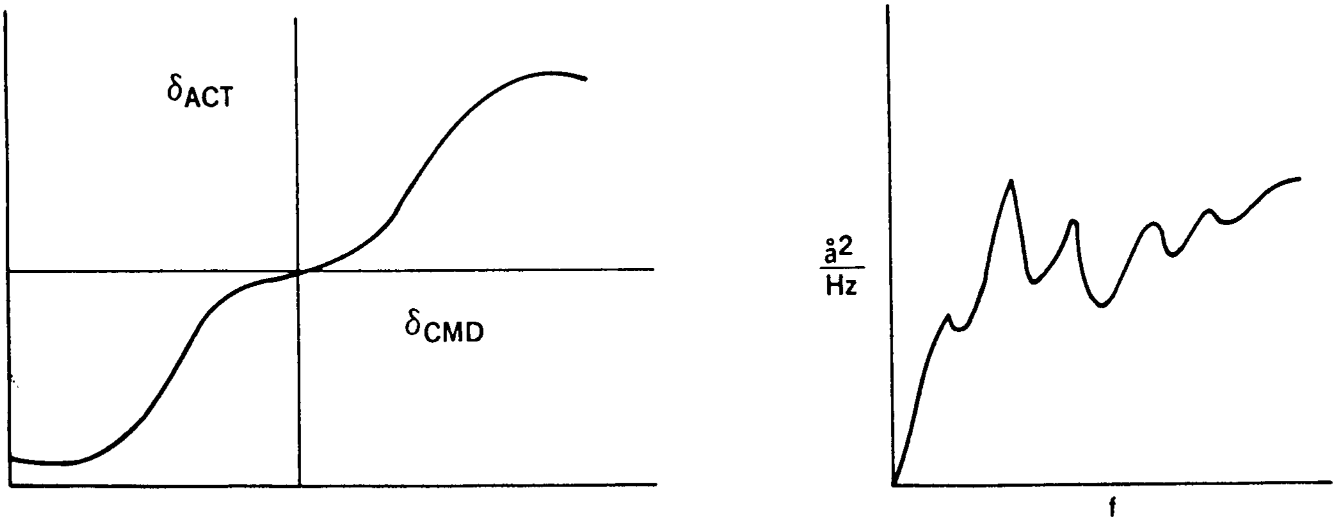
Figure 10. PSD gust--present criteria.

- BOTH DISCRETE AND PSD REQUIRED



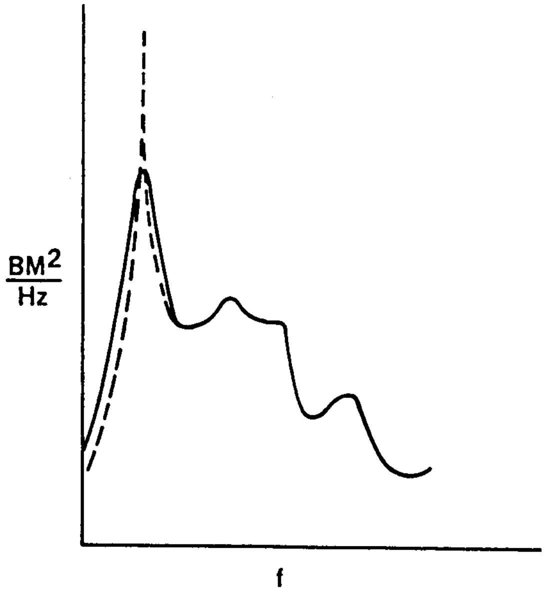
- MASS PARAMETER GUSTS CANNOT REPRESENT A/P STABILITY AND VIBRATION MODES
- PSD IMPORTANT PART OF FATIGUE-DTA

Figure 11. Gust criteria--present.



