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Response of B-2 Aircraft to Nonuniform Spanwise Turbulence

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Design load requirements for random gusts prescribe a one-dimensional gust field, i.e., a field that is uniform spanwise for a vertical gust. By definition, such a gust will produce purely symmetric vehicle response with corresponding symmetric stresses. The more general case of a three-dimensional gust will cause an asymmetric response. The difference in response characteristics which may result are exemplified by the fact that at the centerline of a flying wing, symmetric shear and torsion are zero, whereas, the asymmetric values are not. Solution techniques based on cross-spectral methods have been applied to the B-2 aircraft to assess the nonuniform spanwise gust response characteristics. Results are presented comparing key vehicle response parameters for uniform and nonuniform gust loading. It is concluded that the uniform gust model generally produces the higher loads and that no additional design conditions are derived from the nonuniform gust loading.

Nomenclature

$\hat{A}$	=	normalized root-mean-square response
$[H_{rg}]$	=	frequency response matrix
$[I_e]$	=	diagonal editor matrix
$[K_r]$	=	covariance matrix
$K_{x/y}$	=	modified spherical Bessel function of the third kind of order x/y
L	=	gust scale of turbulence
N_0	=	mean frequency of zero crossings
$[PHF2]$	=	MSC/NASTRAN generalized gust force matrix
$p(x, y)$	=	bivariate Gaussian probability density function
$[QHJL]$	=	MSC/NASTRAN force-downwash influence coefficient matrix
$\bar{q}$	=	dynamic pressure
S	=	gust correlation strip separation distance
V	=	velocity
$[w_g]$	=	gust downwash matrix
Γ	=	gamma function
γ_{ij}	=	cross-correlation coefficient between responses i and j
ν	=	reduced frequency, $\omega L/V$
σ	=	dimensionless spanwise separation distance, S/L
σ_w	=	gust root-mean-square velocity
$[\phi_g]$	=	gust cross-spectral density matrix
$[\phi_r]$	=	response cross-spectral density matrix
ω	=	circular frequency

Introduction

DESIGN load requirements for random gusts[1,2] prescribe one-dimensional gust fields, i.e., fields that are uniform spanwise for a vertical gust and uniform in the vertical direction for a lateral gust. The variation in the lateral and vertical gust velocities is only accounted for along the longitudinal axis, and the aircraft response to the lateral and vertical gust are treated independently. By definition, the vertical gust will produce a symmetrical vehicle response with corresponding symmetrical stresses, and the lateral gust will produce an antisymmetrical response with corresponding antisymmetrical stresses. Criteria for defining the corresponding design loads utilize these gust response characteristics in conjunction with specified turbulence field parameters, limit load exceedance requirements, and factors applied to the root-mean-square (rms) responses to arrive at "limit" loads. Most of these criteria are based upon studies of successful aircraft that relied on one-dimensional analysis techniques for deriving the appropriate requirements.[3,4]

The more general case of a three-dimensional gust will cause an asymmetric response, i.e., a combination of symmetric and antisymmetric responses. The one-dimensional assumption (spanwise uniformity for the vertical gust) can be unconservative, as exemplified by the fact that at the centerline of a flying wing symmetric shear and torsion are zero, whereas, the asymmetric values are not. This concern is not new and has been expressed in Refs. 5–9. Therefore, the problem is to determine how much coupling exists between the symmetric and antisymmetric responses of the vehicle for the general three-dimensional case.

Eichenbaum[9] has presented comparisons between one-dimensional and three-dimensional analyses for the C-5A aircraft. The results showed a decrease in loading on the wing while there was a small increase on the horizontal stabilizer. These results were explained by the effects of spanwise-averaging on the symmetric responses and the relative contributions of the antisymmetric responses to the overall loads on the components. These results were verified in part by comparison to flight test data which showed that the three-dimensional results compared much better to test data than did the one-dimensional results when assuming the von Kármán turbulence model.

Hoblit[10] has summarized comparisons of one-dimensional and three-dimensional analyses performed on the L-1011 aircraft. The results generally showed that the effect of the three-dimensional analysis is to reduce wing shear and bending moment responses. However, significant increases in wing torsion inboard of the engine were noted due to excitation of the first antisymmetric bending mode by the spanwise variation of gust velocity.

Johnston[11] compared measured L-1011 aircraft response to turbulence with both uniform and nonuniform gust analyses. These comparisons indicated that the nonuniform gust model more closely matched measured data than did the uniform gust model.

The USAF/Northrop B-2, because of its low wing loading and requirement to fly low-altitude terrain-following missions, includes one-dimensional gust conditions in its design set of

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