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A new correlation method for the aerodynamic service loads determination of a rigid wing based on CFD analysis

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ABSTRACT

A new correlation method for the aerodynamic service loads determination of a rigid wing based on CFD analysis is presented. All flight conditions can be handled by the proposed method. The derived correlation equations are achieved by considering a training fighter aircraft as a prototype. Each wing of aircraft is divided into thirty three parts in the span wise direction. Extensive numerical solutions have been attempted by varying a number of parameters that directly affect the wings aerodynamic loads, such as Mach numbers, angle of attack, control surfaces deflections and etc. For each set of input parameters, the corresponding aerodynamic loads applied to different wing parts are calculated. The resulted loads and the corresponding input parameters are incorporated into a linear regression method in order to develop the appropriate correlation equations. The outputs of the developed equations are the aerodynamic loads at each part of the wing based on the independent variables, which are the above mentioned input parameters. The validity of the developed equations is shown by comparing the loads obtained from the latter equations with the corresponding ones calculated through numerical analysis for different flight conditions. The correlation equations can now be used to calculate the aerodynamic loads at each part for any set of arbitrary values assigned to the input parameters.

1. Introduction

The strength of aircraft structure can be significantly affected by the presence of a crack and is usually substantially lower than the strength of the undamaged structure. Structural failures in several aircraft in the late 1960s and early 1970s that were caused by existing flaws resulted in changes to the principles of design against structural fatigue: the damage-tolerance analysis [1].

The purpose of damage tolerance analysis is to ensure that flaws which may exist in safety-of-flight structure will not grow to a critical size which would cause catastrophic failure during the design or operational usage period and that a

Abbreviations: a_0 a_i a_{ij} a_{ii}, coefficients of linear regression equation; c0 c1…. cn, coefficients of the load equation; $x_{1 \ldots}$ x_n, independent variables; y, dependent variable; α, angle of attack (degree); M, mach number; ΔA, angle of ailerons (degree); ΔE, angle of elevator (degree); ΔR, angle of rudder (degree); ΔF, angle of flaps(degree); β, sideslip angle (degree); deg, Degree; ASL, aerodynamic shear load (N); APM, aerodynamic pitching moment (N. m); CFD, computational fluid dynamics; FDR, flight data recorder.

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specified level of residual strength is maintained during this period [2]. In simple terms, the damage tolerance analysis is the prediction of crack growth rate and determination of residual strength level of a given structure.

Among the factors affecting aircraft structural reliability such as fatigue, corrosion, and wear etc., the structural fatigue life is the main factor to determine the aircraft service life [3]. The fatigue is caused by the applied stresses emanating directly from structure applied loads. Therefore, the determination of applied load spectra is a necessary step for a proper damage-tolerance analysis. Since the contribution of aerodynamic loads is more pronounced than that of inertia loads, the estimation of aerodynamic loads have been attempted by many researchers.

In 1976, nonlinear prediction of aerodynamic loads on lifting surfaces was suggested by Kandil et al. [4]. They developed a numerical method for predicting the distributed and total aerodynamic loads on non-planar lifting surfaces for steady, inviscid and incompressible flow. Using this method, they investigated the effects of tip and leading edge vortex on wing lift.

Drela [5] also developed a method for simultaneous wing aerodynamic and structural load prediction. He modeled the wing aerodynamics by using lifting line theory with roll rate, yaw, and yaw rate effects being included. The wing structure was modeled as a nonlinear beam in which the vertical and horizontal displacements as well as torsional degrees of freedom were accounted for. The aerodynamic and structural problems together were constituted a coupled nonlinear system for the aerodynamic and structural unknowns, which were discretized and solved using a Global Newton method.

In 1998, Nagode and Fajdiga [6] developed a new method for prediction of the scatter of loading spectra based on probability density function (PDF). An algorithm was suggested by Karr et al. [7] for the calculation of loads applied to the airplane structures under the worst gust conditions. Eduardo Salamanca and Luis Quiroz [8] developed a method of interaction between flight loads (i.e. maneuver and gust loads) that is applied to a probabilistic damage tolerance analysis in an acrobatic aircraft.

A study about generation and use of standardized load spectra and load-time histories was presented by Heuler and Klatschke [9]. In their paper, an overview on and a summarizing description of standardized load-time histories was given followed by a discussion of principles, approaches and generation of standardized load-time histories. A research on the subject of aerodynamic load of aircraft horizontal tail was carried out by Qin and Sun [10]. In this work, they considered double lattice, computational fluid dynamics (CFD) and experimental methods for the loads calculation. Furthermore, the obtained loads via mentioned methods were compared at the Mach number of 0.6 for various deflection angles of horizontal tail, i.e. $-7, -5, -3, 0°$. The numerical studies presented by CFD showed very good agreement with wind tunnel tests carried out on the same model.

In 2009, Lee [11] presented his PhD thesis based on advanced aircraft service life monitoring method via flight–by–flight load spectra. A method for calculation of applied aerodynamic loads on the different parts of aircraft including the wing structure during the service life was developed. For this purpose, the F-16 fighter aircraft was chosen as a prototype. At first, the loads applied to each part of the wing during test flights were calculated by using strain gages. Subsequently, the aerodynamic loads were determined by subtracting the inertia loads from the total applied loads. Using the mentioned aerodynamic loads and the parameters from the flight data recorder (FDR), the appropriate regression equations were established for the calculation of the wing parts aerodynamic loads at any time during the entire flight.

A method for calculating aircraft fuselage aerodynamic loads using obtained data from flight simulation was presented by Gharibi and Khaki [12]. In their research, a training fighter aircraft was selected typically and its fuselage was divided into small parts longitudinally. The CFD numerical solutions were then attempted under different effective parameters such as Mach numbers, angle of attack and control surfaces diversities on the resulting aerodynamic loads. The magnitude of aerodynamic load applied to each part was found for any specific condition. An equation was subsequently derived to determine the applied aerodynamic load at any given part for any arbitrarily chosen flight condition. This was achieved through the implementation of least squares method by using the resulted loads in conjunction with mentioned parameters.

Previous experimental studies of wing aerodynamic service loads were costly and obviously entailed some degree of flight risks. There are some existing CFD studies that determine the loadings distribution on different parts of the aircraft, excluding the wing, in all flight conditions. In other words, in these CFD studies, no specific attention has been paid to the development of relevant correlation methods for the determination of wing loading distribution in all flight conditions within the service life of an aircraft. In the current paper, a new correlation method for the aerodynamic service loads determination of a rigid wing based on CFD analysis is presented. A jet training aircraft for which the wings are assumed to be inflexible has been selected as a prototype. The numerical solutions under different flight conditions are attempted for applied wing aerodynamic loads determination. The different flight conditions are considered by changing the Mach number, angle of attack, control surfaces diversities and etc. The wing is divided into thirty three parts longitudinally (from root to tip) and the amounts of aerodynamic load and moment applied to each part have been calculated.

It is obvious that the any endeavor to replace the extravagant experimental tests seems worthwhile. Besides, the loads determination via CFD numerical solutions is somewhat impractical when all flight conditions are to be considered. Hence, in this paper the equations for the calculation of aerodynamic shear loads (ASL) and aerodynamic pitching moments (APM) applied to each part are specified under all flight conditions. These equations are established via linear regression method by using the calculated CFD aerodynamic loads and the corresponding flight parameters.

The validity of the developed equations is shown by comparing the loads obtained from the latter equations with the corresponding ones calculated through numerical analysis for different flight conditions.