Structures Bulletin

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Number: EN-SB-12-002

Date: 27 June 2012

Subject: Methodology to Establish Bird Strike Design Criteria

References:

1. JSSG-2006, "Joint Service Specification Guide – Aircraft Structures," Department of Defense, 30 October 1998.
2. Lawrence, James H., Coker, Murl J., "Windshield Bird Strike Structural Design Criteria", McDonnell Douglas Corporation, AFFDL-TR-73-103, October 1973.
3. Halpin, John C., Griffin, John M., Jackson, K. Terry, "An Analytical Methodology to Predict Potential Aircraft Losses Due to Canopy Birdstrikes", Aeronautical Systems Division, April 1980.
4. Berens, A. P., West, B. S., Bowman, D. R., "A Probabilistic Model for Evaluating Birdstrike Threat to Aircraft Crew Enclosures", University of Dayton Research Institute, UDR-TR-89-92, November 1989.
5. Gonzalez, Jorge F., "ATF Birdstrike Requirements Analytical Methodology" Aeronautical Systems Division, December 1989.
6. MIL-STD-1530C, "Aircraft Structural Integrity Program (ASIP)" Department of Defense, 1 November 2005.

Background:

A review of the bird strike design criteria contained in Joint Service Specification Guide (JSSG) 2006 "Aircraft Structures" (Ref. 1) indicated an update was necessary to clarify the process for establishing the bird strike design criteria. The existing bird strike criteria in JSSG-2006 contain both deterministic and probabilistic methodologies but does not provide either guidance on implementation or recommend a preferred methodology. This structures bulletin provides the missing guidance and supersedes the criteria in JSSG-2006 until the document is updated to incorporate the content of this bulletin.

Introduction:

Section 3.2.24 and A.3.2.24 of JSSG-2006 provides guidance for foreign object debris (FOD) damage for military aircraft, and 3.2.24 and A.3.2.24.1 addresses bird FOD specifically. The bird strike portion of the first paragraph of the requirement guidance for sections 3.2.24-3.2.24.4 of JSSG-2006 is given below.

REQUIREMENT GUIDANCE (A.3.2.24 through 3.2.24.4)
Provide appropriate foreign object damage requirements and structural degradation limits. For birds and hail impacts, the requirements may be stated in terms of the expected number of impacts of selected sizes of birds and hail being equal to the volume of air swept-out by the projected frontal area of the component for discrete mission segments of all air vehicles times the expected average number of selected birds or hail per volume of air, summed over all discrete mission segments. For air vehicles involving low risk to personnel and small impact on the overall program even if structural damage does occur due to bird or hail impact, a lesser requirement may suffice. Such lesser requirements could be stated in terms of arbitrary sized bird and hail impacting at some arbitrary velocity. Structural degradation limits should be stated in terms of man-hours required to repair or replace damaged components and that no impact will cause injury to personnel, with or without attendant structural damage. For bird impact information, see lessons learned.

This paragraph hints at using a probabilistic approach to determining the bird strike requirements, but it falls short of providing guidance for implementation. JSSG-2006 does provide top level guidance for probabilistic analysis in section A.3.1.2. The guidance is repeated below.

REQUIREMENT GUIDANCE (A.3.1.2)
In some instances, historically based deterministic criteria are not applicable to the specific combination of design approaches, materials, fabrication methods, usage, and maintenance for the structural element being designed. In these instances, it may not be possible to rationally arrive at an alternative deterministic criteria and a combined load-strength probability analysis is conducted to establish that the risks of detrimental structural deformation and structural failure are acceptable. The selection of the maximum acceptable frequency of occurrence of detrimental structural deformation, loss of structural functioning or structural failure can be made by examining relevant historical repair and failure rates. A maximum acceptable frequency of permanent structural deformations would be 1 x 10-5 occurrences per flight. A maximum acceptable frequency of the loss of adequate structural rigidity or proper structural functioning, or structural failure leading to the loss of the air vehicle would be 1 x 10-7 occurrences per flight.

