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Computation of Maximum Gust Loads in Nonlinear Aircraft Using a New Method Based on the Matched Filter Approach and Numerical Optimization

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Motivation

Time-correlated gust loads are time histories of two or more load quantities due to the same disturbance time history. Time correlation provides knowledge of the value (magnitude and sign) of one load when another is maximum. At least two analysis methods have been identified (references 1 and 2) that are capable of computing maximized time-correlated gust loads for linear aircraft. Both methods solve for the unit-energy gust profile (gust velocity as a function of time) that produces the maximum load at a given location on a linear airplane. Time-correlated gust loads are obtained by re-applying this gust profile to the airplane and computing multiple simultaneous load responses. Such time histories are physically realizable and may be applied to aircraft structures.

Within the past several years there has been much interest in obtaining a practical analysis method which is capable of solving the analogous problem for nonlinear aircraft. Such an analysis method has been the focus of an international committee of gust loads specialists formed by the U. S. Federal Aviation Administration and was the topic of a panel discussion at the Gust and Buffet Loads session at the 1989 SDM Conference in Mobile, Alabama. The kinds of nonlinearities common on modern transport aircraft are indicated in figure 1.

The Statical Discrete Gust method of reference 1 is capable of being, but so far has not been, applied to nonlinear aircraft. As stated in reference 1, to make the method practical for nonlinear applications, a search procedure is essential.

The method of reference 2 is based on Matched Filter Theory and, in its current form, is applicable to linear systems only. The purpose of the current paper is to present the status of an attempt to extend the matched filter approach in reference 2 to nonlinear systems. The extension uses Matched Filter Theory as a starting point and then employs a constrained optimization algorithm to attack the nonlinear problem.

- **Time-correlated gust loads are generated to obtain physically realizable design loads for the analysis and design of aircraft structures**
- **Active control systems of modern aircraft contain significant nonlinearities:**
  - Hardware nonlinearities . . . control surface rate and deflection limits
  - Coded nonlinearities in digital control system
- **The objective is to employ optimization to determine the excitation that produces the maximum gust loads on nonlinear aircraft**
  - Matched filter theory for linear systems provides starting guess

Figure 1

Schematic of Matched Filter Theory as Applied to Linear Systems

Figure 2 contains a schematic of the steps necessary to generate maximum time-correlated gust loads for a linear system using Matched Filter Theory. The signal flow diagram is presented as two paths; the top path illustrates the generation of the system impulse response; the bottom path illustrates the generation of the maximum response of the system.

In the top path, a prefilter (transfer function) representing the gust dynamics is excited by an impulse of unit strength to generate an intermediate gust impulse response which, in turn, is the excitation to the aircraft. Computationally, the time history of the response is carried out until the magnitude of the response dies out to a small fraction of the largest amplitude of the response. The response is normalized by its own root-mean-square (rms) value. This normalized response, reversed in time, is the "matched" excitation waveform for the output y. This becomes the input to the next part of the computational process.

The bottom path illustrates how the maximum response of the system and the critical gust profile are obtained. The matched excitation waveform is applied to the same "known dynamics." The intermediate gust response is referred to as the critical gust profile. The final time histories are time-correlated gust loads. The maximum guaranteed response, y_{max}, is equal to the rms of the impulse response and may be scaled to correspond to the gust intensity levels of interest. It should be mentioned that to obtain both the critical gust profile and the maximum response for a different output, a separate but similar analysis needs to be performed.

