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Review of Aircraft Vibration Environment Prediction Methods

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Abstract

Aircraft vibration response environment prediction, which is adopted in aircraft initial vehicle development, has not been got enough attention and wide application yet. This paper briefly reviews theoretical and engineering significance of aircraft vibration response environment prediction firstly. Then the paper summarizes the main aircraft vibration response environment prediction methods and indicates their advantages, disadvantages and applicability scopes, including extrapolation of similar structure, theory analysis and analytical solution of differential dynamical equation, statistical parameter modeling, simulation calculation modeling and machine learning. Finally, the paper points out that uncertainty and non-linear structures, nonstationary signal analysis and complex vibration environment response prediction are major problems for aircraft vibration response prediction and directions for future research work.

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1. Introduction

To ensure the reliability of the aircraft movement, assess its performance and test its adaptability to the environment, we must carry out simulated environment experiment about the dynamics system. And determining the appropriate dynamic environment conditions has a crucial importance for the development of aircraft. However, the too low dynamic environment condition will lead to short-test, poor test of aircraft, and even invalid flight in actual bad dynamic environment. On the contrary, the over

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dynamic environment condition will lead to over-test. And it makes the development of aircraft more difficult and causes longer developing period and more costs.

We can determine the corresponding dynamic environment condition by analyzing with large volumes of test data and flight telemetry data. However, because of the limits of test costs and the difficulties of testing and arranging points, the test obtains only response information about local test points in limited test environment. Meanwhile, for the newly developed aircrafts, the many uncertain parameters and lack of experimental data, will bring greater error to directly use the data of old types of aircrafts. Therefore, during initial stage of the vehicle development program, an effective prediction method for dynamic environment is required to analyze a variety of excitation sources, and obtain relatively accurate vibration responses, which provides a reliable basis for structural design [1].

2. Extrapolation of similar structure

Based on similarity theory, extrapolation method utilizes the working environment data and test data of the existing products to predict the corresponding new products vibration environment. In this case, the new products are similar to the existing products in geometry structure, size and so on. A common approach is to analyze existing vibration data with regression methods to obtain vibration response prediction data of the new product. Another reasonable method which includes mainly proportion method and frequency response method, is using model test to obtain vibration environment data of real work environment. During the simulation test, through these methods we can use volumes of collected measured vibration data of aircraft to analyze excitation source, and then determine one or more excitation sources for ground simulation test.

However, as the traditional methods, extrapolation of similar structure is very rough for processing the similar parameters and may causes large prediction error. It depends on experience. Moreover, due to the complex relationship between the strong non-linear structural dynamic responses, although the advantages of similar design are definite, its development process is very slow. And so far, the application of similar design is limited to structural design of small deformation.

3. Theory analysis and analytical solution of differential equation

The usual dynamic equation is

$$[M]\ddot{X}+[C]\dot{X}+[K]X=\{r(t)\} \tag{1}$$

Where $[M]$, $[C]$, $[K]$ are mass, damping and stiffness matrix respectively; $\ddot{X}$, $\dot{X}$, X are acceleration, velocity and displacement vector respectively; $\{r(t)\}$ is the given load vector. The obtained result is accurate by theory analysis and analytical solution [2]. It can be used to assess the quality of numerical simulation and test research, so it is of great significance for the vibration theory study and development. It can also be combined with sensitive method or perturbation method to make qualitative and quantitative analysis, but it is difficult to solve. So it is limited in the real engineering, especially, for the complex dynamic system.

4. Parameter statistical models

Given the dynamic data sets, parameter statistical method establishes model from the statistical point of view. The model is usually expressed in the form of differential equations. Although it is not directly established on the base of Newton's law, but through comparing it with the differential form of motion equations established by Newton's law, we can find out the relationship between them under certain conditions. Therefore, parameter statistical model can be used to analyze the vibration system.

4.1. Transfer function model

When doing shaking table test for structures, if the non-evenness degree of the test table is small, equation (1) could be considered as response of a multi-degree of freedom system with a single point of excitation, namely single-input multiple-output (SIMO) system. Given two states, a, with complete input and output test results and b, the random vibration state to be predicted, there are only the input of the power spectral density. The input and output of two states correspond with the same measuring point. State a can be calculated by the following equation:

$$\left|H_i(\omega)\right|^2 = \frac{S_{yiyi}(\omega)}{S_{xx}(\omega)} \tag{2}$$

And the response power spectrum of state b can be obtained by the following formula:

$$S_{yiyi}(\omega) = \left|H_i(\omega)\right|^2 (S_{xx}(\omega))_b = \frac{(S_{xx}(\omega))_b (S_{yiyi}(\omega))_a}{(S_{xx}(\omega))_a} \tag{3}$$

By analyzing the vibration transmission characteristics and using test results under structure random vibration, structure random response with relatively high order of magnitude or with more difficult experiment was predicted. RMS error of most tested points was smaller, and RMS error of some points was more than 10%. Vibration transfer characteristics is carried out under the linear model assumption, when the nonlinear response is highly non-linear, RMS error is larger in the peak of power spectral density, so the methods can be used to determine the degree of nonlinear of structural response.

