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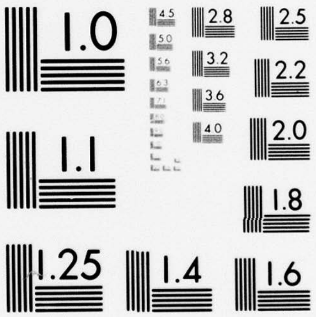

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Technical Report 77131

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STUDY OF DEFORMATION IN A METAL BAR DUE TO SHOCKWAVE PROPAGATION

by

M.P. Wright

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17. Abstract

The work described is aimed at establishing the displacement-time profiles of points on the side and end of a long metal bar when a compression wave travels along its length. The part of the bar to be examined is polished optically flat and is used as one reflector in a conventional two-beam interferometer. The passage of the wave distorts the polished area. The resultant transient fringe pattern representing the distortion in the out-of-plane direction is recorded by high-speed streak photography. From the records obtained graphs of displacement against time can very easily be derived with high resolution.

In many cases satisfactory results can be obtained using a small mirror attached to the bar by adhesive, so avoiding the troublesome process of optically polishing part of the surface.

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SUMMARY

The work described is aimed at establishing the displacement-time profiles of points on the side and end of a long metal bar when a compression wave travels along its length. The part of the bar to be examined is polished optically flat and is used as one reflector in a conventional two-beam interferometer. The passage of the wave distorts the polished area. The resultant transient fringe pattern representing the distortion in the out-of-plane direction is recorded by high-speed streak photography. From the records obtained graphs of displacement against time can very easily be derived with high resolution.

In many cases satisfactory results can be obtained using a small mirror attached to the bar by adhesive, so avoiding the troublesome process of optically polishing part of the surface.

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1 INTRODUCTION

This paper describes a method for establishing the displacement-time profiles of points on the side and end of a long metal bar when a compression wave travels along its length, the wave being induced by striking one end with a steel ball. With this method of impacting two types of wave can be formed. If the bar is struck axially a longitudinal or compression wave is generated. If the impact is off axis a bending or flexural wave will be generated in addition to the compression wave. However, the experimental technique to be described enables the impact point to be adjusted so as to eliminate the flexural wave.

When a plane compression wave travelling along the bar arrives at the end it is reflected as a tension wave. This wave travels back down the bar and is reflected from the far end as a compression wave[1]. Any particle in the bar can move only when subjected to forces due to these waves: at all other times it is stationary. Thus the particles of the bar move in the direction of impact in a series of steps but with the same mean velocity as would be predicted by applying the principle of conservation of momentum to the original impact which caused the first compression wave.

On the surface of the side of the bar the passage of the compression wave causes not only a small movement in the direction of propagation but also a minute transient displacement out of the surface. The work described in this paper is concerned only with the out-of-plane displacements on the side and end of the bar for the initial passage of the wave.

Several optical methods have been employed to study the deformation of the surface of a material subjected to a transient stress. Gottenberg[2] and Robertson and King[3] used double-exposure pulsed holographic interferometry to determine the profile due to a compression wave in a bar. Aprahamian *et al*[4] studied the transient response of a cantilever beam by real-time holographic interferometry. Ordinary interferometry was used by Barker and Hollenbach[5] to measure the surface displacement at a single point on a flat specimen subjected to impulsive loading.

Of the methods mentioned above, double-exposure holography was ruled out due to the lack of a suitable laser. Real time holographic interferometry was found to be unsuitable as there was insufficient light for photography since extremely short exposures are required to freeze the motion of the fringes. In any case the analysis of holographic interferometry records is complicated by the fact that the fringes can be produced not only by the transient out-of-plane displacement but also by the small displacement in the direction of propagation resulting from the passage of the compression wave. So, ordinary (non-holographic) interferometry was used. The part of the bar to be examined was polished optically flat and used as one reflector in a conventional two-beam interferometer; the other reflector was a plane reference mirror. As the wave progressed down the bar it distorted the polished area. A transient fringe pattern representing the distortion in the out-of-plane direction was seen at the output of the interferometer. Barker and Hollenbach[5] used a photo diode and an oscilloscope to record the fringes. However this method gives the magnitude only and not the direction of the surface movement and so high-speed cinephotography was employed here to record the dynamic changes in the fringe pattern.

Two methods are available for recording the moving fringes. Firstly, a substantial area of the polished bar can be illuminated and successive photographs taken with a high-speed framing camera. But, in the work being described, the speed of the fringe movement is high (over 5 km/s) and so short exposures would be required to freeze their motion. This would necessitate a very intense light source. Another disadvantage of this method of recording is in the analysis of the film. When the fringes are large so that only part of one appears in each frame it is almost impossible to determine the position of the centre of the fringe.

