NEW MODEL OF BIRD IMPACT RESPONSE ANALYSIS AND ITS ENGINEERING SOLUTION

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Abstract

The modeling and analytic methods for the response of windshield transparency to bird impact are studied. The interaction between the impact load and the transparency response as well as the nonlinearity effect is considered. To employ conveniently the existing general–purpose nonlinear finite element analysis programs and to dispel the oscillatory phenomenon arising in numerical solution, the momentum equilibrium method is used, other than the conventional Lagrangian and penalty methods. Meanwhile, instead of the incompressible irrotational fluid, a rubber–like hyper–elastic Mooney–Rivlin material is suggested for the first time to simulate the bird body behavior in impact; thus the difficulty of continuously updating the contact point pairs and adjusting the discretized FE–mesh during the analysis process can be avoided. Remarks similar to those given in other published papers are concluded. In addition, a solution method for the dynamic response under the derivative dynamic load is studied and compared with the coupling solution, and the consequent commends are given.

I. Introduction

Bird impact is one of the causes leading the aircraft structure to failure during flight, though its probability is extremely low. In designing a bird impact–resistant structure, reasonable determination of the spatial and temporal variation of the impact load is requisite and most important. The temporal variation of the impact force depends upon not only the mechanicalbehavior and impact attitude of the hitting bird but also the material property and geometrical parameters of the hit aircraft structure. In addition , to solve such a contact–impact problem as bird impact, the compatibility condition of velocities and accelerations as well as impact forces and deformations on the contact interface between the hitting object and target should be satisfied. Therefore, the bird impact response analysis is a nonlinearly coupled problem. Both overseas practices[1–4] and the authors' experience on this subject have shown that, to achieve an accurate prediction, a coupling solution procedure is of great necessity. The bird impact problem involves mainly the geometrical nonlinearity and high strain–rate where the former stems from large deflection while the latter stems from high impact velocity. Since the high strain–rate significantly changes the material constitutive relation, it would make the material fragile while it improves the yield and ultimate stresses of the windshield transparency [5]. By this reason, in general, the material nonlinearity need not be considered in the practical analysis.

The routine procedures for handling compatibility conditions on the interface may be classified as four categories on the whole, namely, the penalty method, Lagrangian, perturbed Lagrangian and augmented Lagrangian methods [6]. In the Lagrangian method, in addition to the displacement, velocity and acceleration, the impact force is introduced as a new unknown into the analysis to satisfy rigorously the compatibility conditions. A computational difficulty is, however, introduced at the same time. Naturally, to simplify the solution procedure, only the impact force and displacement are required to satisfy approximately the compatibility conditions on the interface, so that the compatibility requirements to the velocity and acceleration can be relaxed. An inherent drawback to the penalty method is the oscillatory phenomenon of the solution to the impact force, displacement and, particularly, the velocity and acceleration, while the degree of oscillation is relevant to the selected value of the penalty parameter.

Another matter of great importance in the study of bird impact problem is the mechanical modeling of the bird body. It is reported [1–4]that the mechanical property of a real bird in the impact process is similar to the incompressible irrotational potential flow so that it can be simulated with a fluid jet column. Since in the case of high speed impact a large deformation of the fluid column will be produced, on the one hand, the interface between the hitting object and target would be rapidly extended and, on the other hand, the discretized grid of the fluid column itself will be greatly malformed and thus the mesh division for finite element analysis is required to be continuously updated and modified in a self–adaptive way. This modeling is accompanied by another computational difficulty and requires such a complicated special code for contact–impact analysis as MAGNA or DYNA3D. To evade such an awkward situation, the hyper–elastic Mooney–Rivlin material is suggested for the first time in the present paper to simulate the bird body behavior during impact process.

II. Momentum Equilibrium Method

Lagrangian method has overwhelming superiority over the others in its applicationto the optimization of constrained problems. Since in the penalty method the penaltyparameters has been specified in advance, it needs not to introduce more variableas one does in Lagrangian method. Thus, from the view point of finite elementanalysis, the penalty method is very attractive as well. The solution of penaltyproblem appriximates to the exact one with a rate of 1 / p where p is the non–negativepenalty parameter. If the value of p is sufficient large, precise approximation tothe exact solution can be obtained. In the numerical implementation of the penalty finiteelement model, however, a spurious oscillatory phenomenon of the solution canoften happen. As a simple example, the penalty solutions with different penalty parameter values to the contact–impact problem of two coaxial elastic bars are shown in Fig.1where the oscillatory phenomenon is evident.

