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The sensitivity of schlieren systems for viewing ultrasound.

La sensitivité des systèmes schlieren pour l'examination des ultrasons.

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SUMMARY: A novel set of simplifying assumptions makes computer prediction of schlieren sensitivity possible economically. Predictions correlate with experimental and published figures. Other means of improving sensitivity are given. A compact schlieren system giving binocular stereoscopic viewing is described.

RESUME : Un nouvel ensemble de suppositions simplificatrices rend économiquement possible la prédiction de la sensibilité schlieren par ordinateur. Les prédictions sont en corrélation avec les chiffres expérimentaux et publiés. D'autres moyens d'améliorer la sensitivité sont aussi présentés. Un système schlieren compact donnant une vision binoculaire stéréoscopique est décrit.

I. INTRODUCTION

The basic schlieren system as used to visualise ultrasound is illustrated in figure 1; the camera shown may be replaced by a television camera or by the human eye. Although variations on this arrangement are possible, they are optically equivalent for the purposes of this analysis.

Figure 2 defines parameters which are under the control of the user. Complete analyses of the effects of these parameters have been presented by various authors using Fourier transform methods and their consequent complex number arithmetic [1][2]. The expressions are necessarily complicated; one of the analyses [2] requires the evaluation of 48 separate integrals, none analytically soluble, for each set of parameters, for each point on the image plane. A full wave analysis by digital computer is not practicable because the enormous number of computations produces unacceptable costs.

This paper presents a novel set of simplifying assumptions which allow an economical computer solution. Resulting predictions are confirmed by experiments and allow further generalised predictions covering the effects of the parameters on sensitivity. Also presented are other methods of improving sensitivity, and a new form of compact schlieren system which gives binocular stereoscopic viewing.

II. NOVEL COMPUTER ANALYSIS OF SCHLIEREN SYSTEMS

II.1. The simplifying assumptions

This analysis is based on the following three assumptions :

a) The phase object is assumed to be of an idealised form lending itself to division into separate parts, for each of which a standard analytical solution of energy distribution in the knife edge plane is available. Figure 3 shows the form adopted; it represents an acoustic pulse moving downwards (or upwards). The sloping part will be called 'the discontinuity'. Its height (controlled by the duration of the ultrasonic wave) is as defined, while its slope (controlled by the amplitude of the wave) is defined by D or Θ.

b) It is assumed that attention can be confined to the knife edge plane and that the part of the slit image (physical, not geometrical) which passes this plane when no discontinuity is present produces uniform background illumination on the screen. It is further assumed that, with a discontinuity inserted, the increase in light energy (again physical, not geometrical) passing the knife edge produces on the screen a uniformly illuminated image of the discontinuity, of correct scale size, whose energy is added to the background. The authors quoted [1][2] have shown that neither of these assumptions is rigorously true, but their untruth is seldom subjectively apparent, and the predictions resulting from them are found to match experimental and published results.

c) In deducing the diffraction pattern in the knife edge plane, scalar addition of the contributions of the diffraction patterns from the different parts of the wavefront was adopted, not vector addition. This can be justified by considering a point in that plane and regarding the phase of the light received from the centre of the field as a reference vector. Then the vector contributions from other parts of the phase object, either the sloping part or the undeviated part, will assemble to form a vector diagram which is symmetrical (because a phase advance from a point above the centre of the field will be matched by an equivalent retardation from a corresponding point below the centre). Hence the resultant vector, for either the sloping part or the undeviated part, will be in phase with the reference vector. Hence scalar addition of the amplitudes from the two parts, derived from the standard analytical solutions, is valid, leading to considerable economy in computer usage.

II.2. The computer program

A program was written for computing image brightness for any set of parameters, incorporating the above assumptions. The assumptions allowed computation by a double numerical integration of scalar quantities. Output was in the form of log brightness values for a series of deviation (D) values in geometric progression. Each series of D values occupied only 1 or 2 seconds of processing time. Computation was in fact performed using normalised units, but the conclusions presented here will be in the form of actual dimensions.

