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Mass and performance optimization of an airplane wing leading edge structure against bird strike using Taguchi-based grey relational analysis

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Abstract Collisions between birds and aircraft are one of the most dangerous threats to flight safety. In this study, smoothed particles hydrodynamics (SPH) method is used for simulating the bird strike to an airplane wing leading edge structure. In order to verify the model, first, experiment of bird strike to a flat aluminum plate is simulated, and then bird impact on an airplane wing leading edge structure is investigated. After that, considering dimensions of wing internal structural components like ribs, skin and spar as design variables, we try to minimize structural mass and wing skin deformation simultaneously. To do this, bird strike simulations to 18 different wing structures are made based on Taguchi's L18 factorial design of experiment. Then grey relational analysis is used to minimize structural mass and wing skin deformation due to the bird strike. The analysis of variance (ANOVA) is also applied and it is concluded that the most significant parameter for the performance of wing structure against impact is the skin thickness. Finally, a validation simulation is conducted under the optimal condition to show the improvement of performance of the wing structure.

1. Introduction

Airplanes and birds occupy the same space during flight and therefore collision between them is inevitable. The damage caused due to these collisions is usually catastrophic. The bird strike to airplanes is not a new problem and has occurred since the early days of aviation history. The first bird strike was recorded by Wright brothers in 1905. According to the Federal Aviation Administration (FAA), in the United States alone,

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Nomenclature

A	Material
B	Skin thickness
C	Rib thickness
D	Rib distance
E	Cut out diameter
F	Spar location
C_v	Intercept of the $V_s - V_p$ curve
D_s, P_s	Constants of Cowper-Symonds law
F_N	Normal force of rivets
F_{NF}	Critical normal force of rivets
F_S	Shear force of rivets
F_{SF}	Critical shear force of rivets
GRG	Grey relational grade
i	Number of each experiment
I_E	Internal energy density per unit initial volume
k	Number of responses
k_t	Total number of responses
n	Total number of experiments
P	Pressure
q	Number of design parameters
V_p	Particle velocity
V_s	Shock velocity
$x_i^0(k)$	Response values
$x_0^*(k)$	Reference normalized response value
$x_i^*(k)$	Normalized response values
y_i	Response value of the ith experiment
α, β	Tie break contact constants
γ_e	Estimated grey relational grade
γ_i	Grey relational grade for ith experiment
γ_m	Total average grey relational grade
γ_0	Gruneisen gamma
Δ_{max}	Largest value of $\Delta_{0i}(k)$
Δ_{min}	Smallest value of $\Delta_{0i}(k)$
$\Delta_{0i}(k)$	Deviation between normalized response and reference values
$\dot{\varepsilon}$	Equivalent strain rate
ζ	Distinguishing coefficient
μ	$\rho/\rho_0 - 1$
ρ	Density
ρ_0	Initial density
$\xi_i(k)$	Grey relational coefficient
σ_n	Dynamic yield stress
σ_y	Yield stress

more than 138000 incidents of bird strikes were reported between 1990 and 2013.[1] The average annual cost of these strikes in the U.S. is at least $187 million. However, this annual cost can be estimated up to $937 million when unreported strikes are considered. Globally, bird and other wildlife strikes killed more than 255 people and destroyed over 243 aircrafts from 1988 to 2013. The number of bird strikes increases every year because of increase in air traffic, bird population and using fewer but more powerful engines per plane.

Therefore, the international certification regulations like Federal Aviation Regulations (FAR) require that all forward facing airplane components need to prove a certain level of bird strike tolerance before they are allowed for operational use. The acceptance of certification by experimental test is very expensive and time consuming. In addition, achieving a low-weight, bird-proof design requires several experimental tests. Consequently, in order to shorten the design time and reduce cost, numerical simulations are often used and are more popular among researchers. In this research, LS-DYNA code has been used to simulate bird strike to the wing leading edge structure.

All forward facing airplane components like engine inlet and fan blades, wing and empennage leading edge, windshield, window frame and radome are subject to bird strike (Fig. 1). As can be seen in Fig. 1, the most commonly damaged airplane components are engines and wing leading edges. About 31% of all damaging bird strikes involve the wing.[2] Consequently, many researchers have investigated bird strike to the airplane wing.[3–7]

Various numerical techniques like Lagrangian approach, arbitrary Lagrangian Eulerian (ALE) method and smoothed particle hydrodynamics (SPH) method are often used to model the bird strike phenomena. In Lagrangian approach, the numerical mesh is attached to material points and therefore any material deflection can distort numerical mesh. The major disadvantage of Lagrangian approach is the possibility of inaccurate results in analyzing large deflection problems. ALE technique combines Lagrangian and Eulerian approaches to get better results. In this approach, the numerical mesh does not follow material points exactly. Simulating bird strike by ALE approach is more complicated to perform than the other two methods. The SPH method is the most recent and the most efficient method to analyze bird strike problem because of its high accuracy and high solution speed. The SPH method is a meshless Lagrangian method in which the elements are a set of discrete and mutually interacting nodes. Due to the absence of a mesh connecting individual particles, the SPH method is perfectly suitable for solving problems involving large deformation.

Many studies and investigations have been conducted in the past in order to design the aircraft components which can resist in bird strike events. Barber et al.[8] were the first researchers that

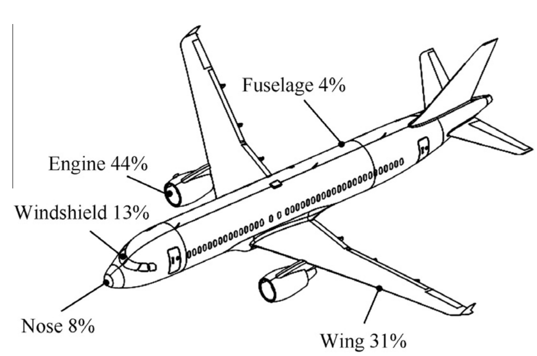

Fig. 1 Airplane components struck and damaged by bird worldwide (1999–2008).