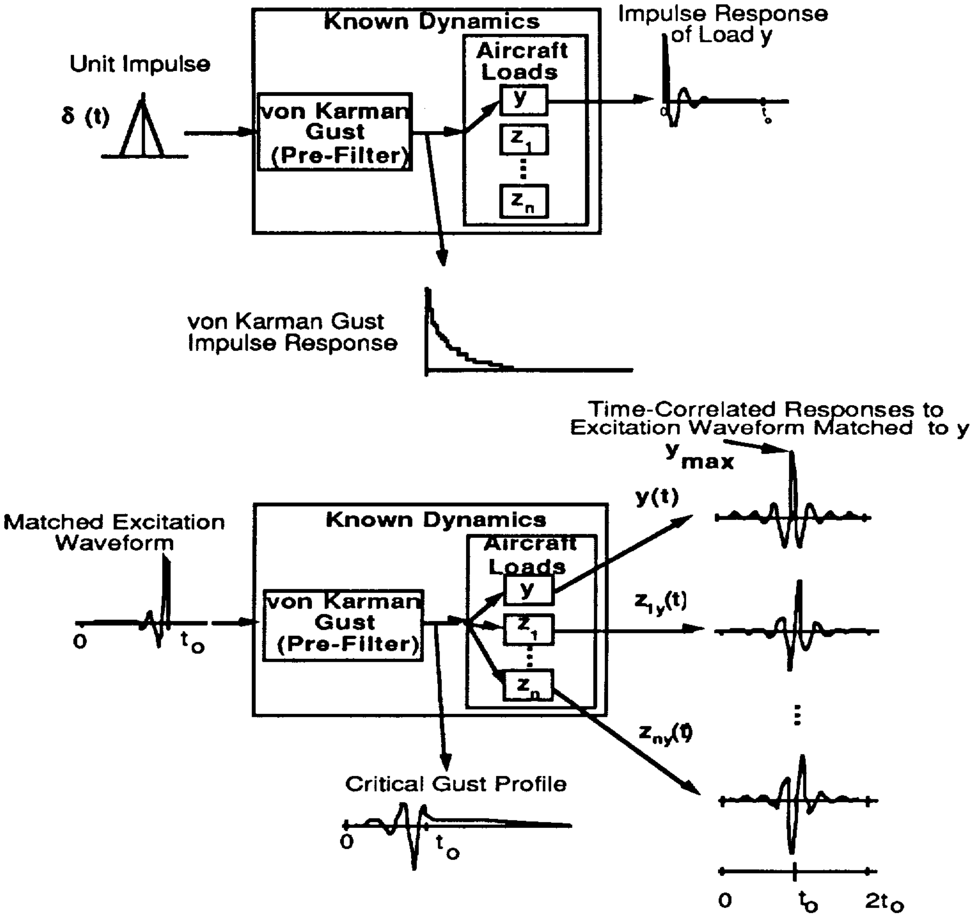

Figure 2

Optimization Scheme to Obtain Maximum Gust Loads for Nonlinear Systems

The objective of the present research is to determine the excitation, with a prescribed rms, that results in a maximized peak gust load response while producing a gust profile of constant energy level (and thus a constant probability level) in an aircraft with a nonlinear element. This figure illustrates how an optimization algorithm may be employed to compute maximized gust loads and their corresponding critical gust profiles for nonlinear systems. The matched filter approach (as described in connection with figure 2) is used to provide an initial estimate of an excitation waveform for turbulence of a given intensity, shown in the upper-left corner of figure 3. The optimization scheme begins with the computation of the coefficients of a set of orthogonal functions in a series approximation to the waveform, normalized to a unit rms. The approximation to the excitation waveform is the input to the gust prefilter, whose output is an iterative gust profile. The gust profile then becomes the input to the nonlinear airplane model. The final output is a time history of the load quantity of interest. Note that the shaded area in the optimization loop is analogous to the "known dynamics" element in figure 2.

The orthogonal approximating function coefficients, which are the design variables in the optimization scheme, are systematically varied by the optimizer until a maximum peak in the load response in obtained. The coefficients are constrained to produce a waveform approximation with a unit rms. Since the approximating functions are orthogonal, Parseval's Theorem allows the rms of the excitation waveform to be written simply as the sum of the squares of the coefficients.