In the alternative method only a narrow strip of the polished bar is examined. This strip is imaged onto the slit of a streak camera and the image is swept continuously along the film at a constant speed. As the fringe pattern on the strip changes it is recorded on the film. This second method, which is the one used in this work, has the great advantage that all the available light can be concentrated into the small area of the strip. For if, in the framing method, an area H high by L long is illuminated by a laser beam of total power P, then the illumination is P/LH. But in the streak method the area illuminated is of the same height but of width W. Thus the illumination is greater in the ratio L/W. As W is about a millimetre and L is tens of millimetres, the gain in light is quite considerable. The exposure time for the framing method is the shutter speed. In the streak method it is equal to the slit width at the film plane divided by the streak speed. The longest permissible exposure time depends on the amount of fringe movement that can be tolerated during exposure. As this movement is dependent only on the speed of the fringes the maximum exposure is the same for both methods. However in the streak method the same exposure time can be obtained for different slit widths by suitable choice of streak speed and so by using a speed which is slower than that of the fringe pattern motion the same length of film can be used to record for a longer time and so there is a compression of data which in this work is an additional advantage. As will be shown below this method of photography gives records from which it is extremely simple to obtain data on the magnitude and direction of displacement of the polished surface.

It should, however, be pointed out at once that the streak method is only suitable for certain applications, *ie*, as in this case, when the disturbance traverses a point or line- or in specimens with circular symmetry where the strip to be examined would be a radius. If it is required to find the position on a specimen of a disturbance in the fringe pattern then a framing method would have to be used. A serious disadvantage of using ordinary, in place of holographic, interferometry is the necessity to optically polish part of the specimen; however, as will be shown, it may sometimes be possible to use instead a small plane mirror fixed to the sample.

2 EXPERIMENTAL

Figure 1 shows the equipment set up to examine the side of the bar. The test piece is an L65 aluminium alloy bar, 55 mm square and 1½ m long. The polished section is roughly central, sufficiently distant from the impact end for the compression wave to approximate to a plane wave and far enough from the other end to avoid confusion with the reflected wave. The end of the bar remote from the impact end is also polished. A hardened steel plate is attached to the impact end to avoid denting the bar. The compression wave is induced by striking the plate with a steel ball, which is suspended as a pendulum by two wires from a metal frame. The ball is electromagnetically released so as to ensure repeatability of impact characteristics.

To suit the sensitivity of the high-speed camera an argon ion laser is used; the laser being tuned to a low power line ($\lambda = 502$ nm, Power $\hat{=}$ 30 mW) to avoid accidental overloading of the camera. The output beam from the laser is expanded and collimated in the vertical direction using cylindrical lenses to form a parallel beam about 30 mm high by 1.5 mm wide. This enters a Twyman-Green interferometer in which one of the two mirrors is the polished surface of the bar. The other mirror is adjusted so that, at the output of the interferometer, the vertical bright line is crossed by a few dark fringes (section AA′ in Fig 1). When the surface of the bar is displaced, these fringes move up or down depending on direction of displacement. The effect can be seen at the output of the interferometer when light finger pressure is applied to the polished area of the bar.

The distance moved by the fringes is a direct measure of the out-of-plane displacement. To record the movement of the fringes, the line of light is imaged on the slit of a high-speed streak camera.

A Handland 'Imacon' camera is used as it can be triggered to start recording at the required time with extremely low jitter. When the ball strikes the bar it forms a short circuit which triggers the camera, via a variable delay. The image of the slit is streaked across the film at a constant speed of 1 mm/μs. Fig 2 shows typical records from the camera (the image of the slit is vertical and is swept from left to right). The upper picture is taken from the side of the bar and the lower picture from the end. When the fringes are stationary - *ie* when the surface of the bar is at rest - the records show horizontal black and white lines. When the surface of the bar is displaced due to the passage of the shock wave, the fringes move vertically, causing the dark lines on the film to curve up or down depending on the direction of the displacement.

The recording time of the Imacon camera can be varied from 7 ns to 7 ms by the choice of a suitable plug-in unit. The longest time available to the author was 70 μs. This is insufficient time to record the whole of the wave at once, and so in practice a curve is obtained from at least six runs, each with a different delay to the camera trigger so that there is sufficient overlap between records to couple them together.

On the records obtained the distance in the direction of sweep between adjacent fringes is proportional to the time taken for the surface of the bar to move one fringe, *ie* one half wavelength of the light used. As the sweep speed is 1 mm/μs, time intervals can be read directly from the photographs using a metric ruler. Also one fringe movement represents a displacement of 251 nm (for convenience 250 nm was used which is well inside the limit of accuracy) and so a graph of displacement against time can be plotted directly from the records without the need for intermediate calculations.