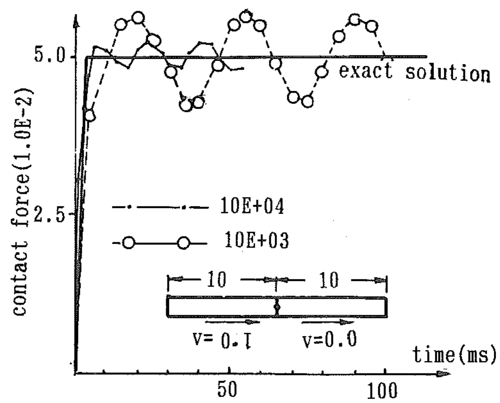

Fig.1 coaxial impact of two bars–penalty solution

In this paper, the sudden transition of velocities of the hitting object and the hit target before and after contact–impact is realized based on the the elastic wave theory. Again, consider the impact of a pair of coaxial bars [7,8]as shown in Fig.2. Let the two elastic bars B_1 and B_2 of the same cross sectional area $A = 1$ have acoustic impedance $(\rho_1 c_1)$ and $(\rho_2 c_2)$ respectively, where $c_i = \sqrt{E_i / \rho_i}$ is the wave front propagation speed, $E_i = 100$ the Young's modulus and $\rho = 0.01$ the density of the material of the bar B_i. It is assumed that before impact the two bars have null initial stresses while the initial velocities are v_1 and v_2 respectively, where $v_1 > v_2$. After coaxial impact, strong discontinuous elastic waves would propagate leftward and rightward from the impact interfaces of B_1 and B_2 respectively. By the compatibility condition, the particle velocities at the interfaces of the bars should be identical after impact, say, equal to v. Thus, following the conservation law of momentum, we have

$$\rho_1 dx_1 (v - v_1) + \rho_2 dx_2 (v - v_2) = 0 \tag{1}$$

Dividing both sides of Equation (1) by dt, we obtain

$$\rho_1 c_1 (v - v_1) + \rho_2 c_2 (v - v_2) = 0 \tag{2}$$

where $c_i = dx_i / dt$.Consequently,

$$v = \frac{v_1 + k v_2}{1 + k}, \qquad k = \frac{\rho_2 c_2}{\rho_1 c_1} \tag{3}$$

In the case where $\rho_1 c_1 >> \rho_2 c_2$, it can approximately be considered that $k = 0$, $v = v_1$. What is described above is the case of impact for two coxial bars. For a three dimensional discrete model,

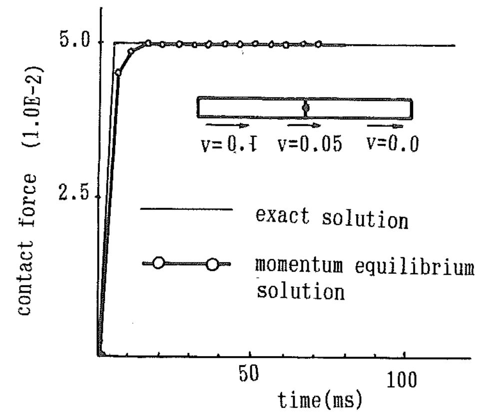

Fig.2 Coaxial impact of two identical elastic bars

the $\rho_i dx_i$ in Equation (1) or $\rho_i c_i$ in Equation (2) will be replaced by the lumped mass M_i,and now c_i is the local velocity of the expansion wave at the impact interface of the three dimensional elastic body B_i. Hence, Equation (3) can be rewritten as

$$v = \frac{v_1 + k v_2}{1 + k}, \qquad k = \frac{M_2}{M_1} \tag{4}$$

In addition, following that

$$M_1 \ddot{u}_1^- + M_2 \ddot{u}_2^- = (M_1 + M_2) \ddot{u}^+ \tag{5}$$

where $\ddot{u}_i$ is the acceleration of the lumped mass M_i at the contact impact point; the subscript "–" denotes the physical quantities under separated state before contact–impact, whereas "+" denotes the physical quantities under the integrated state after impact, thus

$$\ddot{u}_1^+ = \ddot{u}_2^+ = \ddot{u}^+$$

By Eq. (5) we have

$$\ddot{u}^+ = \frac{\ddot{u}_1^- + k \ddot{u}_2^-}{1 + k}, \qquad k = \frac{M_2}{M_1}, \tag{6}$$

Discretize each bar into 10 finite elements as shown in Fig.2 and find the numerical solution to the contact–impact problem of the two coaxial bars. Numerical results together with exact solution are shown in Fig.2. Comparing the result with that obtained by penalty method shown in Fig.1, it can be seen that the moment equilibrium method not only simplifies the problem and dispels the spurious oscillatory phenomenon, but also leads to the fact that the accuracy of the computational result is more than satisfied.

