1992

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Abstract
Interference fringes due to bondline thickness variation were observed in ultrasonic scans of the reflected echo amplitude from the bondline of adhesively joined aluminum skins. To demonstrate that full-field interference patterns are observable in point-by-point ultrasonic scans, an optical setup for Newton's rings was scanned ultrasonically in a water immersion tank. The ultrasonic scan showed distinct Newton's rings whose radii were in excellent agreement with the prediction.

Keywords
FAA Center for Aviation Systems Reliability

Disciplines
Aerospace Engineering | Engineering Mechanics

Comments
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Citation: Applied Physics Letters **60**, 1169 (1992); doi: 10.1063/1.107394
View online: http://dx.doi.org/10.1063/1.107394
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/60/10?ver=pdfcov
Published by the AIP Publishing

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(Received 4 November 1991; accepted for publication 6 January 1992)

Interference fringes due to bondline thickness variation were observed in ultrasonic scans of the reflected echo amplitude from the bondline of adhesively joined aluminum skins. To demonstrate that full-field interference patterns are observable in point-by-point ultrasonic scans, an optical setup for Newton's rings was scanned ultrasonically in a water immersion tank. The ultrasonic scan showed distinct Newton's rings whose radii were in excellent agreement with the prediction.

The phenomenon of Newton's rings and other interference fringes associated with the thickness variation of a material layer are common occurrence in optics.[1] Ultrasonic Newton's rings, on the other hand, have never been reported, perhaps because ultrasonic fields are usually observed in a point-by-point manner instead of in full-field, like in optics. The only mention of Newton's rings in the context of acoustic waves was made by Wilson and Tucker,[2] who observed light and dark contour bands in cold-drawn polypropylene film under a reflection acoustic microscope operated at 0.4 GHz. They attributed these contour bands to the interference associated with the thickness nonuniformity and remarked their similarity to Newton's rings.

Recently, in a study of the ultrasonic characterization of adhesive bonds, we often observed wavy, light, and dark contours in the ultrasonic C-scan of adhesively bonded and riveted aluminum skin lap splices. These wavy contours seemed to follow the rivet pattern. To test the assumption that these light and dark contours were interference fringes caused by the bondline thickness variation, we prepared a lap splice of two 0.040-in.- (0.10-cm-) thick aluminum skins with a layer of room-temperature volcanize (RTV) sealant in between. The lap splice also contained six fasteners and three of these were tightened so as to create a variation of the sealant thickness around them. An ultrasonic C-scan of the echo amplitude reflected from the bondline, shown in Fig. 1, indeed showed concentric rings around the three tightened fasteners. The ultrasonic scan was made in an immersion tank using a 0.5-in.- (1.27-cm-) diam transducer with a central frequency of 15 MHz and a focal length of 3 in. (7.6 cm) in water. The transducer was driven by a spike pulser and operated in the broadband mode. After the scan, the two aluminum skins of the lap splice were separated to examine the sealant thickness variation around the three tightened fasteners. The sealant thickness was indeed found to decrease from a constant value away from the tightened fasteners toward almost zero thickness near the edge of the tightened fasteners. It was therefore reasonable to assume that the concentric rings observed around the tightened fasteners were due to an interference of waves reflected from the two adjacent inner surfaces of the aluminum plates. The configuration resembled that of an optical Newton's rings setup, except that the gap thickness approached a constant *away* from the center. This caused the ring spacing to *increase* as the radius increased, opposite to Newton's rings. To verify this qualitative interpretation and to facilitate quantitative understanding, an ultrasonic scan was performed on an actual optical Newton's rings setup to produce ultrasonic Newton's rings.

The experiment was conducted with a flat glass plate resting on top of an equiconvex glass lens, as shown in Fig. 2. The flat glass plate was 0.5 cm thick. The radius of curvature of the lens surface was 18.5 cm and the thickness of the lens was 0.95 cm at the center. Ultrasonic waves reflected from the bottom surface of the flat glass plate interfered with those reflected from the top surface of the convex lens, thus producing the fringe pattern of Newton's rings. Like in optics, the variable gap between the flat and the spherical surface was the source of interference. Figure 3 shows the ultrasonic Newton's rings obtained in a scan using the experimental setup shown in Fig. 2. The scan was