In most cases, a combined load-strength probability analyses is only selectively used in the analysis of the structural elements for which historically based deterministic criteria are not appropriate. In these cases, a probability analysis of a highly loaded representative structural element is performed. This analysis would address all of the *significant variations in load, material properties, dimensions, etc. Once the design of the element has been completed by these probabilistic means, it is usually possible to develop a set of modified deterministic criteria which, when combined with the appropriate limit and ultimate loads, would yield the same final element design. This updated criteria can then be used to design similar structural elements. In addition to establishing new design criteria, the conduct of the probability analysis also aids in gaining an increased understanding of the more important design drivers and enables an improved design to be produced.*

The challenge is to establish the appropriate bird weight and aircraft velocity at impact to develop a design that provides an adequate level of bird strike resistance for both safety and durability considerations. Section A.3.1.2 describes using a load-strength probabilistic analysis, but this is difficult to apply to the bird strike condition. JSSG-2006 provides limited guidance for establishing these requirements. The purpose of this structures bulletin is to publish a method that is considered acceptable for use in the design of aircraft structure that is consistent with the probability of failure and permanent deformation per flight requirements stated in JSSG-2006. The approach presented in this bulletin is applicable to both developmental programs and modifications of existing aircraft.

Discussion:

The criteria discussed in this document are intended to be applied to the aircraft structure only. Canopy bird strike criteria are documented in JSSG-2010, and bird strike criteria for engines are located in JSSG-2007. The probabilistic methodology was chosen after a review of four studies with different approaches. The documents reviewed were AFFDL-TR-73-103 “Windshield Bird Strike Structural Design Criteria” (Ref. 2), a report entitled “An Analytical Methodology to Predict Potential Aircraft Losses Due to Canopy Birdstrikes” (Ref. 3), UDR-TR-89-92 “A Probabilistic Model for Evaluating Birdstrike Threat to Aircraft Crew Enclosures” (Ref. 4), and a report entitled “ATF Birdstrike Requirements Analytical Methodology” (Ref. 5). It was determined that the methodology presented in Reference 5 had the best balance of accuracy and ease of implementation, and was therefore chosen as the desired method to establish the bird strike design criteria. It will serve as the basis for this structures bulletin.

When considering the bird strike analysis methods, two possible probabilistic approaches were presented. The first is a load-strength method using kinetic energy and the second is a threat-exposure method. The load-strength method is the most analogous to the guidance of JSSG-2006 Section 3.1.2, while the threat-exposure method was introduced in Reference 5.

There are two primary reasons why a load-strength method was not selected as the basis for establishing the bird strike design criteria. (1) The appropriate distribution of applied kinetic energy due to bird strike considering bird weight and aircraft velocity distributions cannot be easily determined and, (2) developing the aircraft strength distribution for all impact locations is deemed to be cost-prohibitive. These reasons are further explained below.

The Air Force Safety Center's Bird/Wildlife Aircraft Strike Hazard (BASH) organization tracks and documents all reported bird strikes for the Air Force. In an attempt to develop a reliable kinetic energy distribution, all strikes from 1995-2011 were reviewed. The database contains 74,574 strikes of which only 15,350 have both a recorded bird species (from which the bird weight can be estimated) and the aircraft velocity at impact. Therefore, a reliable applied kinetic energy distribution from previous impacts cannot be established since 80% of the bird strikes have at least one key piece of data missing.

Determining the strength distribution was deemed to be cost-prohibitive due to the expense of analytically determining the strength distribution accounting for the primary variables (material property, dimensions, etc.). Furthermore a test program would be required to validate the analysis.

The threat-exposure method is based on data that is readily available when BASH data is applicable. The threat is calculated using a bird strike rate from historical data and a bird weight distribution characterized from available data. The exposure is based on the velocity distribution of the aircraft and the exposed frontal area of the aircraft. In its simplest application, the threat-exposure method assumes a constant impact energy capability across the entire frontal area. In some situations this can be conservative. It is possible to calculate exposure by accounting for angle of incidence; however this is not addressed in this bulletin.

Bird Strike Database

ASC/ENFS reviewed two overlapping bird strike databases to obtain data for use in the following analysis. Both databases were obtained from the Air Force BASH team. The first database was described above. The second database used in the review includes bird strike incidents between January 4, 1985 and May 10, 2006 that contained 17,977 bird strikes for fighter/attack, cargo/transport, and trainer aircraft classes that contained a reported bird species. This database was used to estimate the bird weight distribution for all aircraft bird strikes because the average weight for each bird species had been populated for each incident through a labor-intensive manual process. The result of this evaluation is shown in Figure 1. It is recognized that this may not represent the actual bird weight distribution for all bird strikes since most BASH records did not include a bird species from which the bird weight could be estimated. It should also be noted that 97% of all strikes involve birds weighing less than 4 pounds.

