Nonstationary Ascent Wind Analysis

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Theme

A REUSABLE launch vehicle system, such as the space shuttle, may experience structural fatigue damage due to repeated exposure to ascent winds and gusts. It is necessary, therefore, to determine the damage potential by computing various parameters which describe the applied loading. Such parameters previously have been predicted by a Monte Carlo approach in which repeated computer simulations are performed. This study was conducted to assess the feasibility of an alternate method for computing the load spectra parameters. The suggested approach is based on a statistical technique in which the ascent wind velocity is modeled as a nonstationary random process. The model parameters are determined by processing available measured wind data. The wind statistics are then treated as input in a vehicle response analysis. In contrast to the Monte Carlo approach, only a single computer analysis must be performed to obtain response statistics for a given vehicle configuration. Thus, the procedure offers a cost-saving potential if used early in the design phase when the vehicle configuration is subject to continual modification. Then, the final design could be verified by the Monte Carlo simulations as has been recommended in Ref. 1.

Contents

For turbulence analyses of conventional aircraft, it is generally assumed that the turbulence field is homogeneous and isotropic. Then the turbulence velocity, as visualized by an observer on the aircraft (flying at constant speed and altitude), is a stationary random process with respect to the indexing parameter, time. The stationarity in time arises from homogeneity in space through Taylor's hypothesis.

In the case of a vehicle ascending through the atmosphere, the wind velocities encountered are not homogeneous with respect to altitude. This nonhomogeneity prevents us from modeling the wind velocity as a stationary random process. Also, for most launch vehicles, the mass properties and the vehicle velocity change with time; thus, even if the excitation were stationary, the response would be nonstationary. However, the complexities which arise from the time varying system properties and from the altitude varying wind properties can be accommodated by modeling the excitation and response as nonstationary random processes. This technique has been utilized previously by several investigators including Bieber,[2] and Beer and Lennox.[3] In this paper we have extended previous research efforts by computing the average threshold crossing of wingload response for a typical space shuttle configuration, and by assessing the accuracy of the calculations by comparing them with Monte Carlo results.

The theoretical development of the nonstationary analysis is based on the modeling of the zonal component of the ascent wind velocity as a nonstationary random process. It is assumed that the velocity, V, may be written as a function of altitude, y, as

$$V(y) = \mu_v(y) + v(y) \qquad (1)$$

where $V(y)$ is the zonal wind velocity, $v(y)$ is the "turbulence" wind component, and $\mu_v(y)$ is the ensemble average or first moment of the process. We further assume that the turbulence component is a uniformly modulated nonstationary random process, that is

$$v(y) = C(y)G(y) \qquad (2)$$

where $C(y)$ is a deterministic function, and $G(y)$ is a stationary random process which is Gaussian distributed.

For an excitation process described by Eq. (1), the response statistics of the launch vehicle system mabe computed by a number of techniques including time domain analyses, frequency domain analyses, and combined time-frequency analyses. The evolutionary spectral analysis developed by Priestley[4] is the combined time-frequency technique which was used in this study. The evolutionary spectral analysis was chosen because it provides a representation for the spectrum of the uniformly modulated process which has a simple physical interpretation. Also, evolutionary spectral analysis leads to computationally convenient expressions for the response statistics, particularly when the excitation varies slowly with time.

Expressions for the variances and covariances of nonstationary response derived by the evolutionary spectra analysis procedure have been given in the literature.[4–7] For the present application, these equations can be developed as follows. Let the vehicle total response be

$$Q(t) = \mu_Q(t) + q(t) \qquad (3)$$

where $\mu_Q(t)$ is the time varying ensemble average of response, and $q(t)$ is the response to the turbulent wind component. It can be shown that the variance of the response item $q(t)$ is

$$\sigma_q^2(t) = \int_{-\infty}^{\infty} |B(t,\omega)|^2 \Phi_{GG}(\omega)\, d\omega \qquad (4)$$

where

$$B(t, \omega) = \int_0^t h(t,\tau)C(\tau)e^{i\omega(\tau-t)}\, d\tau \qquad (5)$$

and $\Phi_{GG}(\omega)$ is the power spectral density function for the stationary process, $G(t)$. $h(t\tau)$ is the impulse response function. Similarly, expressions for the variance of the rate of change of response, $\sigma_{\dot{q}}^2$, and for the correlation coefficient, $\rho = E[q\dot{q}]/\sigma_{\dot{q}}\sigma_q$, can be readily determined.[3,5]

The response statistics σ_q^2, ρ, and $\sigma_{\dot{q}}^2$ are not, in themselves, indicative of the fatigue damage potential. However, by combining these parameters with the ensemble averages of Q and $\dot{Q}$, we obtain the ingredients required to compute the

