

Nonlinear Aircraft Loads in Severe Atmospheric Turbulence

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The problem of predicting loads due to turbulence for aircraft with nonlinear flight-control systems is reviewed, and related recent research in this area is described. Two alternative approaches to the problem, stochastic simulation and worst-case analysis, are compared and problem areas associated with each are identified. It is concluded that the latter method, which involves a search over a specified family of gust patterns to find the pattern that causes maximum load, is appropriate for investigating a limited number of critical cases, but that a preliminary simplified method of estimation is called for by computational considerations as a means of identifying such critical cases. A new genetic algorithm is described and proposed as the most reliable method of performing the search. It is illustrated how this search algorithm can be simplified computationally by introducing a weighting factor that penalizes the more complex gust patterns, a step that is supported by measurements of the amplitudes of gust patterns in severe turbulence.

Nomenclature

\bar{A}	= measure of response found by power spectral density analysis
a	= empirical constant in Eq. (2)
b	= empirical constant in Eq. (2)
e	= energy-reduction factor
n	= number of component ramp gusts in the discrete gust pattern
p_i	= absolute value of the wavelet coefficient
S_I	= information entropy
U	= energy of the single-wavelet pattern
U_σ	= design gust velocity

I. Introduction

ACCORDING to a manufacturer's survey [1] of the impact of nonlinear flight-control systems on the prediction of aircraft loads due to turbulence, there is an increasing need to model control-system nonlinearity, to avoid designing control systems that degrade structural performance, and to demonstrate the effectiveness of alleviation systems for aircraft certification. The manufacturer is faced with the conflicting needs to perform a thorough investigation of the effects of such nonlinearity on aircraft loads due to turbulence and at the same time to constrain the potentially rising cost of the load-prediction process. Although a range of analytical tools is currently in existence to investigate this nonlinear problem, according to [1] there is an ambiguity regarding interpretation of the continuous-turbulence (CT) airworthiness requirements [2] that has led to the development of an assortment of methods based on different assumptions and there is a need for the continuing development of nonlinear analysis techniques that provide practical means of compliance with the airworthiness requirements. This paper is intended as a contribution to this process.

Control-system nonlinearity manifests itself in various ways. In [1], the major types of nonlinearity exhibited by the electronic flight-control systems of a typical modern jet transport aircraft are summarized under the following categories:

1) Elemental nonlinearity refers to the existence of nonlinear control-law elements, typically associated with actuator limits and

rate limits that can be exceeded when the demand in severe to extreme turbulence becomes sufficiently great.

2) Additive laws are control functions that involve the operation of additional control laws in combination with the normal flight-control laws and are typified by load-alleviation systems. The alleviation function is activated when the excitation due to turbulence becomes sufficiently great and ceases operation when the turbulence subsides.

3) Unidirectional switching is a type of nonlinearity that involves switching between two flight-control functions, for example, from a normal function to a flight-protection function, such as stall protection. Switching to the protection function is triggered by the turbulence, and reversion to the normal flight-control function is only possible with pilot intervention. Consequently, an analysis of the response to turbulence that does not allow for pilot intervention will start in the normal control function but end within the protection function.

Mandatory aircraft limit-load requirements for flight in continuous turbulence [2] are currently formulated in terms of a prescribed power spectral density (PSD) for the turbulence. The load requirement, which follows the design-envelope approach [3], is formulated specifically for linear aircraft response and is expressed in terms of a response factor \bar{A} , calculated as a ratio of standard deviations of output and input, multiplied by a specified gust intensity U_σ to obtain the design load. The procedure to calculate \bar{A} is generally implemented by means of frequency-domain calculations [3].

When the aircraft response is nonlinear, the preceding formulation of the load requirement in terms of \bar{A} is no longer applicable, and some kind of generalization, compatible with the procedure for linear aircraft, is called for. The standard approach, typified by [4–6], involves stochastic simulation. In this method, the system is excited using synthetic turbulence time histories having Gaussian statistics, based on the von Kármán model [3] for the power spectral density. As described in the preceding references, the procedure for estimating the nonlinear aircraft design gust load is based on the measurement of threshold-exceedance counts for the response.

The application of this stochastic simulation method is faced with two distinct types of problem: one conceptual and one practical. The conceptual problem is that it is inherently tailored to a mission analysis approach rather than a design envelope [3]. Whereas the results obtained are in the form of a statistical distribution, the requirement in the airworthiness regulations [2] takes the form of a design-envelope criterion that calls for the calculation of a single amplitude of response for each load. In the case of a nonlinear aircraft, there is no unique way of calculating this single load from the measured statistical distribution. In practice, approximate methods have been developed [4–6] to estimate the single design load, as required by the design-envelope requirement, from the results of a stochastic simulation.

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