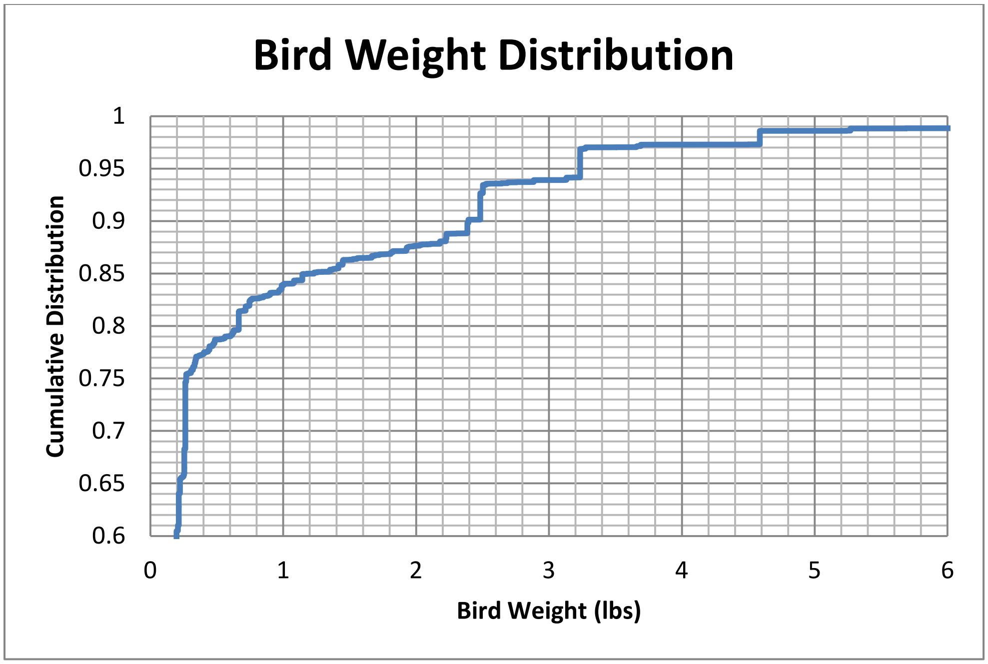

Figure 1 - Bird Weight Distribution

Another important consideration in the analysis is the probability of bird strike by altitude. The latest BASH database which contains strikes from 1995-2011 was used for this data. Of the 74,574 recorded bird strikes, 38,540 had a recorded altitude. The cumulative altitude distribution is plotted in Figure 2 and is given as Above Ground Level (AGL).

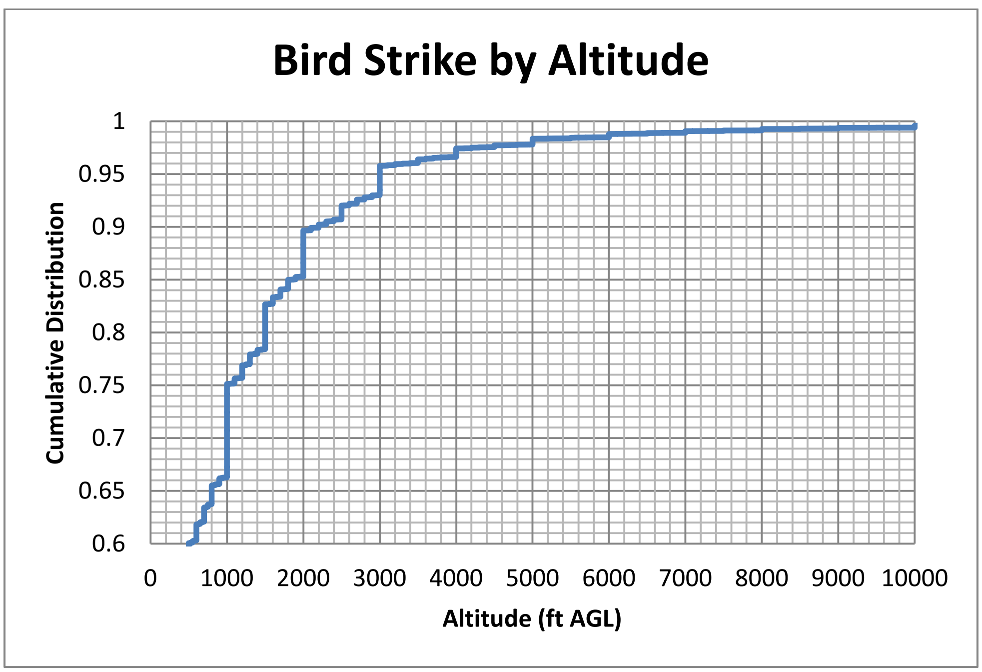

Figure 2 - Bird Strike Altitude Distribution

The 1995-2011 BASH database also contains aircraft velocity for 33,942 recorded bird strikes. Although not specifically used in the analysis described below, the results may be of interest. Figure 3 shows the speed distribution in knots indicated airspeed (KIAS) for fighter aircraft and Figure 4 shows the distribution for cargo/tanker aircraft.