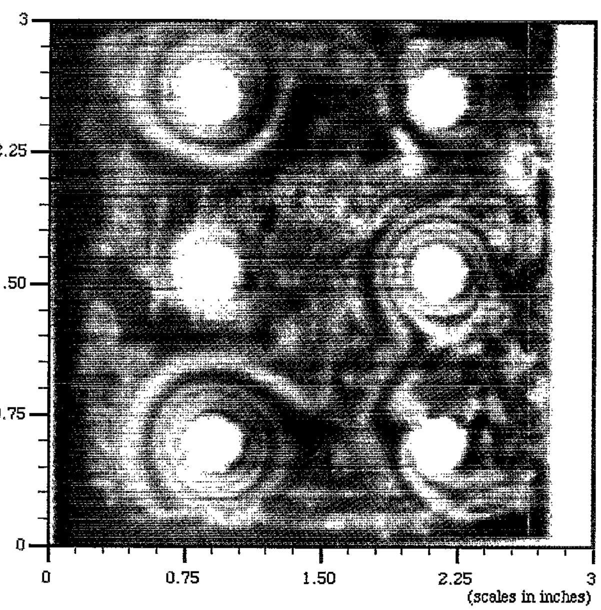

FIG. 1. Ultrasonic scan of the RTV sealant bondline between two aluminum skins. The three fasteners with concentric circles were tightened to vary the bondline thickness.

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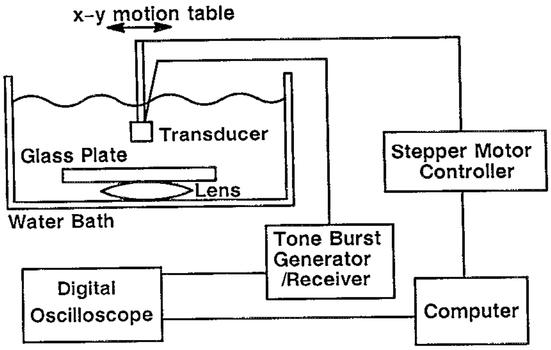

FIG. 2. Schematic diagram of the ultrasonic Newton's rings experiment.

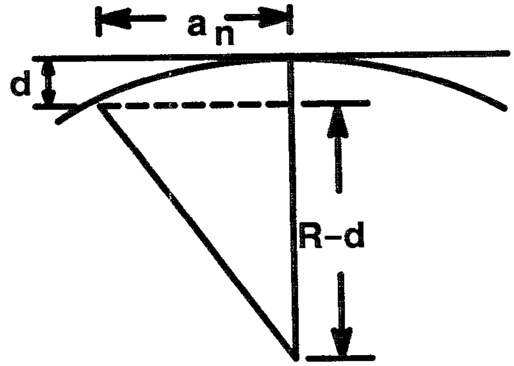

FIG. 4. Relationship between radii of Newton's rings and the gap distance.

made using a 15-MHz transducer with a focal length of 3 in. (7.6 cm) in water. The transducer was driven by a toneburst of approximately 20 cycles at a frequency of 13.3 MHz. The map in Fig. 3 was a grey-scale representation of the echo amplitude and the scan was done over a square area of 0.75 in. (1.91 cm) on one side. The rings in the ultrasonic Newton's rings were very slightly out of round because the transducer scan plane was not precisely parallel to the flat glass plate. However, more than seven rings were clearly observed and quantitative measurements of the radii were made to compare with the calculated radii.

The radii of the rings can be calculated with the aid of the simple diagram in Fig. 4 where R is the radius of curvature of the round surface, a_n is the radius of the nth dark ring, and d is the gap distance between the curved and the flat surfaces. Destructive interference occurs when the distance d is equal to an integral multiple of a half wavelength of the wave travelling in the medium between the surfaces. Since the measurements were done in the pulse-echo mode, destructive interference occurred when the pathlength differences between the two reflected waves equaled to integral multiple of a full wavelength. The interference was destructive because the medium in the gap, namely water, has a lower acoustic impedance than glass, thus introducing a phase change of π in the reflection from the curved surface.