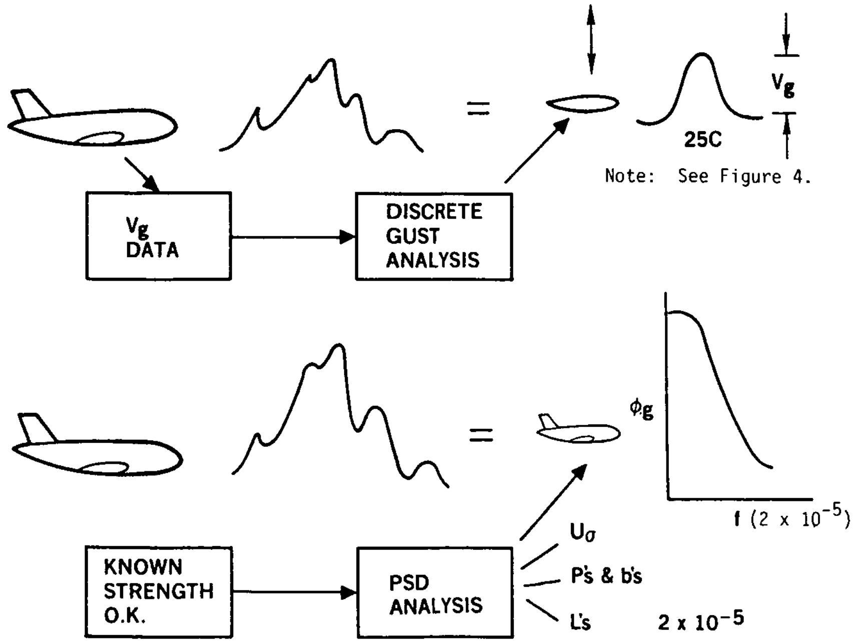
- REPRESENTATIONS OF CONTROL SYSTEM NONLINEARITIES
- INTEGRATION FOR ACCELERATION No DOES NOT CONVERGE

Figure 12. PSD--problems.



- PSD LOADS → ∞ AS ξ_{DR} → 0

Figure 13. PSD--problems.



Note: See Figure 4.

Figure 14. Criteria--background.

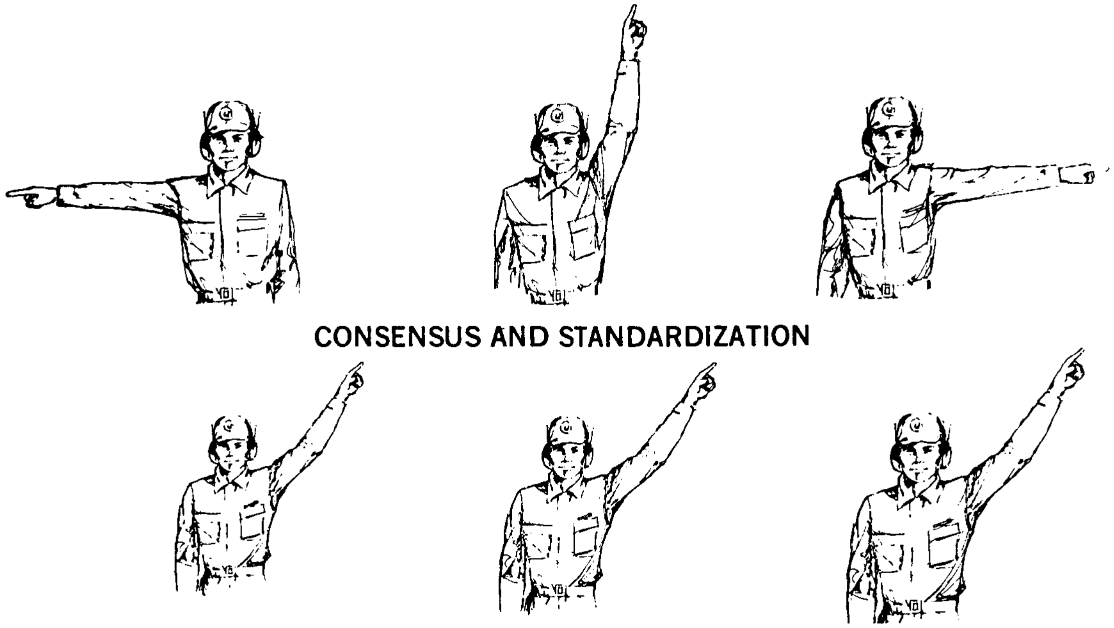
- ANALYSIS/CRITERIA USED TO ASSURE EQUIVALENT LEVEL OF SAFETY
- RELATIVE CHARACTERISTICS ARE PREDICTED

Figure 15. Criteria--philosophy.

