Determination of Shed Ice Particle Size Using High Speed Digital Imaging

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Abstract

A full scale model of an aircraft engine inlet was tested at NASA Lewis Research Center’s Icing Research Tunnel. Simulated natural ice sheds from the engine inlet lip were studied using high speed digital image acquisition and image analysis. Strategic camera placement integrated at the model design phase allowed the study of ice accretion on the inlet lip and the resulting shed ice particles at the aerodynamic interface plane at the rear of the inlet prior to engine ingestion. The resulting digital images were analyzed using commercial and proprietary software to determine the size of the ice particles that could potentially be ingested by the engine during a natural shedding event. A methodology was developed to calibrate the imaging system and insure consistent and accurate measurements of the ice particles for a wide range of icing conditions.

Keywords: aircraft, icing, imaging, digital, calibrate, ice, high speed, particles, accretion

1. Introduction

In flight icing has been a hazard to aviation since its earliest days. Ingested ice has the potential to damage the engine requiring maintenance or overhaul and in severe cases, it can cause loss of power or engine flame out. Engine inlets typically have anti-ice systems on the leading edges and portions of the inlet to protect against ice buildup. Civilian aircraft are all required to comply to specific ice protection standards for the wing and inlet surfaces, including ice ingested foreign object damage (FOD) criteria for engine survivability. Military aircraft have ice protection and ice ingestion requirements based on the mission of the vehicle. In cases where there is a concern about the level of ice protection on and inside the inlet a determination needs to be made to assess the potential for ice ingested damage to the engine. One way to define the potential for damage is to quantify the size of the shed ice particles that shed off the inlet and duct surfaces in front of the engine.

The use of sharp leading edges and a long sinuous inlet duct have raised a question about the final particle size of naturally shed ice and the benefit of particle breakup as it impacts the sides of the inlet duct as it travels down the body of the inlet. The purpose of the test described within this paper was to simulate the accretion and natural shedding of ice on an engine inlet, and by using imaging techniques assess the risk posed by the ingested particles. This was determined by measuring the shed ice particle size at a plane in the inlet where the engine section would begin. This plane is designated as the aerodynamic interface plane (AIP).

The imaging of such phenomenon presents several challenging technical problems; determining the size, location, and distribution of large numbers of particles in a high velocity low temperature environment. The purpose of this paper is to describe in detail the steps taken toward solving this problem. This test was performed in March of 1995 in the NASA Lewis Research Center’s Icing Research Tunnel (IRT). The IRT is the worlds largest refrigerated wind tunnel and has been a pioneering facility in the study of icing as it relates to aviation (see Figure 1). The imaging support for this test was provided by the Imaging Technology Center’s Scientific Imaging Group.

![Figure 1.—Schematic of Icing Research Tunnel.](image-url)
2. Experimental

The engine inlet duct was instrumented along its length with a variety of imaging systems. This included conventional RS-170 black and white video cameras with customized pinhole optics, and Kodak Ektapro high speed video systems utilizing remote imager heads. In all, two RS-170 cameras and two Kodak Ektapro EM (electronic memory) systems were mounted directly to the inlet duct, with two additional Kodak Ektapro EM high speed video systems located outside the test section.

Attachment points for all imaging hardware and environmental enclosures, as well as window size and placement, were designated during the model design phase. Steel mounting plates were embedded into the fiberglass resin of the model during fabrication, providing solid attachment points for all imagers and environmental boxes. Electrically heated windows measure one foot square and 3/4 inches thick were installed at the AIP to provide clear views for the imagers even under the most severe icing conditions. A large area between these two Ektapro imagers was designated for illumination, which contained several individually reinforced halogen lamps which reflected off the inside of the enclosure in order to provide a diffused, flat illumination.

Due to the severe environmental conditions inside the test section all imaging hardware and lighting assemblies attached directly to the inlet model had to be ruggedized and protected. This was accomplished by designing and fabricating enclosures to seal out moisture and maintain internal operating temperatures by means of electric heaters. Additionally, the enclosures required aerodynamic profiles to reduce model vibration and drag.

All four Kodak Ektapro EM intensified imagers were used to capture views of ice particles as they shed off the front lip of the inlet and traveled inside the duct to the AIP section. Two imagers (EM3 and EM4) were placed at the front of the model to view the ice as it shed from the inlet lip (see Figure 3). EM4 viewed the upper lip of the leading edge while EM3 viewed the inboard side of the leading edge.