From Fig. 4, the radius of the nth ring is given by

$$a_n = (2Rd - d^2)^{1/2}. \quad (1)$$

Combining with the destructive interference condition

$$d = n\lambda/2 = (n/2)v/f, \quad (2)$$

we obtain the radii of the rings

$$a_n = [nR(v/f) - (nv/2f)^2]^{1/2}. \quad (3)$$

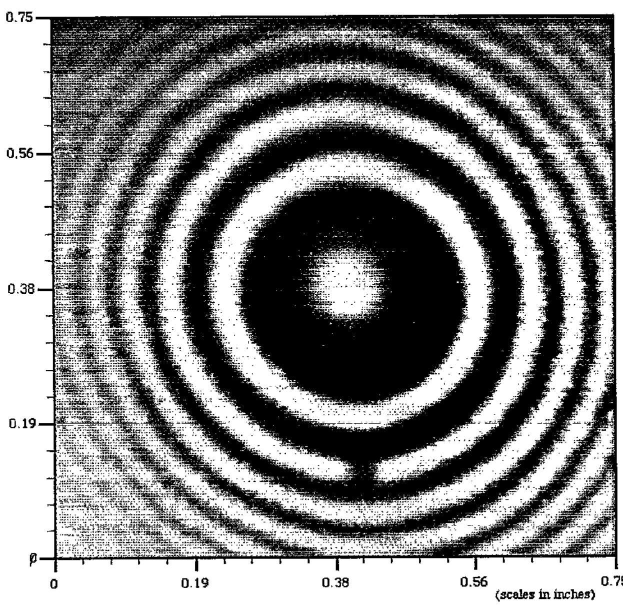

FIG. 3. Ultrasonic Newton's rings obtained using the setup in Fig. 2.

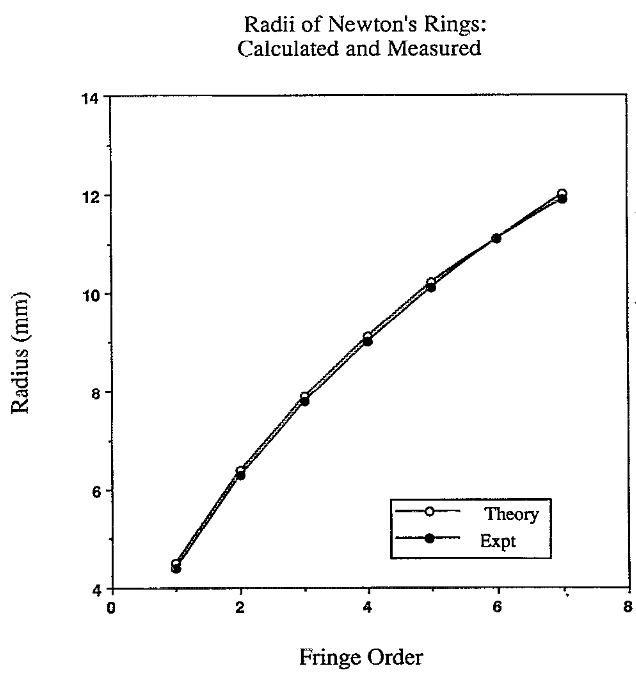

FIG. 5. Comparison of calculated and measured radii of ultrasonic Newton's rings.

Here v is the velocity and λ is the wavelength of the wave in the gap, and f is the frequency. To compare with the measured results, Eq. (3) was used to calculate the radii based on the experimental parameters: $R = 18.5$ cm, $v = 0.149$ cm/μs, and $f = 13.3$ MHz. The computed and measured radii of the ultrasonic Newton's rings are compared in Fig. 5; the agreement was excellent. It should be noted that for large radius of curvature R, the radii of the Newton's rings are given approximately by $a_n = (nRv/f)^{1/2}$ and are proportional to the square root of the fringe number n.

When the experiment shown in Fig. 2 was repeated with the transducer driven by a spike pulse instead of the long toneburst, the scan produced only one or two broadened rings before the fringe pattern diffused out. This was anticipated for interference with "polychromatic" sources covering a range of frequencies.[3] The small number of rings was also expected because, for short pulse length, the echoes from the two surfaces soon became temporally separated and ceased to interfere with each other. The fact that multiple rings were observed on the lap splice containing RTV sealant, as shown in Fig. 1, indicated that the sealant layer was quite thin near the tightened fasteners.

In conclusion, we have demonstrated that variations of bondline thickness can lead to interference fringes in the ultrasonic scan of adhesively bonded structures. Furthermore, a point-by-point raster scan of a flat surface in contact with a spherical surface produced the ultrasonic analog of Newton's rings and the measured results were in excellent agreement with the calculation. The ability to interpret the interference fringes would help the quantitative evaluation of adhesively bonded aircraft structures.

This work was sponsored by the FAA Center for Aviation Systems Reliability, operated by the Ames Laboratory, U.S. Department of Energy, for the Federal Aviation Administration under Contract No. W-7405-ENG-82 with Iowa State University.

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[2] R. G. Wilson and P. A. Tucker, Appl. Phys. Lett. **35**, 755 (1979).
[3] W. T. Welford, *Optics*, 2nd ed. (Oxford, New York, 1981), pp. 40–42.