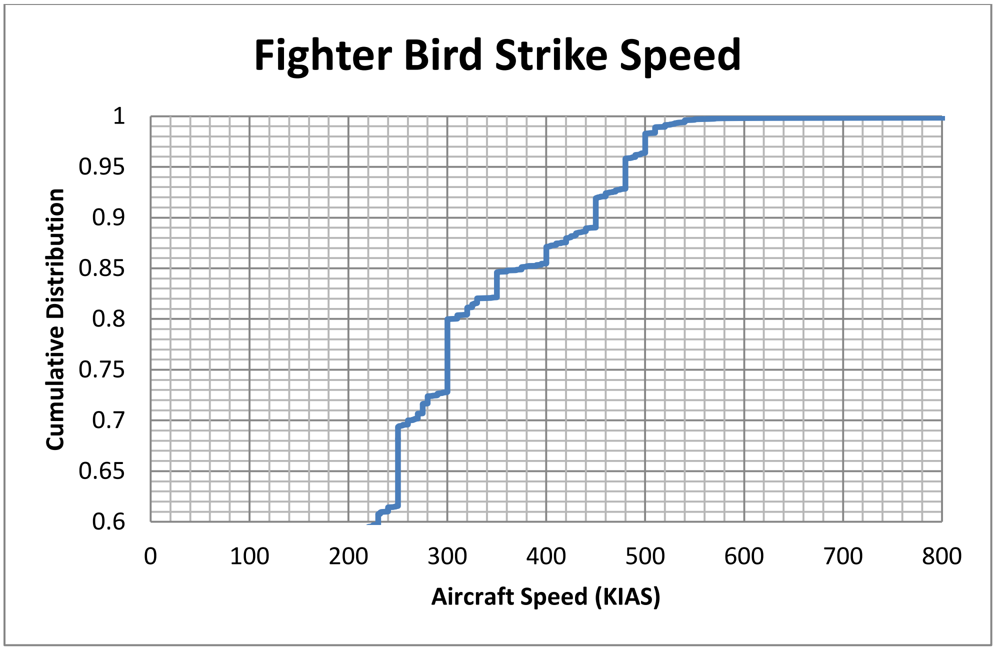

Figure 3 - Bird Strike Speed for Fighters

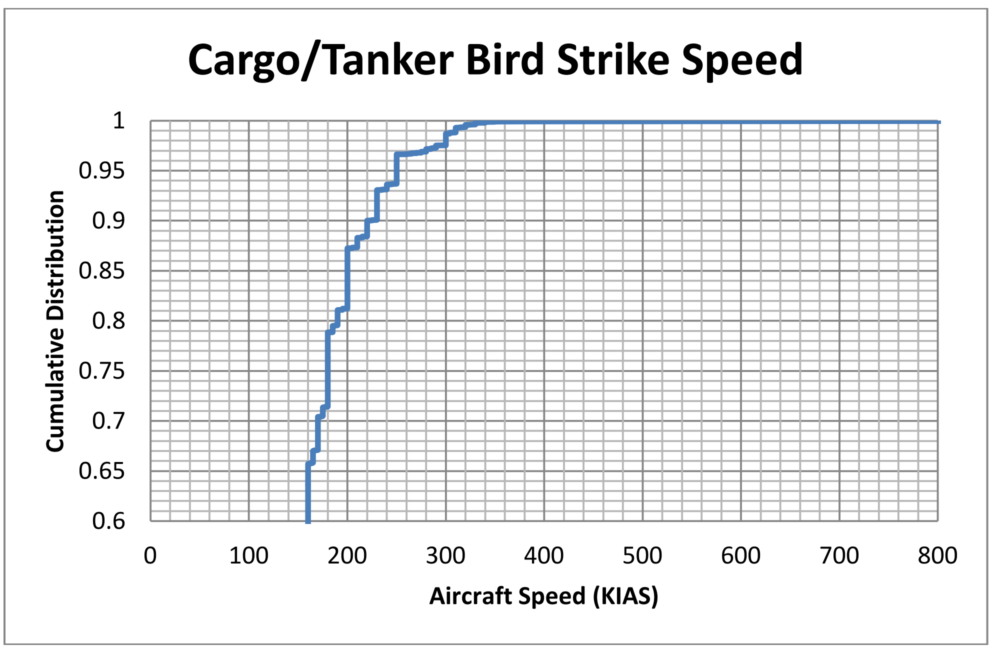

Figure 4 - Bird Strike Speed for Cargo/Tanker Aircraft

Using the data in the BASH database from 1995-2011 and the flight hour data over the same time period from the Air Force Safety Center, a bird strike rate was calculated.

Table 1 contains the flight hours, bird strike totals, number of Class A mishaps, and bird strike rate for most USAF aircraft. Inherent in this data is the variation in aircraft frontal area, volume of air traveled through, bird population density, and other factors that influence the bird strike rate.

Table 1 - Bird Strike Rate for Several USAF Aircraft

Aircraft	Flight Hours (1995-2011)	Bird Strikes	Class A Mishaps	Strikes/hr
E-4	25,953	401	2	1.55E-02
B-2	92,037	1,091	0	1.19E-02
B-52	383,764	1,895	0	4.94E-03
E-8	136,818	603	0	4.41E-03
C-130	4,800,202	17,826	0	3.71E-03
C-17	2,068,231	6,830	1	3.30E-03
KC-135	3,841,787	11,954	2	3.11E-03
B-1	406,130	865	0	2.13E-03
C-5	1,038,483	1,974	3	1.90E-03
F-22	109,808	184	1	1.68E-03
E-3	352,461	572	1	1.62E-03
T-1	1,485,330	2,378	0	1.60E-03
A-10	1,922,134	2,839	1	1.48E-03
T-38	2,197,879	2,840	2	1.29E-03
T-6	1,132,592	971	0	8.57E-04
F-15	2,928,487	2,414	6	8.24E-04
F-16	5,557,433	4,502	7	8.10E-04
RQ-4	52,783	2	0	3.79E-05
MQ-1	1,145,064	30	0	2.62E-05

Methodology to Establish Bird Strike Design Criteria

The probabilistic methodology recommended in this bulletin is derived from the process outlined by Gonzalez in Reference 5. The report documents the analysis performed to determine the bird strike requirements for the F-22 Raptor. The threat accounts for the aircraft bird strike rate and the percentage of birds below a given weight (in this case, four pounds). The method documented in the report uses a threat-exposure method. The exposure accounts for the aircraft velocity distribution and the aircraft frontal area. The method presented in the following paragraphs closely matches the report with a few deviations that are described below. The important equations and other information necessary to perform the analysis are given below. ASC/ENFS has developed an Excel spreadsheet that processes the calculations given the appropriate inputs, and is available upon request.