II.3. Equipment used for experimental confirmation of computer predictions

The compact schlieren system of figure 4 was used. A transducer consisting of a PZT plate bonded to a steel backing gave the acoustic waveform of figure 5. Measurements of apparent brightness of the image (and of the background) were taken with the spot photometer shown in the figure. Control of discontinuity amplitude was by means of a calibrated attenuator in the electrical feed to the transducer.

Stroboscopic 'freezing' of the pulses was achieved using a xenon-filled stroboscopic lamp as the source of illumination in the schlieren system. Since the computer predictions are based on the assumption that the discontinuity image is of uniform brightness, the stroboscopic light flash must not be so short as to reveal any fine structure in the image. Fortuitously the lamp used had a flash duration of about 0.2 μs, which is long enough to 'smear' the image sufficiently to suppress the fine structure and to allow mean brightness to be measured.

II.4. Results from computer program : 'grey field' setting of knife edge

For wind tunnel work the knife edge is often set to obscure about half the geometric slit image. This is not the most sensitive setting, but it gives 'brighter than background' for discontinuities of one polarity and 'darker than background' for the other. On setting X as $-\frac{1}{2}W$ in the program this behaviour was correctly predicted, as figure 6 shows.

II.5. Results from computer program : 'black field' setting of the knife edge

For ultrasonic work the knife edge is positioned for 'best sensitivity', a position which results in its obscuring the whole of the geometric slit image. Correspondingly the computer also predicted a 'best position' and this setting is assumed throughout what follows.

Figure 7 shows a computer prediction of the relation between the discontinuity deviation and brightness. Figure 8 shows corresponding experimental observations. The qualitative correlation is apparent.

In all cases the general form of the curves was as in figures 7 and 8. So far as the author is aware, the form of this 'standard' response of a schlieren system has not been reported before. The behaviour can be expressed in words thus :

> When amplitude is progressively increased from zero, the image remains invisible until a certain threshold value of amplitude is reached. There is then a transition to an approximate square law relationship between amplitude and brightness, followed by a saturation effect at large amplitudes.

Recent work by Urquhart [3] has confirmed this 'standard' behaviour with continuous illumination, using for the discontinuity a static phase object, namely a glass wedge of controllable effective deviation angle.

The 'threshold' feature of this standard response is of importance when considering whether schlieren sensitivity can be enhanced by making small changes in brightness more apparent; for example by taking a photograph and artificially increasing its contrast. On figure 7, point A can be taken to represent 'reasonable visibility' because it implies a discontinuity image brightness of about 3 times background. Suppose that a brightness of 1.1 x background can be made easily visible by artificial enhancement of contrast; this is represented by B. Reference to the log deviation scale implies that the minimum deviation detectable has been improved by a factor of about 5.

However, this is about as far as this technique can be taken, because point B is nearly on the flat part of the curve. A lower deviation value, for example a value of unity (zero on the log scale), is effectively on the flat part and no amount of contrast enhancement will produce visibility. Hence this approach to further improvement of sensitivity is unprofitable.

II.[illegible]. Influence of scattered light

Quantitative correlations between curves of the kind in figures [illegible] and [illegible] were attempted and it at once became apparent that a good 'fit' could be obtained at the top regions but not for the lower brightness regions. Investigation established that this effect could be ascribed to scattering of light in the lenses and water-filled cell, an effect not surprising since the total light energy in the slit image is typically 1000 times that which passes the knife edge.

The computer program was therefore modified to represent the presence of scattered light, and it was then found possible to fit experimental curves to predictions over a wide range of adjustment of the parameters.