4.2. ARMAV time series model

For the n degree of freedom vibration system, when the excitation is white noise, you can use one-dimensional ARMA model to represent. If using only measured data with a degree of freedom to model, it is one-dimensional $ARMA(2n, 2n-1)$ model. When the excitation is a stationary random process, n dimensional differential equations can be used to describe the vibration response $\{Y\}$ of the system, and you can use equation (4) to describe.

If only one degree of freedom is used to model the measured data, it is a one-dimensional $ARMA(2n+g, 2n+g-2)$ model. There, g is used to describe excitation. We can use the formula to make vibration analysis by comparing the model with the state equation of invariant vibration system. ARMAV time series model is mainly used for predicting vibration mode, and there is a fixed-order problem about statistical parameters. Currently, from the perspective of information theory, a number of criteria have been proposed, such as the residual sum of squares criterion, F distribution test, AIC criterion, BIC criterion and FPE criteria. All criteria must follow the following two principles: the first is that they can reflect the characteristics of the data, and the second is that the order is as low as possible.

$$\Delta(B)\{Y_m\} = \Omega(B)\{x_m\} \tag{4}$$

5. Theory analysis and analytical solution of differential equation

5.1. Time domain solution

Traditional approaches for the time-invariant system, such as Wilson method, Newmak method and Houbolt method, are sensitive to the time step and are not highly precise. The new precise integration method [4] gives a highly precise numerical result, which approaches the full computer precision.

However, the method involves a series of matrix operations in solving non-homogeneous structure dynamic equation, even if the non-homogeneous terms were constant, too. The calculation of matrix inversion causes difficulties in program implementation, in particular, the inverse process produces numerical instability and the inverse matrix does even not exist. Precise Cotes integration method is proposed by combining precise exponential matrix calculation and higher accurate Cotes integration calculation process. It avoids the difficulty of the inverse matrix calculation, and it is unnecessary to approximate the non-homogeneous vector. The accuracy and reliability of the method is better.

5.2. Frequency domain solution

Numerical methods with a sound mathematical basis and with lower cost, have been widely used in engineering practice. Among them, the traditional modal method (including the finite element method, boundary element method, etc.) are suitable for prediction of low frequency vibration environment, statistical energy analysis is suitable for prediction of high frequency acoustic vibration environment, while energy finite element method is suitable for prediction of mid-frequency.

Currently, the finite element method as a low-frequency mechanical environment prediction technology is mature with high accuracy and the relevant commercial software promote low frequency vibration response prediction progress. However, the traditional modal method limited to some low order modes, must be clearly identified. If the frequency is increased, the finite element mesh must be very small, which will greatly increase the system degree of freedom and computation cost. At the same time, difficulty increases with augment of structural complexity. And meanwhile, errors increase with expansion of the frequency range.

The basic idea of statistical energy analysis is dividing complex large system into several coupled subsystems which will exchange energy with each other, and then using statistical model for structural analysis and response calculation. Compared with fluid-solid coupling calculation method, the finite element method and boundary element method, statistical energy analysis is suitable for more wide frequency range, also simple and with small computation. Therefore, it is widely used in engineering.

Currently, dynamic environment prediction for spacecraft mid-frequency has become a research focus and challenge. One research method is to expand the upper limit frequency of finite element modeling. Vlahopoulos [3] solved the mid-frequency response prediction by EFEA. Langley et al [4] proposed hybrid FEM-SEA theory to solve displacement coordination of the FEM and SEA modeling components in interface. It was applied to aircraft acoustic prediction, rocket fairing interior noise analysis and vehicle chassis vibration and had got better results.