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average rate at which the response, Q, crosses the threshold level, ξ, from below. This crossing rate statistic is designated $E[N_+(\xi,t)]$, and it is related to fatigue damage potential. For a Gaussian distributed random process with nonzero mean value, $E[N_+(\xi,t)]$ is given by

$$E[N_+(\xi,t)] = \sigma_{\dot{q}}(2\pi\sigma_q)^{-1}(1-\rho^2)^{1/2} \cdot \exp(-\eta^2/2)[\exp(-\zeta^2) + \pi^{1/2}\zeta(1+\mathrm{erf}\zeta)] \quad (6)$$

where

$$\mathrm{erf}\zeta = \frac{2}{\sqrt{\pi}}\int_0^\zeta e^{-t^2}\,dt$$

and

$$\eta = (\xi - \mu_Q)/\sigma_q$$

$$\zeta = [\mu_{\dot{Q}}/\sigma_{\dot{q}} + \rho\eta]/[2(1-\rho^2)]^{1/2}$$

The average number of times the process crosses ξ between the flight times t_1 and t_2 is

$$E[\eta_+(\xi)] = \int_{t1}^{t2} E[N_+(\xi,t)]\,dt \quad (7)$$

The primary objective of this study was to evaluate the accuracy of results obtained from Eq. (7) under the assumptions which have been stated above. To this end a structural configuration and ascent wind data were chosen for use in the analysis. The vehicle system chosen for the structural analysis was the Phase B North American/General Dynamics space shuttle configuration. This system consisted of a flyback data wing orbiter mounted in piggyback fashion on a flyback delta wing booster. The idealized structural system consisted of pitch plane rigid body motion plus booster wing bending. The response quantity chosen for evaluation was the wing-root vertical shear. The measured wind data used in the study were the 150 FPS-16 Radar/Jimsphere profiles[1] for the month of March. Only the zonal components of the March winds were used, and a due east launch from Cape Kennedy was simulated.

For the Monte Carlo analysis a conventional launch simulation computer program was used. The launch program was used to compute the time varying vehicle response to each of the 150 March wind profiles. For each simulated flight the numbers of crossings of wingload above various levels were recorded.

The same 150 March wind profiles were used in the nonstationary analysis. Data processing techniques were applied to the wind velocities to determine the functions and parameters necessary to implement Eqs. (1) and (2). The mean value of the wind velocities, $\mu_v(y)$, was then used as input to the launch simulation computer code discussed above. This single calculation yielded the mean value of various response quantities to the March winds. To determine the variances and covariances of wingload response, a small perturbation analysis was performed. In this analysis linearized equations of motion were used to compute the appropriate vehicle transfer functions. These transfer functions vary continuously with time into launch. To minimize computational efforts, the transfer functions were computed at various times in the flight and the time varations of the response statistics were determined by interpolation procedures. Having thus computed μ_Q, $\mu_{\dot{Q}}$, $\sigma_{\dot{q}}$, σ_q, and ρ, the average number of exceedances per launch was determined through Eqs. (6) and (7).

The final results are presented in Fig. 1. This figure shows

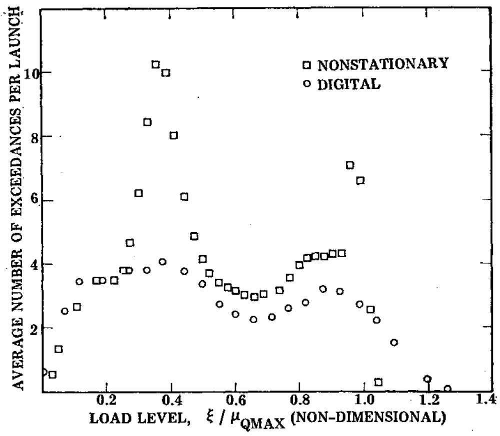

Fig. 1 Ensemble average of the wingload exceedances.

the average number of wingload exceedances per launch as a function of normalized load level. Although the nonstationary results are encouragingly similar in trend to the Monte Carlo (digital) results, the discrepancies in magnitude near the load level ratio 0.4 and above the ratio 0.9 are excessive. It appears that additional effort is required to improve the accuracy of the nonstationary analysis. However, it is worth noting that the nonstationary results were obtained for less than 10% of the digital computer time needed to generate the Monte Carlo results.

We will conclude by suggesting a method for improving the accuracy of the nonstationary analysis. The most questionable assumptions used in the nonstationary analysis were those concerning the physical nature of the ascent wind. In particular, data processing results showed that the assumption of uniform modulation of the wind velocity was somewhat restrictive. Improved accuracy could be realized by allowing the turbulent component of velocity to assume a less restrictive nonstationary characterization; clearly, however, computational requirements would then be more excessive.

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