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A Preliminary Study on Ice Shape Tracing With a Laser Light Sheet

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A PRELIMINARY STUDY ON ICE SHAPE TRACING WITH A LASER LIGHT SHEET

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SUMMARY

Preliminary work towards the development of an automated method of measuring the shape of ice forming on an airfoil during wind tunnel tests has been completed. A thin sheet of light illuminated the front surfaces of rime, glaze, and mixed ice shapes and a solid-state camera recorded images of each. A maximum intensity algorithm extracted the profiles of the ice shapes and the results were compared to hand tracings. Very good general agreement was found in each case.

INTRODUCTION

The aerodynamic characteristics of aircraft components are affected by the shape of ice accreted on their surfaces. Traditionally, ice shapes have been recorded by making a clean horizontal cut in the accreted ice, and tracing the ice shape on a piece of cardboard placed in contact with the ice. Although this method is reliable, it is labor intensive and impractical to sufficiently document the shape variability because of the large number of cuts required. Additionally, hand tracings cannot be made while ice is accreting.

Our goal is to develop an automated method of measuring the shape of ice forming on an airfoil during wind tunnel tests. An optical measurement system could quickly acquire many profiles, or measure real time ice accretion. The first step towards the development of such a system is to determine whether image processing can be used to characterize ice shapes. In order to do this, a laser light sheet was used to illuminate several ice shapes (ref. 1). Glaze, rime, and mixed ice accretions were imaged onto a solid-state camera. An image processing algorithm was used to extract the shape and to correct for distortions introduced by the angle of the camera. The obtained shapes were compared with hand traced shapes to verify the optical measurement. In addition, a wood ice model was optically measured and the results were compared against the known shape of the model.

DESCRIPTION OF EXPERIMENT

The test was conducted in the Icing Research Tunnel (IRT) at NASA Lewis Research Center (ref. 2). The IRT is a closed loop atmospheric refrigerated wind tunnel. The rectangular test section is 9 ft wide, 6 ft high, and 20 ft long. The airfoil used was a NACA–0012 mounted on the test section turntable at an angle of attack of 4°. The tunnel test conditions were varied to produce glaze, rime, and mixed ice accretions.

The optical setup is shown in figure 1. The beam from a 5-W multiline argon ion laser was expanded by a 40X microscope objective lens. A second lens was positioned ahead of it to produce a 90-mm diameter collimated beam. A 795-mm focal length cylindrical lens focused the beam to a sheet approximately 2 mm thick. The sheet was formed at the leading edge of the airfoil by reflecting the laser beam off of a mirror above the test section, through a window in the ceiling of the test section, and off of a second mirror mounted on a post in the tunnel so that the light intersected the airfoil horizontally at midspan. The post was removed during ice accretion. A solid-state camera mounted above the tunnel test section was positioned along the optical axis to image the light sheet with as close to a grazing angle as the tunnel geometry would allow. This angle was about 13° from vertical.

At each test condition, an image of the light sheet intersecting the ice was recorded. A ruler mounted horizontally on a fixed surface at the same height as the light sheet was also imaged to provide scale. A 6 mm thick hot knife was used to cut the ice at approximately the same spanwise position that was illuminated by the light sheet, and a hand tracing of the ice profile was made in the traditional way by inserting a cardboard template and tracing the ice with a pencil. All of the ice was then removed from the airfoil, and the image of the light sheet intersecting the bare airfoil was recorded. The aperture of the camera lens was manually changed between the ice, airfoil, and ruler recordings; care was taken to avoid moving the camera between exposures.

DATA REDUCTION

The laser images were digitized using a frame grabber installed in a personal computer. An array-based computer language was used to process the 512×492 pixel eight-bit images. In each image column the peak intensity was determined, and the pixel with that value was selected to represent the edge of the ice shape. Where the peak intensity occurred at several pixels within a column, the position of each occurrence was averaged to produce an edge of single pixel width. The y-coordinates of this edge were then plotted against column number to produce a plot which is hereafter referred to as an optical tracing, where the x-axis represents the transverse direction along the airfoil and the y-axis lies along the chord. The plots were smoothed and median filtered with a neighborhood of three pixels to clarify large-scale features. Absolute scale was determined by digitally enhancing reference markings on the ruler images and counting the number of pixels between them in both the x- and y-directions. Image foreshortening along the y-axis caused by the nonzero camera viewing angle was compensated for because the ruler was foreshortened by the same amount as were the ice and airfoil images.

