VISUAL DISPLAY OF SOUND WAVES IN TWO-DIMENSIONAL MODELS

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At the British Acoustical Society meeting in Loughborough, England, in 1972, there was a demonstration in which the passage of an ultrasonic pulse through water was made visible by a schlieren system using Ronchi grids. That system was used to display the effect of submerged sections of pipes or other shapes on the reflection and transmission of underwater sound.

The present project was devised to apply the same principles to display the reflection of sound from the surfaces of an auditorium, using either air or water as the propagation medium in the model. Such a display, which can illustrate focussing effects and excessive delays between arrivals of direct and reflected sound waves, was desired for demonstrations in connection with a proposed course in architectural acoustics and for testing models of halls designed by local architects for the University or other clients.

Basic Schlieren Principles

Optical inhomogeneities (*schlieren* in German) are usually made evident by the difficulty they cause: unstable density variations in the atmosphere make the stars twinkle and shift their apparent positions irregularly. Under some conditions the density variations are relatively stable, as in still air above a hot road surface, and distant objects may be seen clearly but displaced from their normal position by the gradual refraction of light rays.

An optical system designed to observe such inhomogeneities is commonly called a schlieren system. A simple example is illustrated in Fig. 1. In the absence of inhomogeneities in the system the image of point source S is focussed by lens L onto a small opaque spot on a transparent screen. Thus no light passes beyond this point, except for light scattered by dust particles.

When optical inhomogeneities are present (in practice confined to a thin region called the schlieren field), light rays passing through the inhomogeneities are deflected and no longer are focussed on the opaque spot. The refraction which causes this deflection is proportional to the transverse component of the gradient in refractive index. The schlieren field effectively becomes an object which can be viewed directly from behind the spot or whose image can be focussed on a screen by lens L'.

To allow more light to enter the system, the pinhole can be replaced by a narrow slit. The image of the slit may be absorbed by a parallel opaque line on the transparent screen or, more commonly, the screen is replaced by a knife edge that is parallel to the image of the slit and can be adjusted to block all or part of the light reaching the image. If about half of the light is intercepted by the knife edge, areas of the schlieren field will appear either lighter or darker than average, depending on whether they refract light away from or toward the opaque blade. In this case the only effective component of the refractive index gradient is the one perpendicular to the slit and knife edge.

Use of Ronchi Grids

Ronchi grids, which consist of alternating opaque and transparent bands that are parallel and nearly equal in width can also be used to replace the point source and opaque spot combination. The system is arranged so that the image of the transparent bands of the first grid is focussed by the lens on the opaque lines of the second grid. The required grid positions may be found experimentally by observing the moiré fringes at the second grid and adjusting the positions of both grids along the axis of the lens so that a single moiré fringe covers the whole visual field. This arrangement may be considered as multiple slits and multiple knife edges, with the advantages that the first grid may be illuminated by an extended light source and that the position of the observer's eye beyond the second grid is not critical, as is the case with the opaque spot or knife edge.

Folded Schlieren Systems

The system used in the present work is shown in Fig. 2. A simple Ronchi grid is placed at the centre of curvature of a concave mirror of 305 mm diameter and 3.05 m radius of curvature. The fact that the folded systems pass the light twice through the schlieren field makes the folded systems more sensitive than the single-pass systems but it also decreases the resolution since only the light ray along the axis is reflected exactly along its original path. To minimize the loss of resolution, the schlieren field is placed as close to the mirror as possible.

The lower half of the grid is illuminated by a strobe lamp with a reflector and a ground glass diffusing screen, via a plane mirror inclined at about 45° to the vertical. The horizontal top edge of this mirror is parallel to the grid lines and as close as possible to them.

In most of the work reported here, the Ronchi grid was produced photographically from a Letratone sheet LT 111 (available from Letraset Canada Ltd., of 24 Progress Avenue, Scarborough, Ontario) with the transparent bands 0.424 mm wide and the opaque ones 0.666 mm wide. The coarseness of the grid and the difference in width of the bands made it possible to obtain dark-field conditions in spite of imperfections in the glass windows. Tested samples of either plate or float glass were found to have inhomogeneities or thickness variations predominantly in one direction so they didn't contribute a schlieren pattern of their own if care was taken to assemble the cell so that both windows caused defocusing only in the direction parallel to the grid lines. With windows of better quality, a finer grid would be preferred for visual observation. For photography, any difficulty with the coarse grid can be avoided by using a camera with a long-focus lens and a lens aperture much larger than the grid spacing or by using an auxiliary lens near the grid to project a real image that can be photographed by a camera with a lens of shorter focal length.

Since the transition from dark-field to light-field conditions requires the grid to be moved in its own plane by only 1/4 of the distance between grid lines, a fine control for this motion is essential.

Sound Source in Air

The source of sound waves to be studied in a model auditorium must produce density gradients great enough for detection by the schlieren system and the disturbance should be of short duration so that a single wavefront and its various reflections can be clearly distinguished. An electric spark satisfies both of these requirements and is also small enough to simulate the production of sound by a single speaker or instrument in an auditorium.

A satisfactory spark was produced between two vertical wires projecting into the schlieren cell from the top, with their lower ends bent toward each other so as to leave a 10 mm gap parallel to the axis of the optical system. The long spark and cell thickness of only 5 cm (other dimensions 21 cm high and 22 cm wide) were chosen to make the shock waves in the two-dimensional model nearly cylindrical, rather than spherical, in order to improve sensitivity. Under these conditions, a wave could be followed for a path length of at least 40 cm.