The method described below should be performed for two scenarios. One is the probability of loss of aircraft and the other is the probability of detrimental deformation. According to JSSG-2006 (Ref. 1) the aircraft loss rate should be no greater than 1×10^{-7} per flight, and the rate of permanent detrimental deformation should be no greater than 1×10^{-5} per flight.

This methodology also requires a definition of a vulnerable area to a bird strike. When considering the loss of aircraft scenario, the vulnerable area is the sum of the projected frontal areas of the aircraft components or systems where a bird strike would result in catastrophic consequences. If this summation results in overly stringent criteria for some components, sub-dividing the aircraft components may be appropriate. However, the subdivisions should be limited to 2 or 3 since the overall risk will be greater than 1×10^{-7} unless different allocations are established. When considering the permanent detrimental deformation scenario, the vulnerable area should be selected based on economic considerations (i.e. cost of repairs/replacements).

In the case where a modification changes the frontal area of the aircraft, a new assessment must be performed. When using the 1×10^{-7} criterion, the new frontal area should be added to the total or to the appropriate zone if subdivided to determine the criteria for the modification. If the structure was subdivided, the original criteria apply to the zones unaffected by the modification. When using the 1×10^{-5} criterion, the new frontal area should be added to the economic frontal area of the aircraft. Again, the analysis should be performed with the new data, and the resulting criteria should only be applied to the modified section.