Ⅲ. Mechanical Modeling of Bird Body

In the bird impact analysis, another important factor which is closely relevant to the accuracy of the computed impact force as well as to the complexity of analysis is the mechanical modeling of the bird body. To avoid the trouble encountered in the computer implementation of the bird impact analysis, the incompressible hyper–elastic Mooney material is used in the present paper for simulating the mechanical property of the bird in impact, rather than the fluid jet column as has been proposed and widely adopted in overseas studies. Since the Mooney material will not cause a significant variation of the contact interface during impact while preserve the feature of incompressibility, there is no need for continuously updating and modifying the discretized mesh during analysis and thus much computational difficulty can be reduced.

The strain energy function W of an incompressible hyper–elastic body is relevant only to the principal invariants I_1 and I_2 [9]. The strain energy function of Mooney material being most widely used is

$$W = C_1(I_1 - 3) + C_2(I_2 - 3) \quad (7)$$

where

$$I_1 = \delta^{ir} G_{ri}$$
$$I_2 = \frac{1}{2}(\delta^{ir}\delta^{js} G_{ri} G_{sj} - \delta^{ir}\delta^{js} G_{ij} G_{rs})$$
$$G_{ij} = \delta_{ij} + u_{i,j} + u_{j,i} + u_{m,i} u_{m,j}$$

with C_1 and C_2 the material constants. For a natural and sulphurated rubber material, the strain energy function (7) is applicable to a wide range of deformation. By those features of Mooney material, the authors consider that it is well worth trying to use this kind of material in the simulation of the mechanical property of bird. The values of material constants C_1 and C_2, fixed by comparison of numerical test and physical experiment, determine the mechanical property of Mooney material defined in Eq.(7). Since the bird body consists of muscle and skeleton of different orientations, its bio–mechanical property is more complicated than that of an artificial material. Thus it is even more difficult to determine the values of C_1 and C_2 by experiment in the circumstance of impact. In this paper, values of C_1 and C_2 are determined iteratively by comparing the computational results with experimental ones.

Ⅳ. Application

The present study aims at the establishment of a computational model and corresponding analysis method possibly to be used in the practical design and analysis of a bird impact–resistant windshield transparency by use of a commercial general–purpose nonlinear finite element analysis programme now available. To verify its feasibility, the computational model and analysis method proposed in this paper are applied to the analysis of the windshield transparency of a jet trainer aircraft, by use of the code ADINA implemented in computer IBM 4341. The discretized mesh of the transparency shell shown in Fig.3, for reasons of comparison, is the same as given in [10]. The finite element model consists of 16–node brick elements, 8–node shell elements and transition elements. The bird weighs 1.1816 kg with an initial horizontal velocity of $v = 111.1$ m / s. The windshield is made of #3 PMMA, a kind of polymethyl methacrylate made in China. The geometrical nonlinearity of both the bird and shell, hyper–elasticity of the bird model, and the coupling effect between the impact force and structural response are all considered in the analysis. The time step for direct integration is chosen as 0.03 ms; thus the total CPU time needed for computation is about 7200 s. In Fig.4, the deformation curve of the symmetric cross section of the windshield at $t = 2.55$ms after impact is shown, in which the peak normal displacement is 32.89 mm. Since the test data which can be used to adjust the values of C_1 and C_2 are verylimited, values of C_1 and C_2 can not be modified in this paper.However, as a preliminary error estimation, the C_1 and C_2 valuesare a little (about 10–15%) lower than that they should be. In Fig.5, comparison of the impact load obtained from the present paper and [3] is shown. If the values of C_1 and C_2 can be updated in the light of abundant experimental data, the accuracy of the computational results would be further improved.