The hand traced ice shapes and the airfoil shape of the template were both digitized with a tablet in order to provide direct comparison with the optical tracings. Scale was preserved by digitizing reference points a known distance apart in both the x- and y-axes.

The profiles from the two techniques are thus independently scaled, although the orientation of either in a plane is arbitrary. The optical tracings were rotated and translated vertically and horizontally until the airfoil profiles obtained by both techniques were aligned. The ice and airfoil profiles were always rotated and translated as a unit.

RESULTS

The optical tracings are shown superimposed over the hand tracings in figures 2 to 6. In each case the data shows good general agreement with the front surface of the ice shape; specifically the ice thickness, angle, and large-scale features are all closely matched.

Figures 2 and 3 show the profiles of rime ice accretions. Rime ice is opaque, relatively smooth, and does not form horns. These conditions are ideal for this optical measurement technique because of the unobstructed view of the complete ice shape and the diffusely reflecting ice surface. The measured ice profile extends further back than the measured airfoil profile in figure 2 because the black airfoil reflected less light. In figure 3 the airfoil profile is beyond the camera's field of view because of the ice thickness.

Figures 4 and 5 show the profiles of glaze ice accretions. Glaze ice is generally transparent, rough, and forms horns. Also, the ice shapes (most notably the horns) vary significantly along the span. The horns obstruct both the illumination and the view of the sides of the ice shape in the optical configuration used. Furthermore, the light was able to penetrate the transparent ice, where internal boundaries caused scattering, which, together with surface roughness, effectively broadened the light sheet. This reduced the spatial resolution.

Figure 6 shows the profile of a mixed ice accretion. The profile shows qualities of both rime and glaze ice. The data obtained from glaze ice (figs. 4 and 5) show discrepancies between the optically traced and the hand traced profiles at the tip of the horns. The optical traces extend beyond the hand tracings. Inaccurate positioning of the hand tracing can account for some of the difference, but, more importantly, each column's peak intensity can occur at any spanwise location within the broad light band. Therefore, the optically measured profile is a combination of any of the profiles within the light band. This causes inaccuracies along the entire profile, which are manifested as false high frequency detail in the optical tracing, as well as extension of the horns. The horns are extended because the widest profile within the band is always selected.

Figures 7 and 8 show the light sheet intersecting glaze ice. Light sheet broadening is visible in figure 7, as is the spanwise variability of the ice shape. Figure 8 shows the same light sheet imaged with a smaller camera lens aperture; this image was used to obtain the optical tracing shown in figure 4. Figure 9 shows the light sheet on rime ice: it can be seen that less broadening occurred. Figure 9 was used to obtain the optical tracing shown in figure 2.

A wood model was mounted on the airfoil in the wind tunnel. A photograph of the model is shown in figure 10; figure 11 shows the light sheet intersecting the model. Hand and optical tracings of the model were made and are shown in figure 12. The same high frequency detail that was present in the optical tracings of rime ice is present in the optical tracing of the smooth wood model. This high frequency detail is caused predominantly by electronic camera noise. It is smaller than the noise present in the glaze ice tracings which, again, include inaccuracies caused by reduced spanwise spatial resolution.

Additional sources of discrepancies between the optical tracings and the hand tracings may arise from the manner in which the hand tracings were made. Nonperpendicular ice cuts, tilted templates, and nonuniform pencil tilt combine to cause inaccuracy in the hand tracing. If these errors are present they always produce a hand tracing which is larger than the true ice shape. Error in the comparison between the hand and optical tracings may also be introduced by inexact positioning of the cut relative to the light sheet, and by inexact digitization of the hand tracings.

CONCLUSION

The first step in the development of an automated ice shape measurement system has been completed. Five ice shapes were illuminated by a thin sheet of light and imaged onto a solid-state camera. The images were digitized and a maximum intensity algorithm was used to obtain the ice shapes. The resultant ice shapes showed very good agreement with hand tracings for both rime and glaze ice. The glaze ice, which is transparent and has a complex structure, effectively broadened the light sheet, reducing the spanwise spatial resolution. This effect may be reduced by applying a powder or matte paint to the ice.