One of the distributions needed for the analysis is the bird weight distribution, from which a bird weight is selected. The probability of exceeding this value is accounted for as a simple factor in the analysis. A bird weight of 4 pounds should be used because it is consistent with historical bird strike analysis and testing completed on both military and commercial aircraft. Furthermore, the current bird strike testing equipment is calibrated and designed to accommodate a 4 pound bird. As shown in Figure 1, 3% of the bird strikes are expected to exceed 4 pounds, and this is accounted for in the analysis (Reference 5 cited 6.5% using a more limited database.)

The maximum altitude for potential bird strikes must be selected to determine the velocity distribution for use in the analysis. ASC/ENFS recommends that an altitude AGL that encompasses 99% of all reported bird strikes be the basis for this selection. Using Figure 2, an altitude cut-off of 7,000 feet AGL appears to be reasonable. (Reference 5 used 2,000 feet.) It should be noted that the probability of bird strike above this altitude (and corresponding velocity distribution) is not accounted for in the analysis. Therefore, selection of a higher percentile (>99%) may be appropriate in some cases.

The velocity distribution used in the analysis can be determined once the maximum altitude for bird strike is selected. The velocity distribution should either be based on historical usage data, which may be obtained from Loads/Environment Spectra Survey (L/ESS) reports, or the design mission profiles up to the altitude limit.

This velocity distribution then needs to be converted to a cumulative distribution function (CDF) of the volume swept out by the vulnerable frontal area of the aircraft. This conversion takes into account the fact that an aircraft flying for 10 seconds in the bird zone at 300 knots has half of the bird exposure of an aircraft flying for 10 seconds at 600 knots. The higher speed increases the volume swept out, thereby increasing the exposure to the bird environment and a potential bird strike.

To calculate the exposure, a curve fit to the tabulated volume distribution is created to provide a continuous curve. This is used to calculate the exposure in an iterative manner over the design speed. The design speed is defined as the speed at which the component can withstand an impact of a four pound bird. The exposure is calculated using equation 1 below.

$$Exposure = (value\ of\ CDF\ of\ volume\ at\ design\ speed) * (vulnerable\ area) \quad \text{Eq. 1}$$

Table 2 below provides example calculations and steps through the process of determining the CDF of the volume swept out for a representative fighter aircraft.

Table 2 - Sample CDF Calculations

	A	B	C	D	E	F	G	H
	Mach Range	Average Mach in Range	Average Airspeed (knots)	Hours Spent at Mach Range or Speed	CDF Hours	% Time Spent in Range	Volume/Hour at Average Speed	CDF of Total Volume Swept Out
1	0	0.00	0.00	0.00	1.000	0.00%	0.00	1.000
2	0.0<M<=0.1	0.05	33.05	4.98	0.999	0.12%	0.40	1.000
3	0.1<M<=0.2	0.15	99.15	33.63	0.991	0.82%	8.13	0.997
4	0.2<M<=0.3	0.25	165.25	469.77	0.876	11.45%	189.23	0.942
5	0.3<M<=0.4	0.35	231.35	691.09	0.708	16.85%	389.74	0.827
6	0.4<M<=0.5	0.45	297.45	784.26	0.516	19.12%	568.65	0.660
7	0.5<M<=0.6	0.55	363.55	642.87	0.360	15.67%	569.71	0.492
8	0.6<M<=0.7	0.65	429.65	788.09	0.168	19.21%	825.40	0.249
9	0.7<M<=0.8	0.75	495.75	597.40	0.022	14.56%	721.94	0.037
10	0.8<M<=0.9	0.85	561.85	84.40	0.001	2.06%	115.59	0.003
11	0.9<M<=1.0	0.95	627.95	5.80	0.000	0.14%	8.87	0.000
12	>1.0	1.10	727.10	0.03	0.000	0.00%	0.06	0.000
13	total			4102.33			3397.72	

The first column in Table 2 contains the Mach number ranges used for the analysis. The midpoint of each range is then shown in column B and the corresponding airspeed in knots is calculated in column C. The airspeed is conservatively calculated using the speed of sound at sea level. In this example, the time spent in each mach range is input into column D. This data is defined in the design usage or is contained in an L/ESS report for evaluation of existing aircraft. If the data is given in speed ranges instead of Mach number ranges, the necessary changes to the columns A-C should be made. The calculation shown in column E is the cumulative distribution function of the percentage of time spent flying below 7,000 feet at or above the average speed of the Mach number range (value in column C).