Because scattered light affects that part of the curves of greatest interest, namely the 'just visible' part, its influence must be incorporated quantitatively if meaningful computer predictions are to be obtained. For this purpose the influence on the image of scattered light was defined as follows :

$$S = \frac{\text{LIGHT ENERGY DUE TO SCATTER WHICH PASSES KNIFE EDGE PLANE}}{\text{TOTAL LIGHT ENERGY ARRIVING AT KNIFE EDGE PLANE}}$$

To produce the correlations referred to, different values of S were tried to find the value producing a 'fit' with experimental observations. The value found was S = [illegible] x 10^{-3}, implying that about one 300th part of the light energy passing through the schlieren lens is scattered to pass the knife edge, a value which is intuitively acceptable.

Tests on a much larger schlieren system indicated scatter of the same order. Hence it will be assumed that this is the irreducible order of magnitude of scattered light in all schlieren systems, and the computer predictions will incorporate values which embrace that figure.

II.7. Predictions from computer program : effect of exit pupil height L

These predictions, and those which follow, were extracted from a large number of computer runs arranged to cover the practical range of parameters likely to be found.

Exit pupil height L may in practice range from about 2½mm, the diameter of the human eye pupil, to the diameter of a camera lens, say 5cm. The predictions showed that, for this range of values, the effect of L on sensitivity was generally small, but that in some cases it would be advantageous to add a further stop (an 'inverted knife edge') above the existing one to minimise the influence of scattered light.

II.8. Predictions from computer program : effect of slit image height ℓ

Here 'height' means the narrower dimension of the geometric image. The general deduction was that sensitivity is not greatly affected by slit image height, which corresponds with practical experience. More precisely it was found that, with realistic values of scatter, excessive slit image heights could introduce loss of sensitivity up to 10dB, but that image heights of a normalised value below about 200 avoided such loss.

To allow the user to apply this criterion using actual dimensions, the constraint can be expressed as follows :

$$\frac{\text{ACTUAL SLIT IMAGE HEIGHT} \times \text{FIELD HEIGHT} \times \pi}{\text{LIGHT WAVELENGTH} \times \text{FIELD TO KNIFE EDGE DISTANCE}} \quad \text{MUST NOT EXCEED 200}$$

Light wavelength may be taken as 0.5 μ, the figure assumed throughout this analysis.

For schlieren systems of practicable proportions, this constraint indicates a maximum slit image height of about 0.5 mm to 1 mm, a limitation not difficult to achieve in practice.

II.9. Predictions from computer program : combined effects of parameters

On the assumption that slit image height complies with the constraint already quoted, the effects of the remaining parameters, extracted from the computer runs, are presented in figure 9. Three different discontinuity heights are shown, but predictions for other values may be extracted by interpolation. The ordinate scaling embodies two different ways of expressing discontinuity amplitude.

It is found that sensitivity is independent of F_L, a property pointed out by several authors(and wrongly denied by others) which cannot be explained by geometric optics alone.

Looking at the vertical displacement between the three values of discontinuity height (representing duration) it is apparent that, for any given field height, larger discontinuity heights give greater sensitivity. This is not surprising, since larger heights imply that a greater proportion of the total light is deflected. However, this exposure of the exact nature of the relationship is believed to be original. It is seen that a ten-fold increase in discontinuity height improves sensitivity by about 10 dB, leading to the rule :

> Sensitivity, on an amplitude basis, varies approximately as the square root of discontinuity height (duration) when other factors remain constant.

The dotted lines show that a given amount of scatter causes greater reduction in sensitivity for small discontinuities than for large ones. This is as expected, since less light passes the knife edge for small discontinuities.

Looking now at the effect of changing field height for a given discontinuity height, it is seen that, for zero scatter, the relevant lines (the solid ones) have a slope which indicates that increasing the field height improves sensitivity. However, it is believed that the 'no scatter' situation is of academic interest only. When scatter is taken into account (the dotted lines), noting that the two values of S shown bracket the typical value found of $S = 10^{-3}$, it is seen that the slope is cancelled or even reversed.

The conclusion is that schlieren systems of large aperture are not, in practice, significantly more sensitive than small ones; a deduction supported by experience. This conclusion is of some importance since the cost of a schlieren system rises rapidly with increase in aperture.