The other two Kodak Ektapro imagers (EM1 and EM2) were placed at AIP, just ahead of the location of the engine (see Figure 3). It is here that the magnitude of the ice particle size is critical. These two cameras were placed orthogonal to each other and mounted on the outside of the inlet.

As shown in Figure 4, the imager heads were mounted parallel to the inlet with first surface mirrors mounted 45 degrees relative to the target to reflect the area of interest into each imager. Both imager/mirror assemblies were then protected by environmental enclosures and instrumented with thermocouples to monitor and maintain operating temperatures.

Natural shedding events are unpredictable and difficult to capture. Therefore, a pneumatic de-icing boot with larger tubes than conventional pneumatic systems was attached to the inlet lip and used to release the accreted ice to simulate a natural shedding event. The Ektapro imaging systems were triggered to initiate the image by the signal to fire the pneumatic de-icing boot. This allowed the high speed imaging systems to capture the ice at the moment it was in the field of view.
2.1 Digital acquisition

The hardware for the acquisition consisted of four Pentium computers connected via GPIB interfaces to the four Kodak Ektapro EMs. Each electronic memory (EM) unit stored a total of 5000 images at a rate of 1000 frames per second. After a shedding event was recorded the images were transferred from the EM's volatile RAM memory to the internal hard drive of the host computers using Kodak's custom transfer utility. Once several sessions of images from different experimental runs were stored on the internal hard drive they were written to CD-ROM for storage. Finally the image files were transferred to an external hard drive where they remained as a back up to the CDs. Each pair of computers utilized one CD writer via a SCSI switch allowing the user to switch between each computer for the writing process (see Figure 5). At the conclusion of the experiment approximately five gigabytes of image data had been stored onto several CD-ROMs.

2.2 Description of imaging zones

There are three types of regions at the engine plane (AIP section) where an ice particle may be viewed (see Figure 6). There is the sweet spot, where a particle is located in the view of both cameras, the upper zones where a particle can only be seen by one camera, the lower zones where a particle is down along the side of the inlet in the view of only one camera. Finally there are the dead zones, near the top of the inlet where a particle cannot be seen by either camera.

The sweet spot zone provides for the most accurate determination of the particle location, while the upper and lower zones allow for the location of the ice particle to be determined within a specific error range. It is impossible to determine if there are particles in the dead zones because neither camera views those areas.

2.3 Grid shots/scaling factor/calibration

Before any measurement of ice particle size could be performed each of the cameras had to be calibrated. This calibration procedure provided a scaling factor used to transform measurements of pixels in the digital images to inches. This could be done analytically by utilizing the magnification of the imaging system and the known distance to the target. However, it was decided to obtain a scaling factor experimentally in order to detect and correct for any nonlinear effects that may influence the size of the particle.

To obtain the data needed to calculate a scaling factor a known size target must be imaged and measured. In our case a white panel with black squares measuring 2.75 inches with 0.25 inch lines was constructed (see Figure 7). This grid board was placed in the field of view perpendicular to each camera. Each time a grid image was captured the distance from the grid to the camera sensor was recorded. This process was repeated through a series of different distances for each camera.
The scaling factor is determined by measuring a single grid square in inches and dividing this value by the square size in pixels from the digital image. This provides a discrete scaling factor for that particular distance from the camera. The scaling factor, or pixel pitch, is the number of pixels in one inch at a particular distance based on the magnification of the imaging system. For example, given that the width of one black square and a single white line of the grid combined is three inches, and the grid board is imaged 45 inches away from the camera, that same black square and line will measure 21 pixels in the digital image. Therefore, each pixel will represent 0.143 inches in the image (see equation 1) in this case.

\[
\text{Scaling Factor} = \frac{\text{grid square size (inches)}}{\text{grid square size (pixels)}}
\] (1)

A scaling factor was calculated for each grid shot and the discrete values plotted as a function of distance. A best-fit equation was then used to determine the scaling factor for any given distance from the camera. This calibration procedure was performed for each of the Kodak Ektapro cameras.

### 2.4 Determining measurable particles

During the acquisition portion of the experiment a total of 109,206 individual images were saved to CD-ROM for analysis. This amount of data proved to be very difficult to handle and it was apparent that a method had to be developed to view the images easily to determine which images held the most significant ice particles. Using Kodak ShoeBox™, an image cataloging application, an entire run (session) could be loaded and viewed (see Figure 8). Each run had between 500 to 5000 images of which only about 200 would be selected for particle analysis. With this application one could load the entire run, quickly view all the images, select images with significant shed ice, and catalog only those images for subsequent analysis.