This optical technique can be extended to allow the measurement of the entire ice shape by incorporating multiple cameras and/or light sources. Further extension to allow multiple spanwise ice shape measurements can also be included. Finally, digital filtering may allow the separation of background noise from the small-scale ice structure.

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1. Yamaguchi, K.; and Hansman, R.J., Jr.: Heat Transfer on Accreting Ice Surfaces. AIAA Paper 90–0200, Jan. 1990.

2. Soeder, R.H.; and Andracchio, C.R.: NASA Lewis Icing Research Tunnel User Manual. NASA TM–102319, 1990.

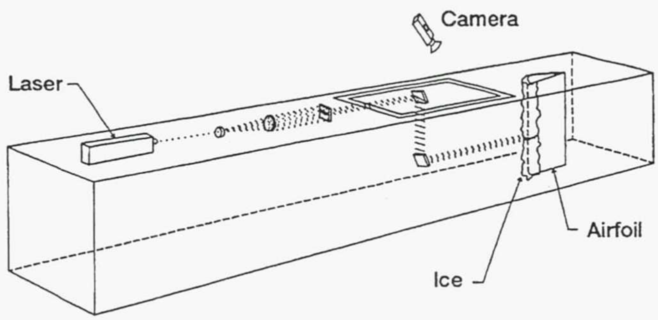

Figure 1.—Optical configuration.

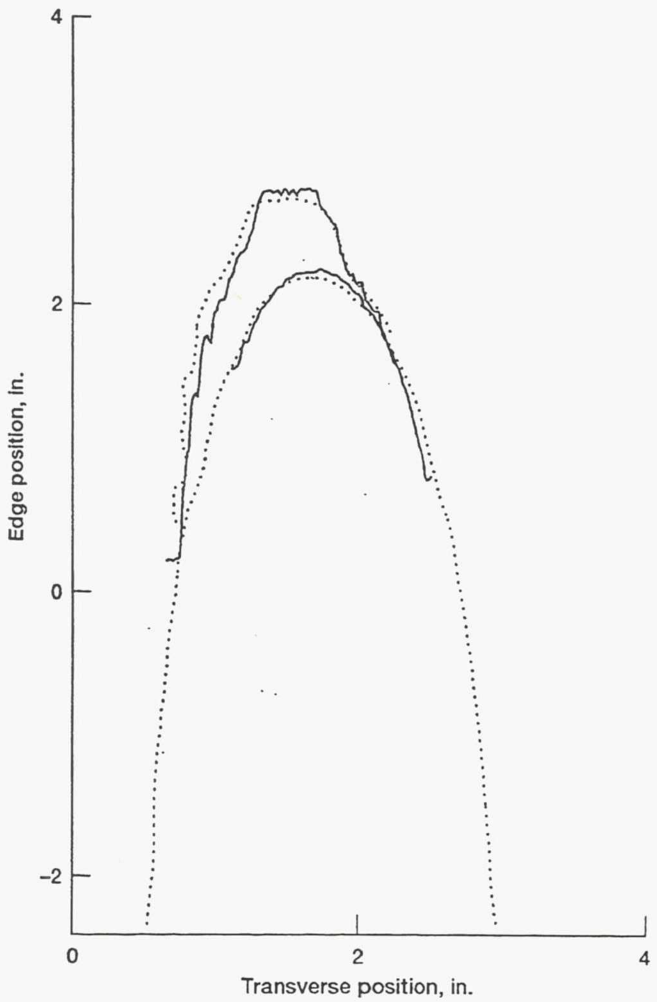

Figure 2.—Optical tracing (solid line) and hand tracing (dotted line) for rime ice accretion.