Refractive index gradient can be converted into peak advance (or retardation) by multiplying by A_D. Applying attention to the two A_D values 0.01 and 0.1 in figure 9, they are seen to cover a decade of discontinuity heights and embrace the range of practical interest. It is seen that their 'working areas', with a realistic degree of scatter assumed, are about a decade apart on the gradient scale, the larger height having the lower gradient. It follows that they each represent a peak advance (or retardation) of about 6×10^{-2} wavelengths of light.

This figure is for 'useful visibility'. As figure 8 indicates, 'threshold visibility' is about 3 times lower. Hence this conclusion :

> In a practical schlieren system, a discontinuity of peak advance (or retardation) of 2×10^{-2} wavelengths of light is approximately the threshold of sensitivity.

This value of peak advance (or retardation) can be converted to peak watts when water is the propagation medium; the figure is about 7×10^{-4} watts. Smyth et al [4] quote a threshold sensitivity of 10^{-3} watts/cm^2, but since the relevant factor is watts, not watts/cm^2 (as explained below), we must make a guess that their figure refers to a practical transducer area of about 1 cm^2. On this assumption, the computer prediction matches closely.

II.10. Validation of figure 9 from published sensitivity data for optical windows.

Holder and North [5] quote the maximum sensitivities available in practical schlieren systems from experience in detecting imperfections in optical glass windows used in wind tunnel work. Their order-of-magnitude figure for 'easily detectable' is 1 wavelength per inch, which converts to 4×10^{-1} wavelengths per cm, marked as point P on the gradient scale of figure 9. Making the assumption that this observation refers to the larger values of field height and that the order of size of the imperfections sought is from 0.1 cm to 1 cm, an area in the region of the point marked Q is indicated, and is seen to correlate well with the gradient represented by point P.

III. OTHER METHODS FOR INCREASING SCHLIEREN SENSITIVITY

III.1. Increasing sensitivity by use of liquids other than water

A survey established that several organic liquids have the physical properties required to give a greater refractive index gradient than does water for a given acoustic pressure gradient. Some of the attractive liquids have undesirable physical properties, but a suitable liquid was found to be carbon tetrachloride. Tests indicated a measured improvement in sensitivity of about 10 times (on an acoustic power basis).

III.2. Increasing sensitivity by use of astigmatic defocusing

As already pointed out, the criterion for schlieren sensitivity is peak acoustic watts, not watts/cm^2. This is because, if a wavefront of given area is halved in the direction of viewing (called here 'lengthwise') the light path length is halved but the peak stress is increased by $\sqrt{2}$; the net effect is a reduction in sensitivity by $\sqrt{2}$. However, a widthwise halving can similarly be shown to <u>increase</u> sensitivity by $\sqrt{2}$. The two effects therefore cancel, and spherical focusing does not effect image brightness. This phenomenon, apparently contrary to intuition, is confirmed by practical observation.

However it follows that, if a given wavefront is extended lengthwise only, an increase in sensitivity should result, and this without apparent degradation of the image since the extension is in the direction of viewing.

To test this hypothesis, the acoustic system of figure 10 was used. With conventional meniscus lenses a plane collimated wavefront of square cross section entering the top lens is focused to a smaller square wavefront in the imaging zone below the bottom lens (this is actually a focusing system for imaging defects [6][7][8]). The ray pattern for this situation is shown in computer-generated perspective in figure 11.

After measuring sensitivity, the lenses were replaced with lenses having cylindrical plus spherical components of curvatures. The expected focusing behaviour is now astigmatic, as shown in perspective in figure 12.

Schlieren photographs covering the whole of the ray paths, seen from two orthogonal directions, were taken. Figure 13 shows the 'side view' and figure 14 the 'front view'. As is seen, the anticipated ray paths are obtained and the desired extension of the image lengthwise has been achieved.