Placing the spark near the top of the cell minimized the optical effect of heated air rising from the spark. To reduce electrical interference, a carefully shielded automotive ignition cable was used to connect the spark gap to the spark generator.

Light Source

Since the shock wave produced by the spark travels at a speed in excess of 330 $m \cdot s^{-1}$ it can be observed or photographed only if it can be illuminated by a light flash no more than a few tens of microseconds in duration. A General Radio Type 1531-AB Strobotac appeared to be a satisfactory light source although the light distribution from the reflector was uneven enough to require the use of a diffusing screen. A single flash would probably suffice for photographic recording but direct observation requires a flash repetition rate of at least 20 flashes per second.

Timing Controls

In order to observe a wave front at different positions as it expands within the model there must be a variable delay between the spark and the light flash which illuminates the resulting shockwave. This delay should be continuously variable between 0 and approximately 2 milliseconds.

The system described used a Tektronix type 162 waveform generator, synchronized to line frequency, to provide a triggering pulse to the spark, and also to provide a sawtooth signal to a Tektronix Type 161 Pulse Generator. The pulse generator produces a pulse of controllable amplitude and duration when the sawtooth signal voltage from the 162 matches a voltage set by the delay control potentiometer in the 161. The pulse from the 161 is used to fix the strobe light. Line synchronization was required because the high voltage spark power supply was powered by an unfiltered rectifier, and did not produce sparks of uniform intensity unless it was always triggered at the same phase of the alternating current cycle.

Modeling

Preliminary tests in a small test chamber have shown that good reflections are obtained from strips of metal, such as aluminum, approximately 50 mm wide and 1 mm thick, with which the contours of interior surfaces can easily be modeled. Figure 3 shows the results obtained using a camera with a 200 mm (zoom) lens directly through the grid.

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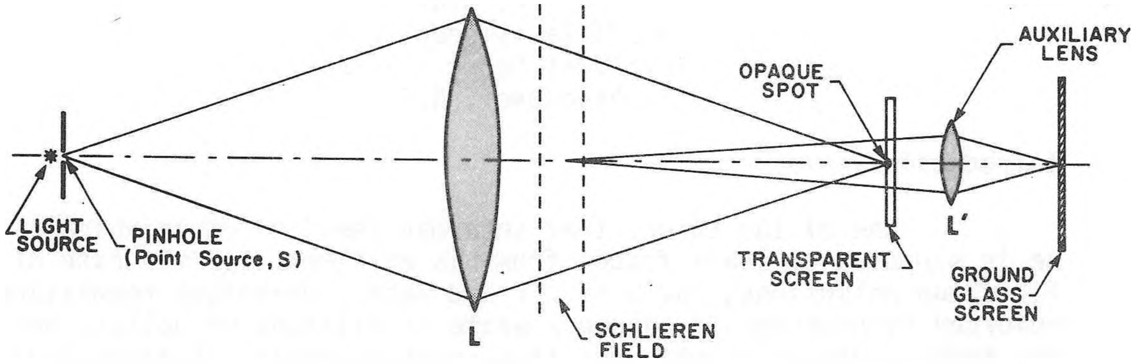

Fig. 1. Simple schlieren system using a pinhole and spot

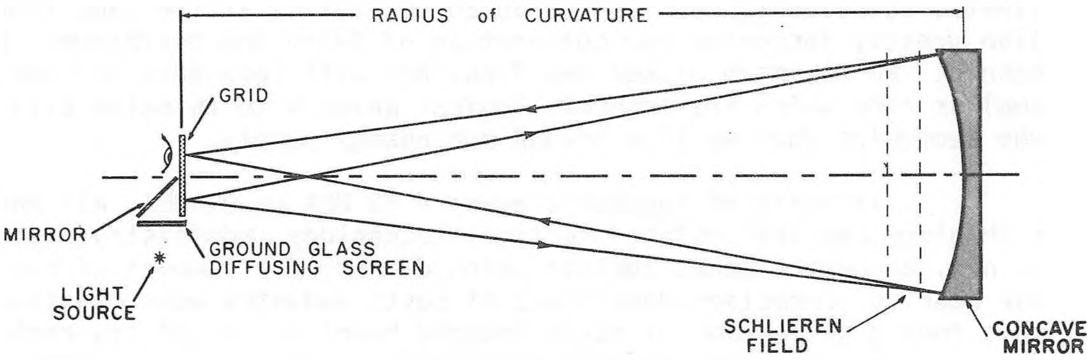

Fig. 2. Folded schlieren system with concave mirror and Ronchi grid

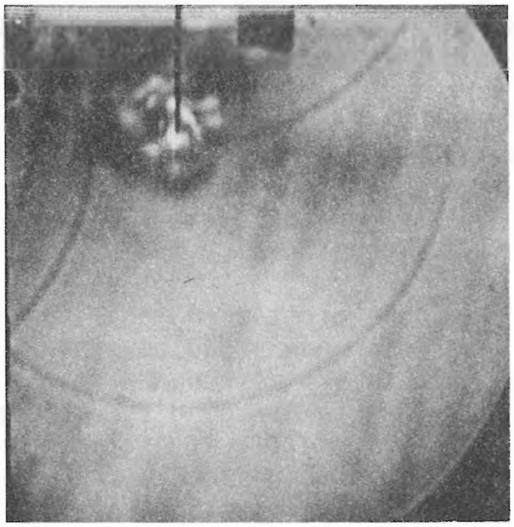

Fig. 3. Sound waves from spark gap, including portions reflected from wall and cover of schlieren cell.