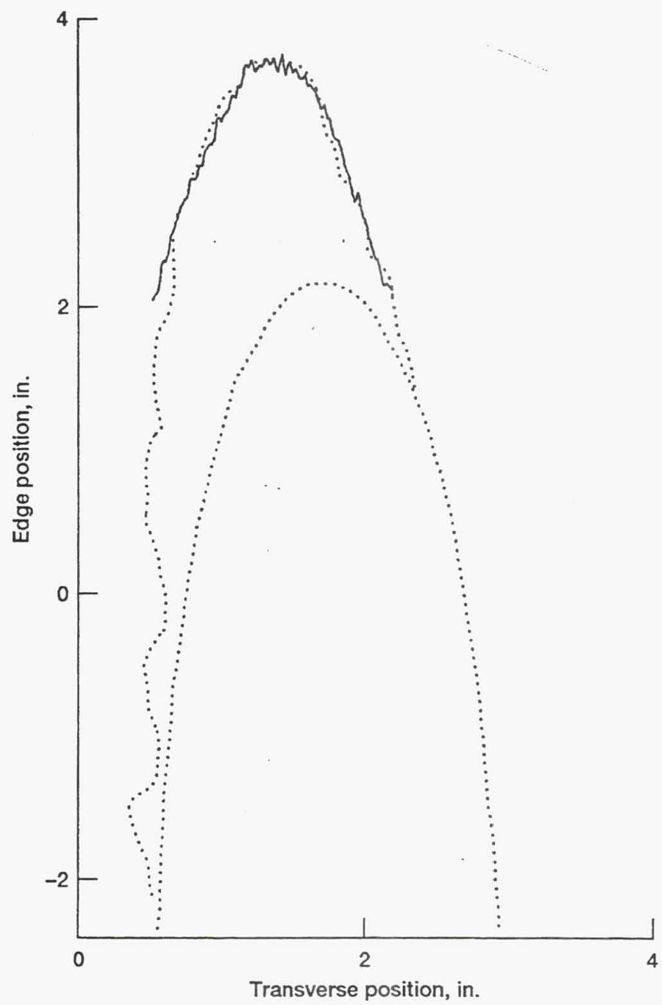

Figure 3.—Optical tracing (solid line) and hand tracing (dotted line) for rime ice accretion.

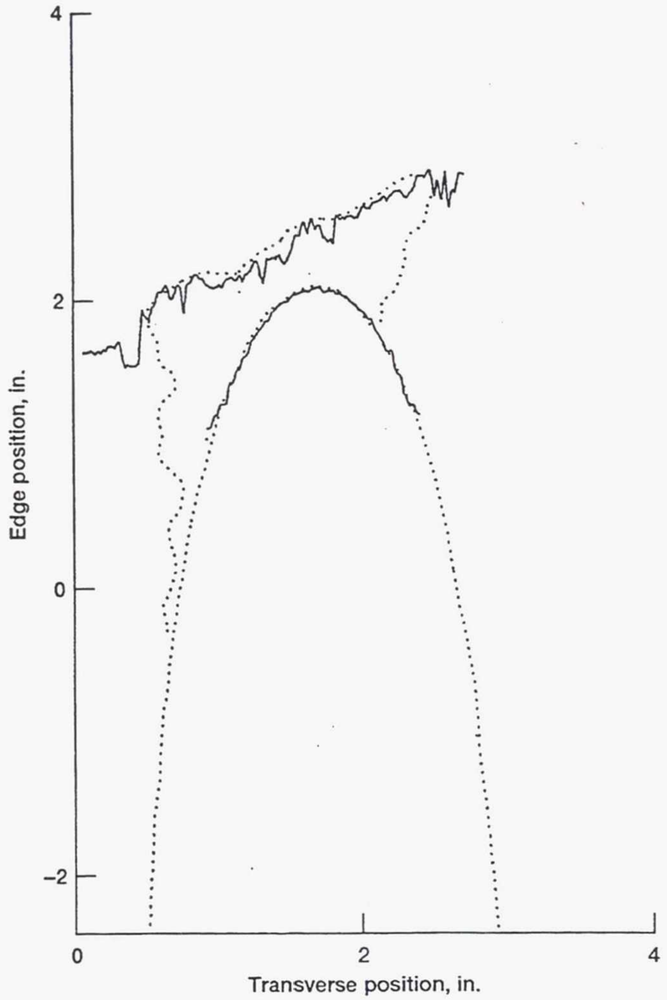

Figure 4.—Optical tracing (solid line) and hand tracing (dotted line) for glaze ice accretion.