Measurements of relative sensitivity in the imaging zones of the two systems showed an increase of about 8 dB; a factor of about six in terms of acoustic power. The theoretical figure was 10 dB. Hence deliberate astigmatic defocusing appears practicable as a means for improving sensitivity.

IV. COMPACT SCHLIEREN SYSTEM GIVING BINOCULAR STEREOSCOPIC VIEWING

By using graticules instead of the slit and knife edge, a compact system was developed having an exit pupil large enough to embrace both eyes of the observer. With it, binocular stereoscopic viewing was successfully demonstrated. Although graticules have been used in schlieren systems before [9][10] this form of application is believed to be novel.

Figure 15 shows the system. A field lens is required, seen to the right of the condenser lens, and careful design is necessary to avoid the need for impracticably large lens apertures[7].

When this graticule system is used in conjunction with a camera (television or photographic) a striking advantage over the slit-and-knife edge system becomes apparent; it is that the increased effective lens aperture restricts the depth of field sufficiently to allow dust and bubbles on the walls of the water-filled cell to be defocused, thus greatly improving image quality.

V. ACKNOWLEDGEMENTS

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VII. FIGURES

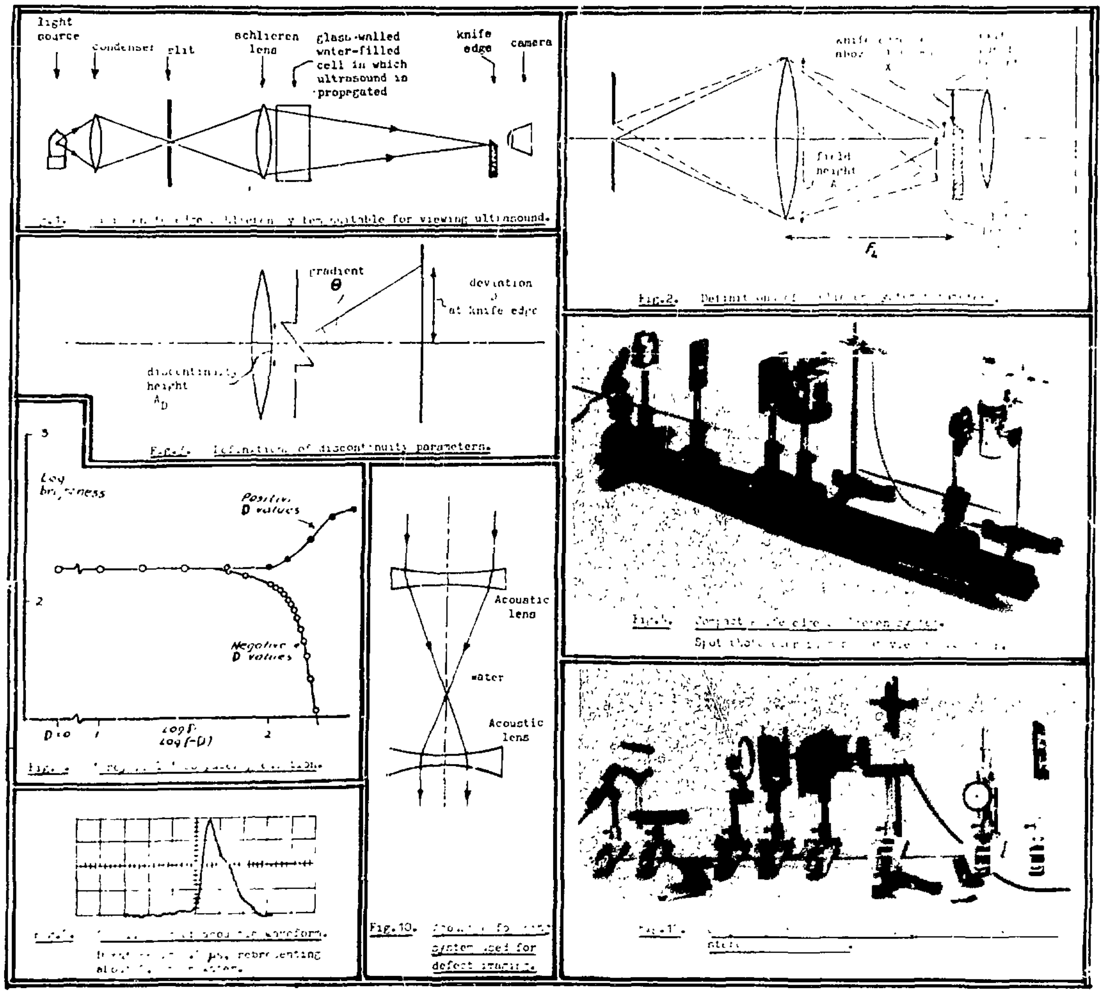

Fig.2.
Fig.10.

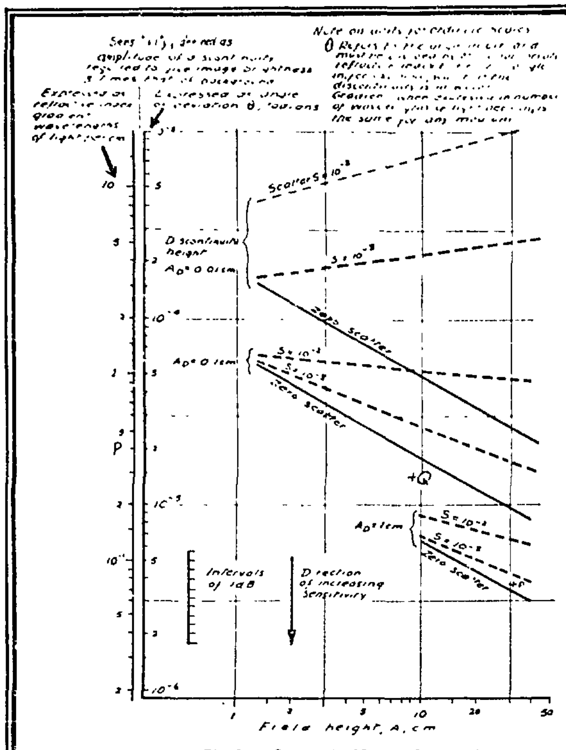

Fig.9. Combined effects of parameters.

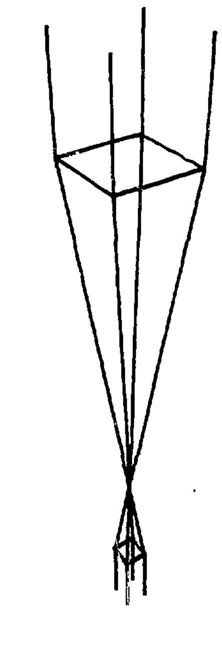

Fig.11. Ray paths for fig.10 : computer-generated perspective.

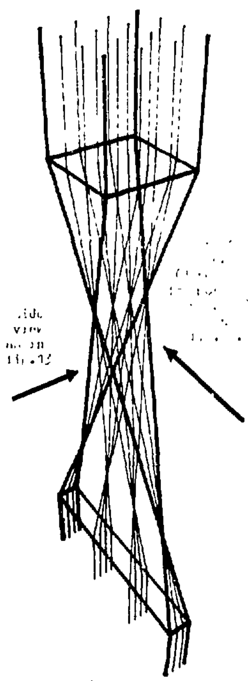

Fig.12. Ray paths with astigmatic defocussing incorporated.

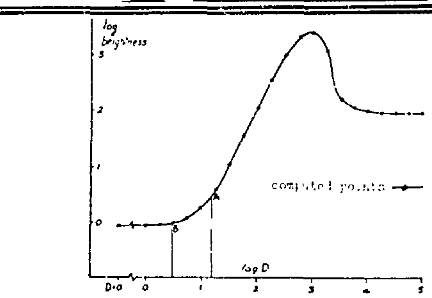

Fig.7. 'Black field' computer prediction.