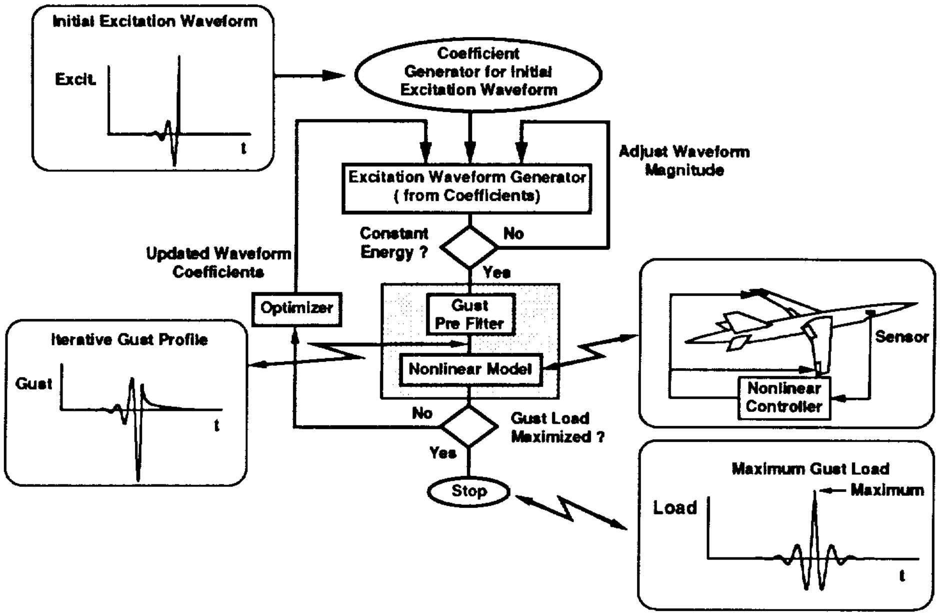

Figure 3

Coefficient Generator Using Fourier Series Approximation

Figure 4 presents an example of approximating the excitation waveform with the coefficient generator. Fourier series has been investigated as a candidate approximating function. The figure shows an initial waveform to be approximated, and two examples of Fourier series approximations. The second plot shows the resultant curve for 41 coefficients. The peak excitation is significantly underpredicted and there is a high frequency oscillation present during the latter portion of the time history. Using 401 coefficients to approximate the excitation sufficiently captures the curve's characteristics, as illustrated in the third plot.

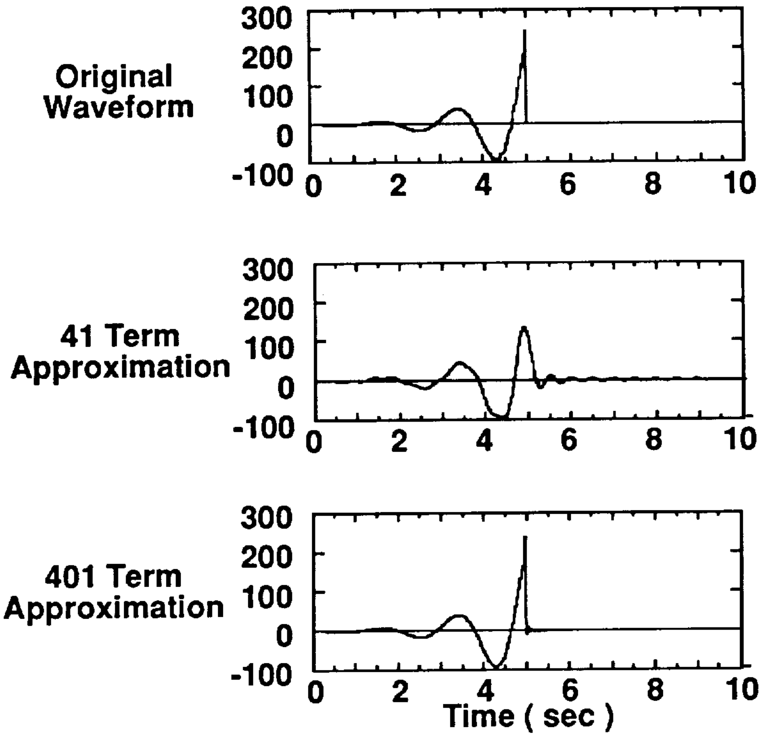

Figure 4

Block Diagram of Aircraft Control System with Nonlinear Element

A simulation model of a drone aircraft was constructed to demonstrate an application of the present method. The model is based on a configuration used to design the gust alleviation control system as discussed in reference 3. Figure 5 shows the block diagram of the simulation model which includes the aeroelastic plant, the gust load alleviation control law, and the nonlinear control element. The shaded block to the left of the plant is the iterative gust profile input. The shaded block to the right of the plant is the wing root bending moment. The maximum absolute value of the wing root bending moment is the objective function.