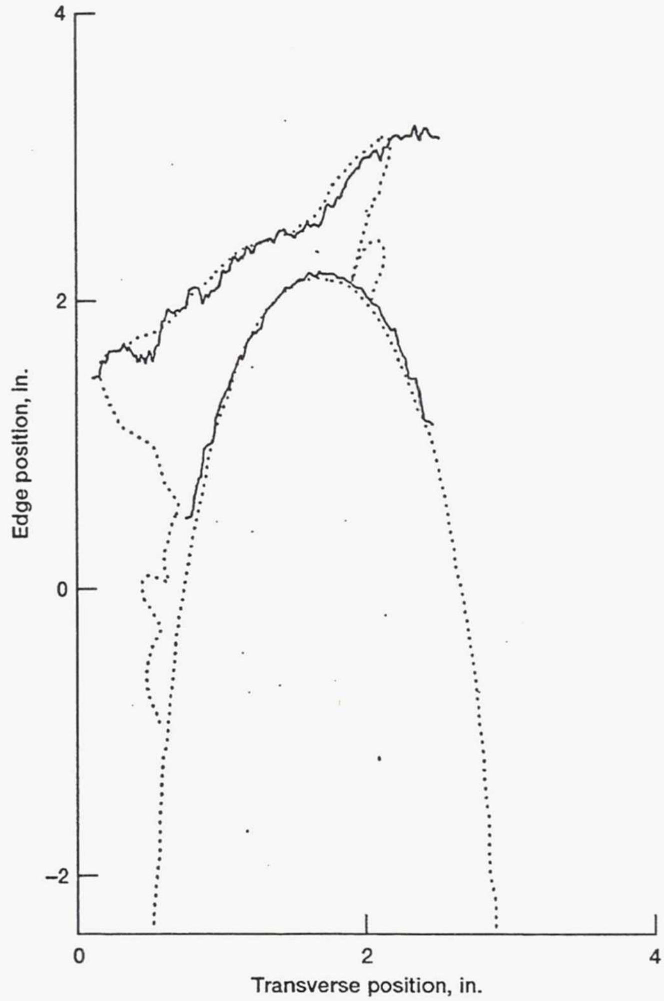

Figure 5.—Optical tracing (solid line) and hand tracing (dotted line) for glaze ice accretion.

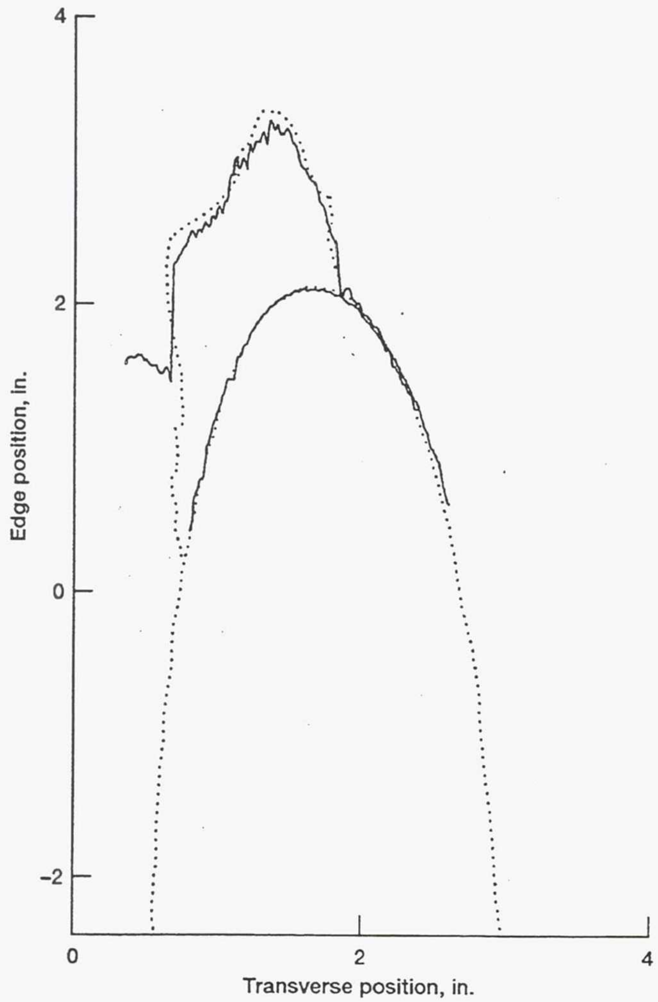

Figure 6.—Optical tracing (solid line) and hand tracing (dotted line) for glaze/rime ice accretion.