- INTEGRATE DISCRETE GUST CRITERIA WITH MODERN ANALYSIS
- DEFINE REALISTIC GRADIENTS
- RECALIBRATE DESIGN GUST LEVELS

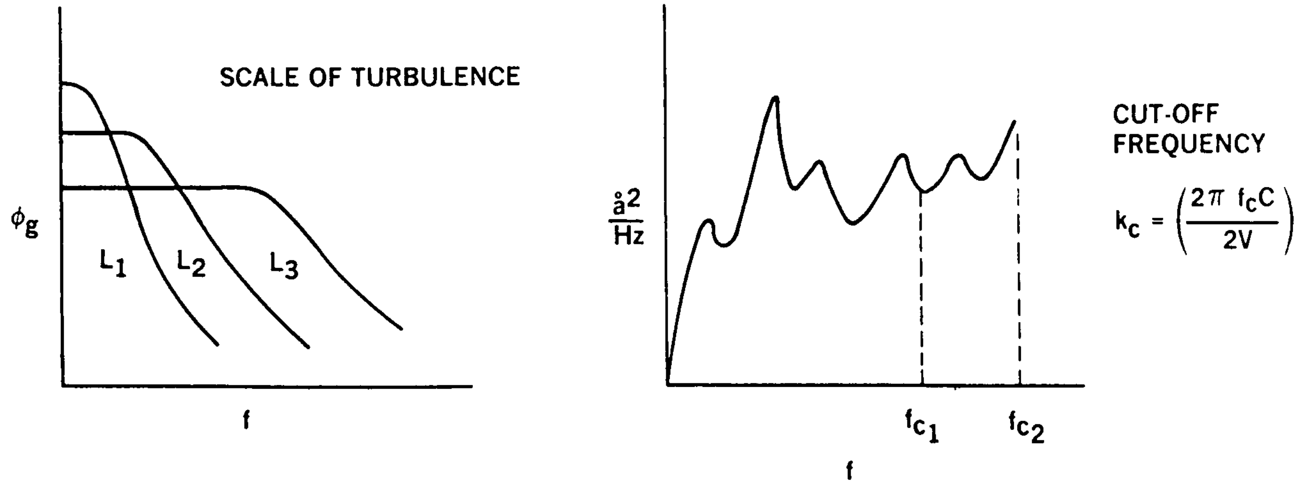
- ACCOUNT FOR DATA ON MODERN AIRCRAFT

Figure 16. Discrete gust--future.



- **PSD GUST FOR DETERMINING DESIGN LOADS?**
- **MISSION VERSUS DESIGN ENVELOPE?**

Figure 17. PSD gust--future.



- **ISOLATED OR COMBINED VERTICAL-LATERAL GUSTS**

Figure 18. PSD gust--standardization.