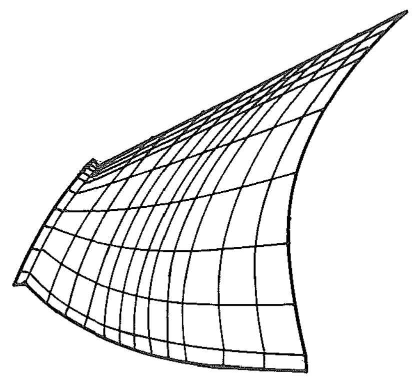

Fig.3 Discretized mesh of windshield in [10]

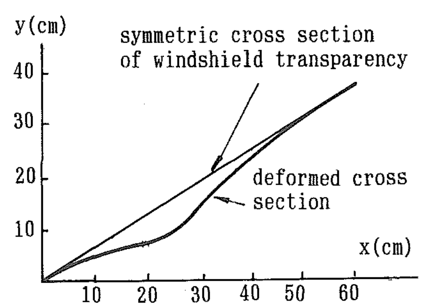

Fig.4 Maximum displacement of windshield at symmetric cross section

Ⅴ. Derivative Dynamic Load Solution

In the coupling solution, the temporal variation of impact force and structural response can be obtained simultaneously, based on the compatibility conditions of impact force, displacement, velocity and acceleration at the contact–impact interfaces of the impact parents. In this section, the impact force $f(t)$ obtained from such a coupling solution is termed as the Derivative Dynamic Load (DDL). Again, if the known DDL is shifted to the right–hand side of the dynamic equilibrium equation of the structure alone to simulate the effect of bird impact, then the dynamic response of the hit

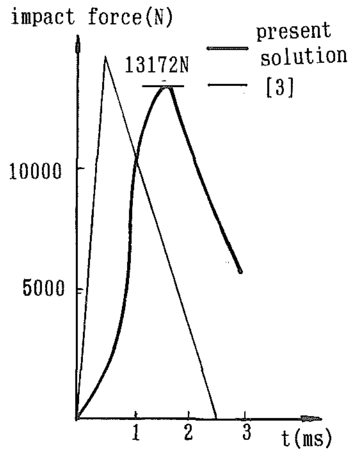

Fig.5 comparison of impact load

structure can be yielded. This structure response is called derivative dynamic load response solution (DDLRS) here in this paper. Practically, the DDLRS is an uncoupled one of the Lagrangian solutions, relaxing the compatibility conditions of displacement, velocity

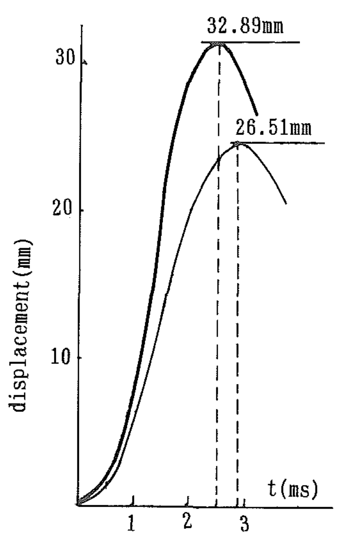

Fig.6 comparison of displacements from coupling solution and DDLRS

and acceleration at the interface. The DDLRS simplifies the problem at hand while the error would be introduced in. In Fig.6, the displacements for both the coupling solution and DDLRS are shown. It can be seen from the figure that the peak value of displacement of DDLRS (dashed line) is 80% only of the coupling one. Obviously, to improve the result of DDLRS, the derivative dynamic load should be increased artificially. Meanwhile, however, the local value of normal stress at the contact–impact location would be inappropriately increased as well. To keep the merit of simplicity of the DDLRS and dispel its demerit of over–error, an alternate procedure is the use of modification factors respectively for displacement and each stress component.

In the deconpling engeering solution to bird impact problem, the impact load can be given, for simplicity, by the analysis of bird impact on a rigid target.In the case where the bird is modelled with incompressible irrotational fluidjet column, the impact load expressed in a form of empirical equationin [3]is a function of the bird weight and impact velocity. Now that the bird is modelledwith Mooney–Rivlin material in the present paper, the rigid impact impact load function given in [3] should be modified and presented in a new form as follows:

$$F = F_{max} F^{*} \qquad (8)$$

$$F_{max} = 251.0 w v^{1.04} / L_{eff}$$

$$L_{eff} = L[1 + 0.5 tan(90^{\circ} - \beta)]$$

$$T = 1.3387 v^{0.1107}$$

where w(kg) is the weight of the bird, v(m / s) the impact velocity, L = 0.17(m)the length of bird model, $(90^{\circ} - \beta)$ the angle included between the axis of bird model and the normal of the rigid target (Fig.7). The distribution of F^{*} is presented in Table 1. The maximum relative error of the rigid impact load F obtainedfrom Eq.(8), as compared with the compliant impact load that obtained from nonlinearfinite element method, would not go beyond 0.36%, provided that the impact velocity is within the range from 33.3m / s to 88.9m / s (from 120km / hr to 320km / hr).