The plant itself is a linear, s-plane aeroelastic half-model consisting of 2 rigid body modes and 3 flexible modes. Unsteady aerodynamics were obtained using the doublet lattice method (reference 4). The plant model also includes the dynamics for the aileron and elevator control surface actuators. The two-input/two-output control law was obtained using a Linear Quadratic Gaussian design approach with the intent of reducing wing root bending moment. The controller uses the two control surfaces simultaneously.

The original control system design did not contain any nonlinear elements. The nonlinear element defined in the figure is based on a spoiler-driven gust load alleviation system used on the Airbus A320 (reference 5). This nonlinearity is intended to simulate some of the important aspects of an actual system; these aspects include allowing motion only in one direction and preventing motion beyond a deflection limit.

It should be added that wing bending moment response is dominated by the short period dynamics and is characterized by a large overshoot and a smaller undershoot. The objective of the load alleviation system is to reduce the overshoot load above a one g level and to ignore the undershoot loads below this level and the neutral load condition. The nonlinear element in the controller accomplishes this type compensated load reduction.

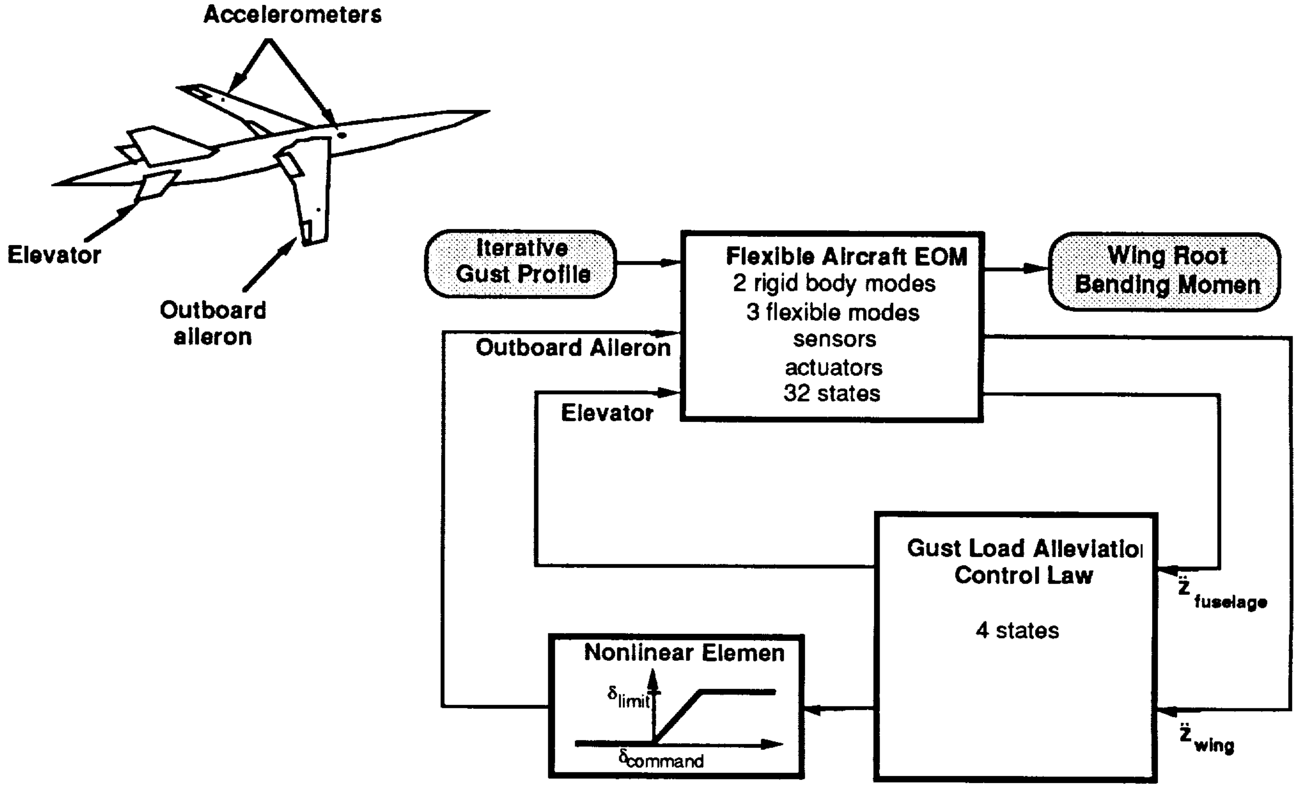

Figure 5

Status

Figure 6 outlines the status of the task. The entire scheme presented in figure 3 has been implemented. The nonlinear control system has been simulated with MATRIX_X SYSTEM_BUILD (reference 6), which uses a high-level interpretive language and nonlinear functions that are built into the program. The simulation is run on a MicroVAX computer. The nonlinear simulation with approximately 2000 time points takes about five minutes clock time to run.

As indicated in figure 4, 401 terms in the Fourier series are necessary for an adequate representation of the initial excitation waveform. Since this is the number of terms used in the implementation, this task required the generation of 200 sine and 201 cosine waveforms for each objective function evaluation.

The optimization is performed using a MATRIX_X Optimization Module (reference 7) that also incorporates a high-level interpretive language. Gradients are generated from within this module using a finite difference method. This part of the computation is estimated to require 402 evaluations (one more than the number of design variables) of the objective functions which means performing the same number of simulations. Using SYSTEM_BUILD and the Optimization Modules, the optimizer was allowed to run for a day and a half clock time and had to be stopped. It was then decided to modify the method to allow more rapid solution of the problem. Figure 7 outlines some of the problems encountered and the possible solutions.

- **Nonlinear control system implemented using MATRIX_X SYSTEM_BUILD**
  - Uses high-level interpretive language
  - Employs built-in nonlinear functions
- **Excitation waveform generator utilized Fourier series**