The value in column F is the change in the time CDF of column E from one range to the next. Equation 2 below is an example. This gives the percentage of total time spent flying in the current Mach number range.

$$F4 = E3 - E4 \qquad \text{Eq. 2}$$

Column G is the volume swept out by the aircraft per hour at the average speed for the Mach number range. This is calculated by multiplying the value in column F by the corresponding value in column C along with the vulnerable area of the aircraft (10 ft^2 in this example).

$$G4 = F4 * C4 * Vulnerable\ Area \qquad \text{Eq. 3}$$

Next the volumes are summed up, which is shown in cell G13. By finding the percentage of volumes swept out in each Mach range a CDF for the % of the total volume swept out per hour can be calculated in column H.

The CDF of volume is the distribution used for calculation of the aircraft exposure. It is calculated the same way as the CDF for time is in column E. This data needs an accurate curve fit to perform a valid calculation for a range of aircraft speeds. Any curve fitting method can be chosen, but it must be accurate at the extreme ends of the CDF function. ASC/ENFS chose to use a combination of linear and quadratic curves as necessary to obtain a reasonably accurate fit over the entire range for this example. Figure 5 below shows the example curve fit.

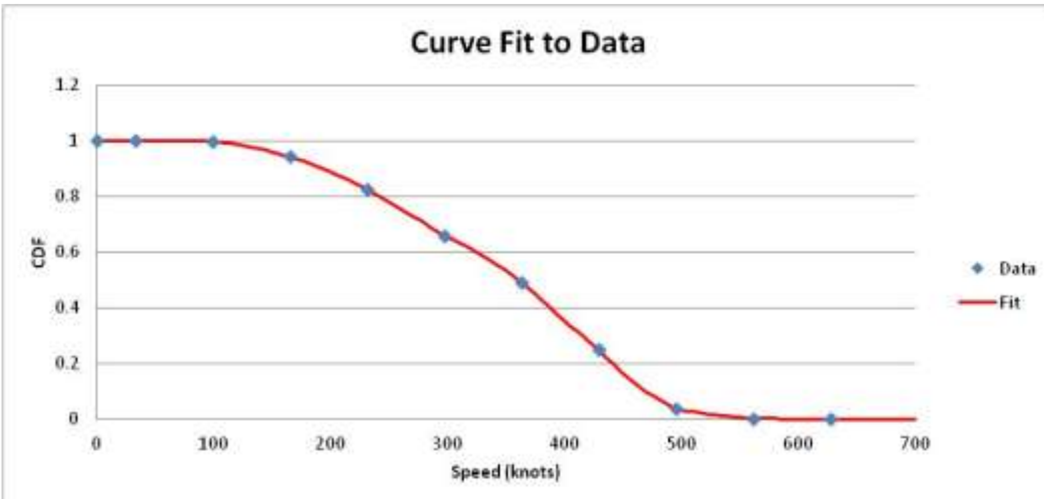

Figure 5 - Example Curve Fit

The next piece of data required to perform the analysis is a comparable aircraft bird strike rate. The bird strike rate should be in units of strikes/area/flight. If the analysis is being performed for an existing aircraft, the historical data for that aircraft should be used. If the analysis is being performed for a new design, the aircraft that it is replacing should be considered if the mission profiles, basing scenarios, etc. are similar. However, the bird strike rate may need to be adjusted for the difference in time spent below 7,000 ft if appropriate. For example, if the aircraft spends 10% of its time below 7,000 ft and the replacement aircraft is estimated to spend 15% of its time below 7,000 ft, then the bird strike rate should be multiplied by a factor of 1.5 for used in the replacement aircraft bird strike analysis. If a comparable aircraft does not exist from which a historic bird strike rate can be used, the basis for selecting a bird strike rate should be determined.

The threat is calculated using the percentage of birds above 4 pounds and the bird strike rate and has the units of strikes/area/flight. The bird strike rates given in Table 1 can be used, but the value must be converted from hours to flights using the average flight duration for the aircraft. The value must also be divided by the frontal area. The threat is calculated using equation 4.

$$Threat = (bird\ strike\ rate) * (1 - \%\ birds\ below\ 4\ pounds) \qquad \text{Eq. 4}$$

The probability of aircraft loss (or detrimental deformation) is the exposure (Eq. 1) multiplied by the threat (Eq. 4) shown in equation 5, assuming no capability beyond the design bird weight and aircraft velocity. The design speed and corresponding distance distribution value are iterated until the probability is below the requirement of 1×10^{-7} per flight for aircraft loss and 1×10^{-5} per flight for detrimental deformation.