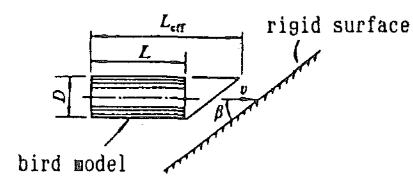

Fig.7 parameter definition

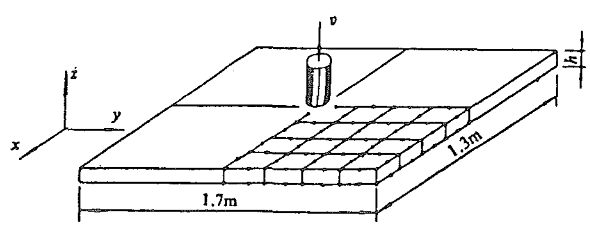

Fig.8 rectangular plate subjected to impact load

To understand the variation of the difference between coupling and decoupling solution with the change of impact velocity, target material and geometry respectively, in this paper, bird impact responses under normal impact velocity 88.9m / s, 62.86m / s and 37.57m / s on six rectangular plates of three different materials are calculated by use of coupling and decoupling solution procedures respectively (Fig.8). In coupling solution, nonlinear finite element method is used, while in decoupling solution, the governing equation $Mu + Cu + Ku = F(t)$is solved directly, where M, C, and K are the mass, damping and stiffness matrices of the individual plate, F(t) is the impact load function obtained from equation(8) 18 sets of impact response are obtained. In the solutions, the displacement and stress res[onse are most interested. Let the superscript c denote the response obtained from coupling solution and D the decoupling solution, and R the ratio of these two responses,namely,

$$R_u = \frac{u^c}{u^D}, R_{\sigma_x} = \frac{\sigma^c_{xx}}{\sigma^D_{xx}}, ect.$$

In Fig.9, modification factors for displacement and stress components are shown, Then, considerably approximate solutions to the conpling solutionof bird impact response can be obtained readily, provided that the deconpling solution to bird impact response and the material, geometry and impact velocity are known.

Ⅵ. Conclusions

By what is discussed above, some conclusive views may be summarized as follows.

1. In bird impact analysis, the momentum equation method is advantageous to an accurate and stable solution as well as its convenient implementation.
2. The use of Mooney material in the modeling of bird body can increase the computational efficiency, but the reasonable determination of material constants C_1 andC_2 is of key importance. Judged by the comparison between test data and computational results, it is better to increase slightly the values of C_1 and C_2 used in this paper.
3. Since the discrepancy existing between coupling and decoupled solutions can not be ignored, full attention should be paid during practical analysis.

Table 1. Impact force funtion

$\frac{t}{T}$	F^*	$\frac{t}{T}$	F^*	$\frac{t}{T}$	F^*	$\frac{t}{T}$	F^*
0.0	0.0	0.4	0.95186	0.55	0.99129	0.95	0.19776
0.05	0.17093	0.45	0.98649	0.6	0.95930	1.0	0.0
0.1	0.33131	0.475	0.99677	0.7	0.83327	—	—
0.2	0.59765	0.5	1.0	0.8	0.62857	—	—
0.3	0.81937	0.5253	0.99873	0.9	0.35675	—	—