  - 401 coefficients necessary for good initial waveform approximation
  - Waveform composed of 200 sines, 200 cosines, and 1 constant
- **MATRIX_X Optimization Module used to maximize loads**
  - Objective function is the peak wing root bending moment response
  - Uses equality constraint to maintain constant energy
  - Generates gradients using finite difference method

Figure 6

Research Problems and Proposed Solutions

Figure 7 presents the major research problems identified to date. The central issue is speed. To deal with this problem three areas are being investigated: simulation speed, number of design variables and optimizer speed.

The simulation constructed using SYSTEM_BUILD was run on a MicroVAX. Both the high-level interpretive language of SYSTEM_BUILD and the machine limitations of the MicroVAX contribute to the slowness of the simulation. To overcome this problem, a FORTRAN-based simulation needs to be generated using HYPER_BUILD (reference 8) and run on a faster computer using RemoteSim (reference 9).

The coefficients used to generate the excitation waveform serve as the design variables in the optimization problem. Using Fourier series to approximate the waveform requires an exceptionally large number of coefficients. Other orthogonal functions such as Chebychev polynomials are being investigated to determine their suitability for approximating the waveform. A reduction of the number of coefficients can be achieved by not approximating the discontinuous drop off to zero of the excitation waveform and explicitly setting waveform to zero at that point.

The speed of the optimization module is the third area for possible improvement. Increasing the speed could be accomplished by using a FORTRAN-based optimization module instead of the high-level interpretive language of MATRIXx. Since maintaining the equality constraint is a difficult task to achieve for most optimizers, the number of iterations through the optimizer loop could be reduced by reformulating the equality constraint as an inequality constraint. Gradients currently generated by finite differencing might also be generated analytically. The number of design variables could be reduced by using only the coefficients with the largest gradients. This would also produce a faster optimization.

Problem:
- SYSTEM_BUILD simulations too slow on VAX computers

Solution:
- Fortran-based simulation such as HYPER_BUILD needs to be generated
- Simulation must be executed on faster machine

Problem:
- Exceptionally large number of Fourier coefficients are needed to generate the excitation waveform

Solution:
- Use other orthogonal functions better suited for waveform approximation
- Precomputed polynomial waveforms for later use

Problem:
- MATRIXx Optimization Module too slow

Solution:
- Incorporate a Fortran-based optimization module
- Reformulate equality constraint as inequality constraint
- Generate gradients analytically
- Choose as design variables only those coefficients with the largest gradients

Figure 7

References

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