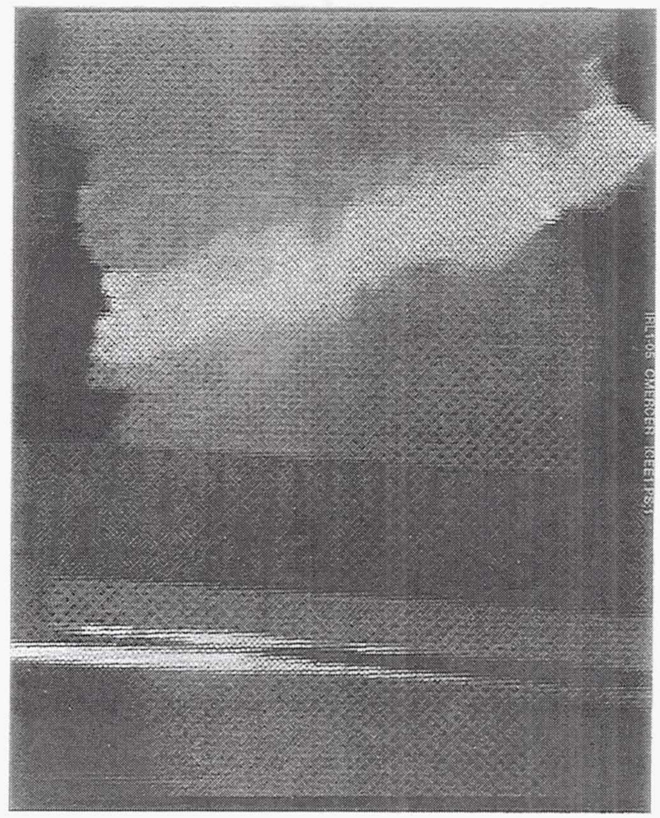

Figure 7.—Light sheet intersecting glaze ice.

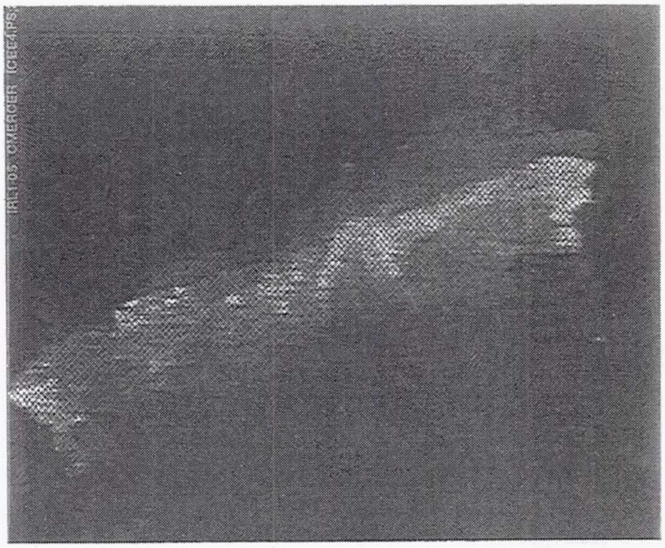

Figure 8.—Light sheet intersecting glaze ice (camera lens stopped down).

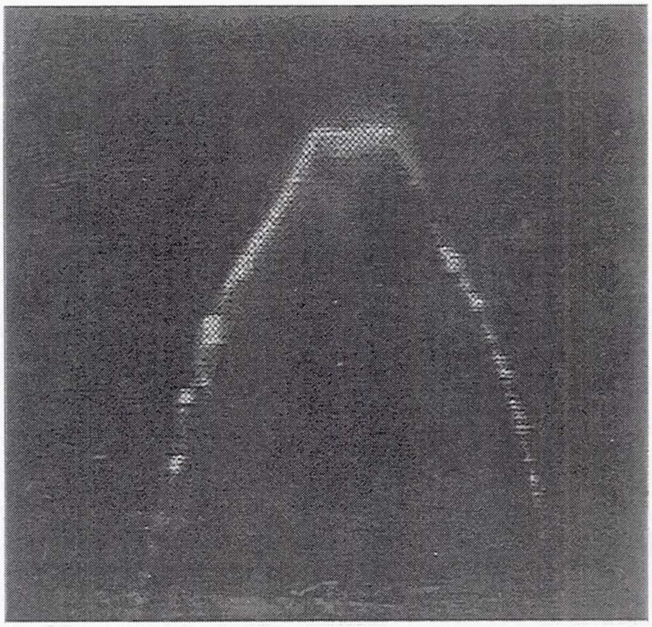

Figure 9.—Light sheet intersecting rime ice (camera lens stopped down).