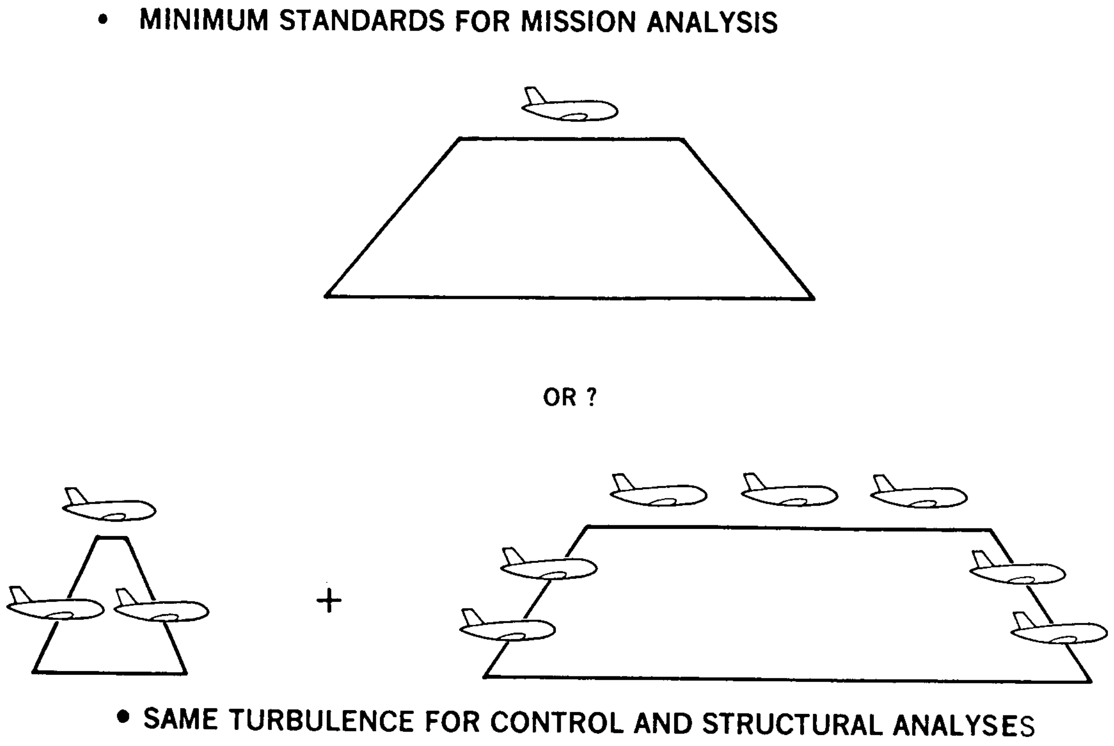


Figure 19. PSD gust--standardization.

$$N_{DL} = p_1 N_0 e^{-\left(\frac{L-L_{IG}}{\bar{A}b_1}\right)} + p_2 N_0 e^{-\left(\frac{L-L_{IG}}{\bar{A}b_2}\right)}$$

- RECALIBRATE p's AND b's
- RECALIBRATE DESIGN ENVELOPE DESIGN VELOCITIES
- RECALIBRATE N_{DL}

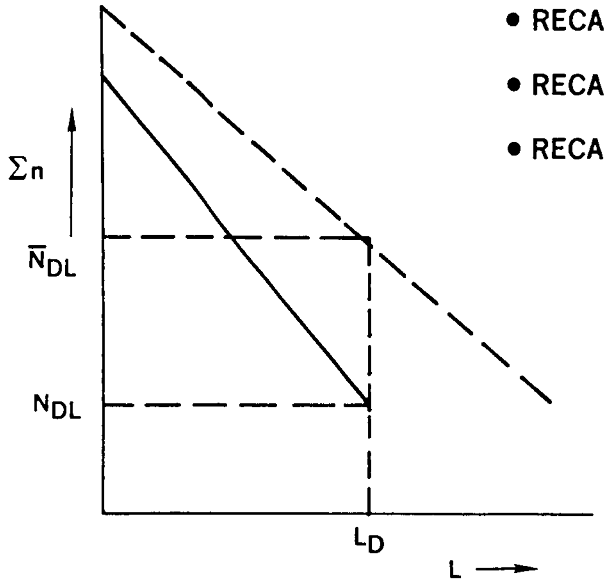


Figure 20. PSD gust--recalibration.

DESCRIBE GUST CHARACTERISTICS ABOVE 50,000 FT

ADEQUACY OF STREAMWISE GUST MODEL FOR LOW ALTITUDES

(b/L) WHERE 3-D EFFECTS BECOME IMPORTANT

Figure 21. Future--general.