### 2.5 Sweet spot/particle distance

To determine if a particle resides in the sweet spot, the runs from both AIP cameras were loaded into Kodak ShoeBox™ on separate computers that were positioned side by side. This enabled the user to view both runs simultaneously to determine if a given particle can be seen in both camera views. Additionally each run was loaded onto a Silicon Graphics workstation and the images were played at video speed to view a sweet spot particle in motion. Both methods of sweet spot particle identification proved to be effective. Once a particle was determined to be in the sweet spot its spatial location was determined by conceptually dividing the region into a cross-hatched, grid zone based on the distance and magnification of both cameras. This spatial location was then measured using a grid ruler.
The grid ruler was constructed from a grid shot taken at the furthest point from the camera. This was displayed on the computer monitor and enlarged. A cardboard square ruler was fabricated to match the scale of the grid board lines across the top and side of the image (see Figure 10). Because the grid ruler has the same dimensions as the grid shot in Figure 7: Typical grid shot the measurement procedure is analogous to overlaying the grid shot on the particle image and determine which square the particle resides in.

Figure 10.—Construction of grid ruler.

The use of the grid ruler provided for the quick location of a particle in the field of view. An image with a measurable particle in the sweet spot was read from the CD-ROM and enlarged to the exact size as the grid was previously. The grid ruler was then placed on the monitor and aligned to the frame of the image. The number of squares (tic marks) from the corner of the ruler to the square where the particle resides, are counted to provide the distance from the bottom of the inlet (see Figure 11).

To calculate the distance from the bottom of the inlet to the particle simply multiply the number of tic marks by three inches, the width of one square and line. Then subtract this distance from 39.8 inches, the farthest grid board distance, giving you the distance from the particle to the camera sensor. All ice in the sweet spot were measured utilizing this method.

2.6 Upper and lower zones / Particle distance

A particle resides in the upper or lower zone if it appears in only one of the two camera views. Determination of whether the particle resides in the upper or lower zone is made on the bases of particle illumination and velocity. The lighting originates from the top of the inlet directly between both cameras, therefore ice particles in the upper zones are very close to the light source and achieve near maximum intensity when digitized. Particles in the lower zones receive less illumination due to increased distance from the light source and achieve a middle to low range intensity value. The determination of upper and lower zone particles were made visually based on this intensity difference. Additionally particles in the upper zones appeared to move very rapidly because of their closeness to the camera, while lower zone particles appeared to move slowly. This second method of zone determination acted as a verification of particle location. The size of a particle that resides in the upper or lower zones could not be calculated using the same method as the sweet spot region because of the inability to triangulate on the particle. The particles were calculated within an error bound based on the upper and lower zone distances from the camera sensor (see Figure 12).

Figure 11.—Particle and grid ruler.

Figure 12.—Error analysis for upper and lower zones.
The error due to only one camera view of the particle can be quantified for both the upper and lower zones. In the lower zone the farthest distance from the camera sensor D2 (Figure 13) to the bottom of the intake is 47.8 inches, with a scaling factor of 0.15 inches/pixel.

Figure 13.—Calculation of error bound.

The distance from EM1 to the boundary between the lower zone and the sweet spot is approximately 36.0 inches D1, with a scaling factor of 0.11 inches/pixel (see Figure 13). The Error Per Pixel (EPP) was calculated using equation 2 resulting in the percentage error for the entire region of ±13%.

$$EPP = \left(1 - \frac{D1}{D2}\right) \times 100$$

Figure 14.—Traditional thresholding effects on image size.

The EPP for the upper zones were determined in the same manner. Since the scaling factors were linear with respect to distance, and the relative difference between the extremes of the upper and lower zones were similar, the EPP for both zones are the same.

2.7 Particle size

Particle size determination was made using a commercial image analysis package called Sigma Scan/Image™. This application allows the user to make very quick and precise measurements with the added feature of compiling all the data into a convenient format for statistical analysis. A main goal in the measurement methodology was to minimize human judgment associated with setting the threshold values which ultimately cause variability in the data.