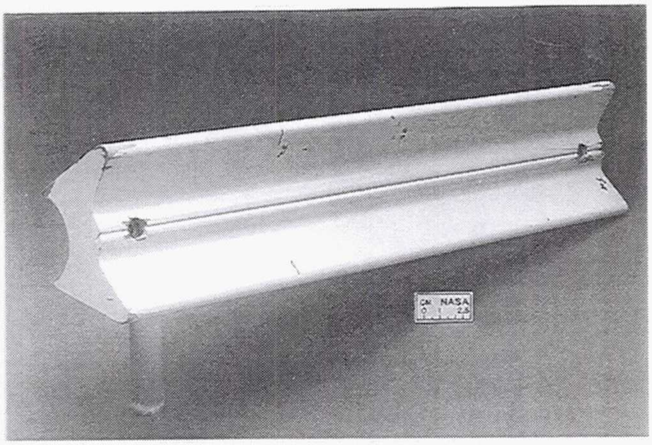

Figure 10.—Photograph of wood model.

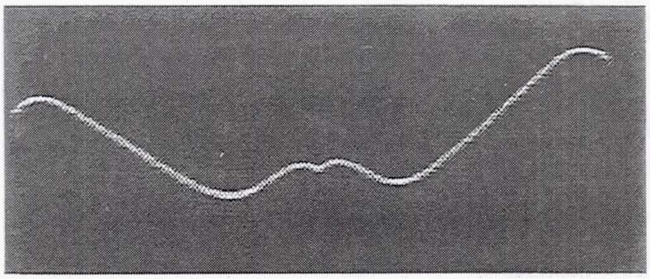

Figure 11.—Light sheet intersecting wood model (camera lens stopped down).

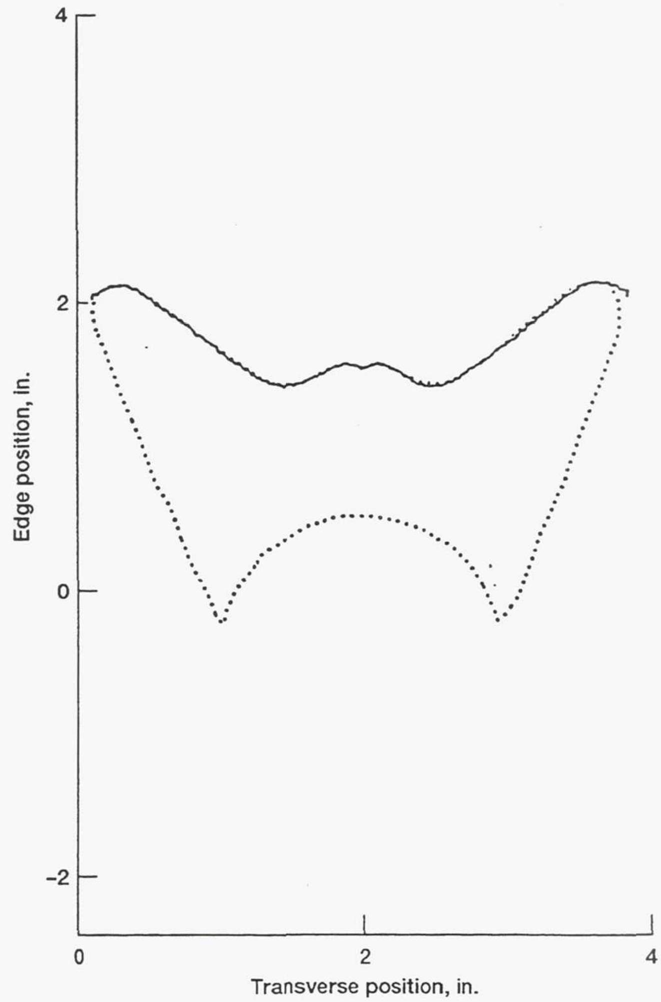

Figure 12.—Optical tracing (solid line) and hand tracing (dotted line) of wood model.

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