$$Probability\ of\ Aircraft\ Loss\ (deformation) = Exposure \times Threat \qquad \text{Eq. 5}$$

Example Calculation

An example calculation for a representative fighter is provided below. The speed and corresponding CDF value of volume swept out above that speed was taken from Table 2. The initial proposed design speed is 475 knots and the vulnerable area is assumed to be 10 ft^2. The bird strike rate was selected as 1.4 x 10^{-5} strikes/ft^2/flight (representative of most fighters).

$$Exposure = 0.084 * 10ft^2 = 0.84ft^2$$

$$Threat = 1.4 * 10^{-5}\frac{strikes}{ft^2 * flight} * (1 - .97) = 4.2 * 10^{-7}\frac{strikes}{ft^2 * flight}$$

$$Probability\ of\ Aircraft\ Loss = 0.84ft^2 * 4.2 * 10^{-7}\frac{strikes}{ft^2 * flight} = 3.53 * 10^{-7}\frac{strikes}{flight}$$

The probability of aircraft loss assumes that there is no capability beyond the design bird weight and aircraft velocity. Since the requirement is not achieved, more iterations were performed until the predicted aircraft loss rate was < 1×10^{-7} losses per flight. Table 3 shows the iterated speed, threat, exposure and risk calculations for the data used in this example. For this example calculation, the appropriate bird strike design criteria are a 4 pound bird at 515 knots.

The example calculation was repeated using 1 x 10^{-5} per flight for detrimental deformation criteria, assuming the economic frontal area is 30 ft^2. The resulting bird strike design criteria are a 4 pound bird at 245 knots. Example iterations for this calculation are shown in Table 4.

Table 3 - Example Iteration Calculations (1×10^{-7})

Speed (KTAS)	Threat	Exposure	Risk
475	4.2E-07	0.841	3.53E-07
480	4.2E-07	0.711	2.99E-07
485	4.2E-07	0.591	2.48E-07
490	4.2E-07	0.480	2.02E-07
495	4.2E-07	0.381	1.6E-07
500	4.2E-07	0.335	1.41E-07
505	4.2E-07	0.300	1.26E-07
510	4.2E-07	0.267	1.12E-07
515	4.2E-07	0.235	9.87E-08
520	4.2E-07	0.205	8.62E-08

Table 4 - Example Iteration Calculations ($1x10^{-5}$)

Speed (KTAS)	Threat	Exposure	Risk
220	4.2E-07	25.516	1.07E-05
225	4.2E-07	25.212	1.06E-05
230	4.2E-07	24.899	1.05E-05
235	4.2E-07	24.536	1.03E-05
240	4.2E-07	24.156	1.02E-05
245	4.2E-07	23.777	9.99E-06
250	4.2E-07	23.397	9.83E-06

To calculate the number of expected losses per fleet of aircraft over its service life, the exposure equation (Eq. 2) must include the number of aircraft in the fleet and the expected service life of each aircraft in flight hours. This can then be multiplied by the threat to give the total number of expected losses. Continuing with the example calculation and assuming a fleet of 500 aircraft with a service life of 8,000 hours and average flight duration of 1.5 hours results in the following calculations.

$$Exposure = 0.084 * 10ft^2 * 500\ a/c * 8000\ hr = 3{,}360{,}000\ hr * ft^2$$

$$Threat = 1.4 * 10^{-5} \frac{strikes}{ft^2 * flight} * (1 - .97)/1.5 = 2.8 * 10^{-7} \frac{strikes}{ft^2 * hr}$$

$$Number\ of\ Expected\ Losses = 3.36 * 10^6 hr * ft^2 * 2.8 * 10^{-7} \frac{strikes}{ft^2 * hr} = 1\ loss\ per\ fleet$$

Summary:

This bulletin provides a method for establishing the bird strike design criteria for both developmental programs and modifications to existing aircraft. Consideration was given to both a load-strength and a threat-exposure probabilistic analysis methodology. Due to the difficulty of developing accurate load-strength distributions, the threat-exposure approach was chosen. A survey of the bird strike database maintained by BASH was completed to find distributions for bird weight, altitude, and aircraft speed during a bird strike event. Using the information from this survey and the analysis method first presented by Gonzalez in Reference 5, an acceptable bird strike probabilistic methodology was presented. If a more rigorous, less conservative methodology is used to define the requirements, the methodology should be reviewed by the program office and ASC/ENFS. The content of this bulletin supersedes the criteria contained the JSSG Section 3.2.24.1 and A.3.2.24.1.

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