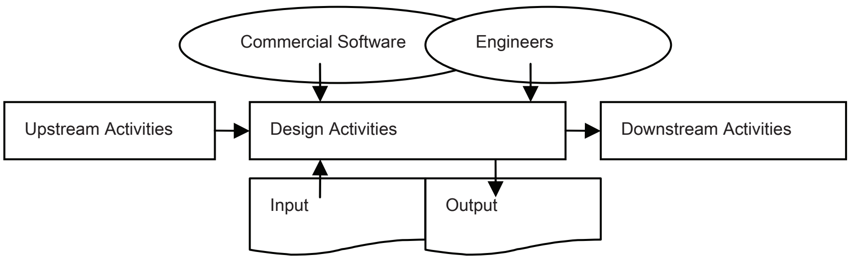

Figure 1：Elements of simulation design activities

Figure 1 [5] shows, numerical simulation cannot carry out without experimental support, which is caused by the complexity of the problem itself. For example, input parameters required in finite element model, such as the damping, modal damping ratio, are from the experimental or engineering experience. Simulation and experiment are complementary. Simulation can replace experimental to some extent, so it can provide the basis for design and modification to reduce costs and shorten the development cycle. However, while experiment provides input parameters and results verification for simulation, simulation cannot completely replace experiment. The modified parameters that can be the elements of the coefficient matrix in equation (1), can also be the physical parameters which compose matrix. Objective function can also be the equation error or error of modal parameters. In general, optimizing objective function is attributed to nonlinear least squares. And sensitive method and perturbation method could be adopted in approximate solution. Moreover, revised calculation accuracy is affected by the test data, and the best excitation frequency and the best point of excitation is of great research importance. After obtaining model parameters, Eigen function of vibration system can be obtained by calculating the eigenvalues.

6. Machine learning

As the complexity and nonlinear of the structure, response of the same structure under different input conditions is nonlinear. So that it is difficult to describe the system with precise mathematical model, and there is a certain degree of difficulty for calculating and predicting vibration response. For these complex systems, machine learning is a practical method for the environment prediction. Without prior knowledge of relation between input and output, we can get laws with test data, and then make environment prediction according to these laws.

6.1. Neural network

Neural network composed of a large number of simple processing units is the nonlinear dynamic system, with parallelism, storage, distribution, structure, variability, highly nonlinear, self-learning ability and self-organization and so on. Due to its inherent properties, neural network has been widely used in vibration engineering, prediction of dynamic characteristics of structure and other fields.

Dynamic neural network has a good result to predict the response of a structure. The following conclusions can be obtained from the dynamic neural network algorithm and simulation results.

a. It only needs historical data of the system.

b. It is regardless of the complexity and nonlinear factors of the system.

c. Prediction accuracy of dynamic neural network is better for system response with different input conditions.

6.2. Support vector machine

Different from the traditional approaches like neural network, the optimization goal of which is training error minimization, support vector machine (SVM), based on structural risk minimization principle makes the confidence interval minimization as the optimal objective. Therefore, the generalization ability of SVM is significantly superior to the traditional neural network. In addition, SVM transforms the income space into a high dimension space through non -linearity transformation, and then seek the optimum linearity classification facet. It guarantees good generalization ability, and solves the curse of dimensionality that makes the algorithm complexity has nothing to do with the sample dimension. Eventually, it becomes the quadratic programming problems, and in theory gets global optimum.

7. Conclusions and further research directions

7.1. Uncertainty

Based on the engineering background, uncertainties may mainly be classified into five areas: material parameter uncertainty, load uncertainty, uncertainty of geometry size, uncertainty of initial and boundary conditions and model uncertainty. The uncertainties and subsequently engendered errors have affected the analysis and design of the engineering structure system. For example, the time-varying structure is still a research focus. It is still immature because of research difficulties. However, with the development of engineering science, there are many dynamic problems of the time-varying structure, which need solving. The main approach currently proposed is uncertain dynamic structure analysis based on interval mathematics and time-varying structural system identifying.

7.2. Non-linear structure

There is weak nonlinearity under high sound intensity environment. In the non-linear structure, the form of differential equation becomes nonlinear Duffing equation. So the corresponding aircraft vibration environment prediction also needs to change into non-linear one. For example, the linear transfer function needs changing into nonlinear transfer function, the time series models need transferring into nonlinear time series ones, and the finite element simulation needs transforming into the nonlinear finite element one.

7.3. Non-stationary

Non-stationary random vibration magnitude during lift-off is larger and is 2 to 3 times in the free flying state. That is one of the many environmental factors leading to flight failure. In a certain range, FFT regards non-stationary data as stationary data, so inevitably brings great error, and cannot get the essential characteristics of vibration during lift-off. Although Modern time-frequency analysis of non-stationary signals processing methods fully describes the joint time-frequency characteristics, there is no mature method to make the equivalent design of test conditions depending on individual sample records for non-stationary random vibration.

7.4. Complex integrated mechanical environment

In working state, the structure is vulnerable to a variety of loads combined effects. For example, during flight, vibration, shock, noise and overload constitute a complex integrated mechanical environment. Currently, theory, simulation and experimental studies have been carried out about acoustic coupling and fluid-solid coupling.

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