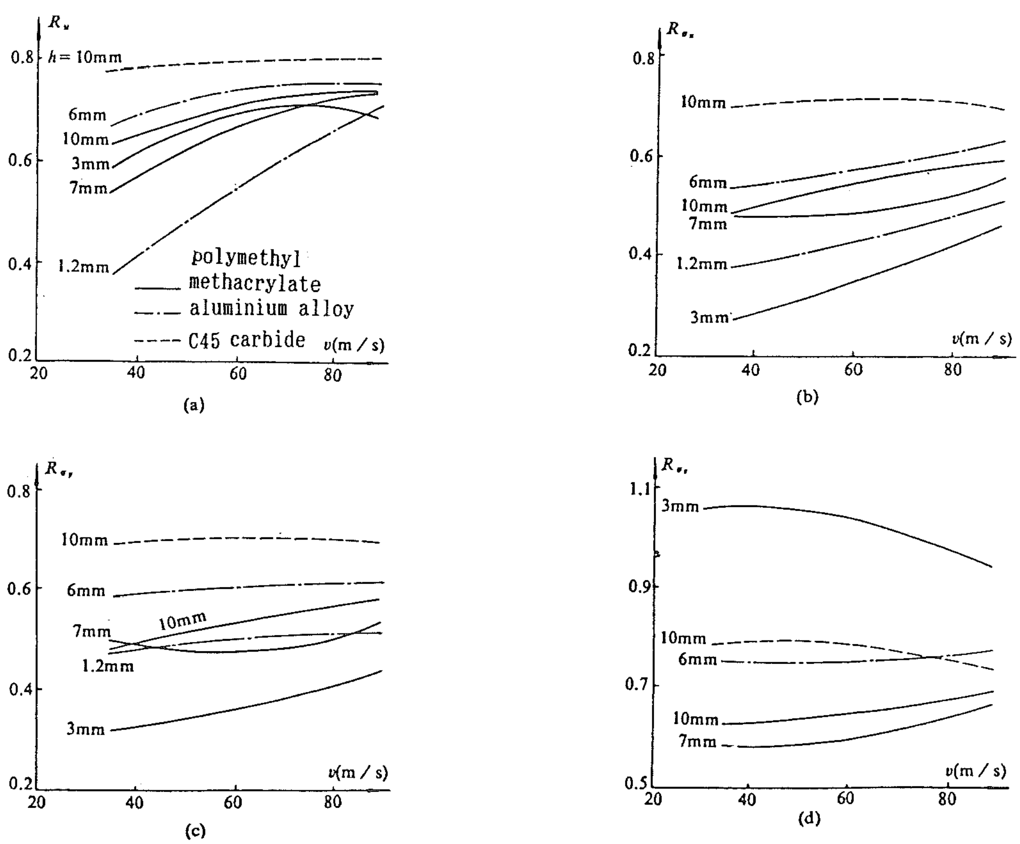

Fig.9

References

1 McCarty R, Hartz, Lt J L. Validation of the MAGNA Computer Program for Nonlinear Finite Element Analysis of Aircraft Transparency Bird Impact. AFWAL–TR–83–4154,1983

2 Brockman R A. MAGNA: A Finite Element System for three–Dimensional Nonlinear Static and Dynamic Structural Analysis. Computers and Structures, 13: 415–423, 1981

3 Barber J P, Taylor H P, Wilbeck J S. Bird Impact Forces and Pressure on Rigid and Compliant Targets. AD A061313, 1977

4 McCarty R E. Finite Element Analysis of F–16 Aircraft Canopy Dynamic Response to Impact Loading. AIAA 80–0804, 1980

5 Experimental Reports on Compressive Stress–Strain Relations of #3 Aero–Polymethyl Methacrylate Material under Low and Medium Strain Rate. Technical Report AFFD–(8640–24–2)–89005, Ninbo University, China 1989 (in Chinese)

6 Zhong Z H. On Contact–Impact Problems. Linköping Studies in Science and Technology. Dissertatioms No.178, Linköping University, Sweden, 1988

7 Wang L L, Zhu Z X. Theory of Stress Wave. National Defence Industry Publishers, 1985 (in Chinese)

8 Huges Thomas J R. A Finite Element Method for a Class of Contact–Impact Problems. Computer Methods in Applied Mechanics and Engineering, pp249–276, 1976

9 Oden J T. Finite Element of Nonlinear Continuance. McGraw–Hill Book Company, pp221–241, 1972

10 Zhang Z L. Dynamic Response Analysis of Aircraft Frontal Windshield Subjected to Bird Impact. Technical Report AFFD–(8640–24–3)–9004, 1990 (in Chinese)

11 He J Y, Zhu J S. Application of Large Scale Finite Element Analysis Program for Linear and Nonlinear Systems APOLANS to Bird Impact Dynamic Response Analysis of Trainer Aircraft Windshield Transparency. Technical Report AFFD–(8640–24–9)–9005 (in Chinese)