A method was developed based on thresholding the image. Normal thresholding allows the user to set a threshold value such that all the intensities above the threshold value go to maximum white (255) and all the intensities below that value go to black (0). This threshold technique is adaptable to the variation of particle intensity found within the digitized images.

Figure 14 shows the effects that traditional threshold has on the size of the particle being measured. The center graphic shows an ideal edge and the edge once it has been imaged. The imaged edge has a slope with a variation in intensity, whereas the ideal edge has a single intensity with an abrupt change to no intensity. Where the imaged and ideal edges intersect is the proper threshold value one would apply to the digitized edge to regain the proper sized ideal edge. The upper left graphic shows the result of setting too low a threshold value, resulting in the particle appearing larger than actual size. The upper right graphic shows the effect of setting too high a threshold value which results in a smaller particle size. Figure 15 shows the effect on particle size utilizing a single threshold value for the entire image. Setting a threshold value too low includes much of background as ice particle data, whereas selecting a threshold value too high excludes particles that should be part of the data set.

There are a number problems with utilizing traditional thresholding. First the user is allowed to make an assumption or judgment of where the proper threshold value lies in relation to the entire image. Secondly, a single threshold value for the entire image results in false particle sizes due to uneven illumination across the field of view. Finally, the threshold value is selected by the user according to their personal perception of how the ice particle should look like. This can certainly create consistency problem for a single user from one image to the next, and a repeatability problem for multiple
users who analyze the same images. The ideal case is to make a measurement based upon a flexible parameter that maintains consistency throughout the experiment and has the ability to be applied to an individual particle regardless of the variation in illumination. Using Sigma Scan's auto threshold feature, a user is able to apply a percentage threshold as a function of the maximum intensity in the ice particle.

The correct percentage to threshold the ice particles was determined by utilizing the 2X2 inch white reference squares painted on the bottom and sides of the inlet. With these known targets several threshold settings were applied to a small set of images initially. A 70 percent threshold value provided the closest to the actual size of the white squares. Figure 16 shows the distribution when the algorithm was applied to two hundred images of the reference squares from a variety of icing conditions.

To make a size measurement the brightest pixel of the measured particle is identified and all pixels at and above the selected percentage of the maximum intensity value are thresholded, and the rest of the image remains unchanged. For example, if a selected ice particle has a maximum intensity of 100 and the threshold percentage is set to 70%, then every pixel with a value of 70 or more within that particle would be counted for the total area measurement.

This process was repeated for each particle and the total area data placed into a spreadsheet. The length and width of the particles were also measured because a particle may be 25 pixels in area, but only 1 or 2 pixels wide, and therefore a fragile sliver able to slip between the turbine blades. On the other hand a block of ice 5 pixels by 5 pixels has a much higher potential to cause engine damage. These two particles have the same area, but present very different potential damage criteria for ice ingestion.

3. Discussion

Several aspects of this project became evident early in the design of the inlet model. It was critical to the success of the experiment that the hardware and mounting points for imaging equipment be designed and integrated into the model during manufacture. This reduced the additional time normally required to fabricate mounting hardware during the model installation and buildup allowing more time to be spent on productive testing. Additionally, the nature of the necessary views was so complex, trying to integrate equipment after manufacture would have been impossible. Finally, this project proved to be the most extensive use of imaging hardware operating under severe environmental conditions that the Icing Tunnel and the Scientific Imaging Group has ever conducted.

Considering the number of data points requested and the complexity of the data gathering system, an effort was made to utilize as much automation and commercial hardware and software as possible. Image analysis proved to be the most challenging and time consuming portion of the research, requiring the use of several software packages along with developing customized methodologies.

During the course of this project several possible improvements were noted for future tests of this kind. In order to image the dead zones, modifications to the aft section could be incorporated. Also, optoelectronic solutions have been proposed eliminating the need and storage for the images.
4. Conclusion

The techniques in this paper represent an icing test in which severe environmental conditions, high speed imaging technology, data analysis methods, computer and related storage technology pushed the state-of-the-art for shed ice particle visualization.

Advances in aerospace technology and aircraft design often necessitate testing under adverse conditions such as those created in the Icing Research Tunnel at NASA Lewis. The results of this test are a product of the continued development of complex imaging systems and data analysis techniques to meet the needs of the IRT by the Scientific Imaging Group at NASA Lewis.

5. References


6. Acknowledgments

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Ice; Tunnel; Aircraft icing; High speed; Digital; Imaging

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