3 RESULTS

3.1 The side of the bar

Initial results shows that in addition to the compression wave there was a flexural (or bending) wave present, the magnitude of which could be altered by changing the position of the point of impact of the ball on the end of the bar. A series of recordings was made with this point at different distances on either side of centre. Fig 3 shows the results obtained. The different curves demonstrate the effect of moving (by steps of 2mm) the impact point between runs. The first peak is due to the compression wave. The secondary effects at about 370 μs are due to the flexural wave which travels down the bar at a slower speed than the compression wave.

To eliminate the effect of the flexural wave, a position for the point of impact was chosen such that a displacement-time graph was obtained with no secondary effects and a level section at the end. Fig 4 shows the result. The surface of the bar returns to zero after 400 μs. The negative excursion of the graph after 450 μs is due to the reflected wave.

It could be seen on the recording that the fringes move up and down as a whole indicating that the bar distorts uniformly across the observed section.

A strain gauge was attached to the bar close to the middle to measure strain in the direction of propagation of the wave. Records were taken of the passage of the compression wave when the end of the bar was struck centrally. If the strain-time curve obtained from these records is normalised to have the same peak amplitude as the displacement-time curve, the two follow each other almost exactly. This is to be expected as the displacement measured photographically is due to strain at right angles to the direction of propagation of the compression wave. This strain is related to that measured by the gauge by Poisson's ratio. The peak strain measured by the gauge is 118×10^{-6}. That measured optically is 43.9×10^{-6} which gives a Poisson's ratio of 0.371, which is about 10% high[6].

If the bar is struck off-centre the strain gauge records show very little secondary effects, indicating that the second peaks seen in the optical readings are due, not to a compression wave, but to a whole body movement of the bar. This movement is caused by the flexural wave which produces very much less surface strain than that produced by the compression wave.

3.2 The end of the bar

Fig 5 shows the results obtained for the end of the bar. The surface is stationary until 300 μs after impact. In the next 300 μs the end moves 49 μm in the direction of propagation of the wave. After 600 μs the polished end of the bar is again stationary and, had the curve been extended, does not move again until 900 μs after impact, this being the time when the wave returns after being reflected from the other end of the bar.

As stated in the introduction, the mean velocity of the bar is predicted by classical mechanics. This can easily be verified. The distance the ball swings before and rebounds after impact can be measured and thus the velocity of impact and rebound can be calculated. Knowing the weight of the ball and the bar and using the principle of conservation of momentum the velocity of the bar can be calculated. This was found to be 84 mm/s. The curve in Fig 5 shows that the bar moves 49 μm every 600 μs, which gives a mean velocity of 82 mm/s.

3.3 Accuracy

The accuracy of timing is affected by a number of factors. The linearity and calibration of the camera was such that the records could be read directly with a maximum error of 1 μs. The delay between impact and application of trigger pulse was recorded on an oscilloscope and could be read to 1 μs. The delay between application of trigger pulse and starting of camera is less than ½ μs. There was no way of checking the jitter when the short circuit was formed on impact, but judging by the repeatability of the curves it is probably small, < ½ μs. From the records for the side of the bar the centre of a fringe could be read to within 1 mm ≡ 1 μs. Thus the maximum possible error in timing is about 5 μs. For the end of the bar the fringes are smaller and can be located to better than ½ mm on the film, so the maximum total error is about 4 μs.

For the side of the bar the displacement can be read to the nearest quarter of a fringe so the accuracy is $\pm \frac{1}{8}$ fringe, or ± 30 nm. On the records for the end of the bar the fringes are so close together that when coupling records it is possible to lose or gain a couple of fringes. Fig 5 was produced from six records, so the maximum error is probably ten fringes which gives an accuracy of 5%.

4 OTHER WORK

As already stated, a disadvantage of the method is the necessity for polishing the specimen. As an experiment a flat strip of front silvered mirror was glued (with 'Certo-fix') to the bar and used instead of the polished surfaces. The displacement-time curves obtained when the end of the bar was struck centrally are identical to Figs 4 and 5. No attempt was made to repeat the tests with an off-centre point of impact but as the indications are that the mirror moves with the surface, the results should be identical with Fig 3. Thus this technique could be applied to unpolished bars.

5 APPLICATION

One proposed application of this work is for calibrating special transducers used in stress wave emission studies. The recorded output of a transducer attached to the bar will be compared with the displacement-time curve obtained from the high-speed camera records.

6 CONCLUSIONS

The combination of a streak camera and a two beam interferometer has made possible a method from which it is extremely simple to obtain data on the displacement-time history of the side and end of a metal bar through which a stress wave is travelling.

It has also been shown that the major disadvantage of this method, the necessity for optically polishing part of the specimen, can be overcome in some cases by the use of a small plane mirror fixed to the sample.

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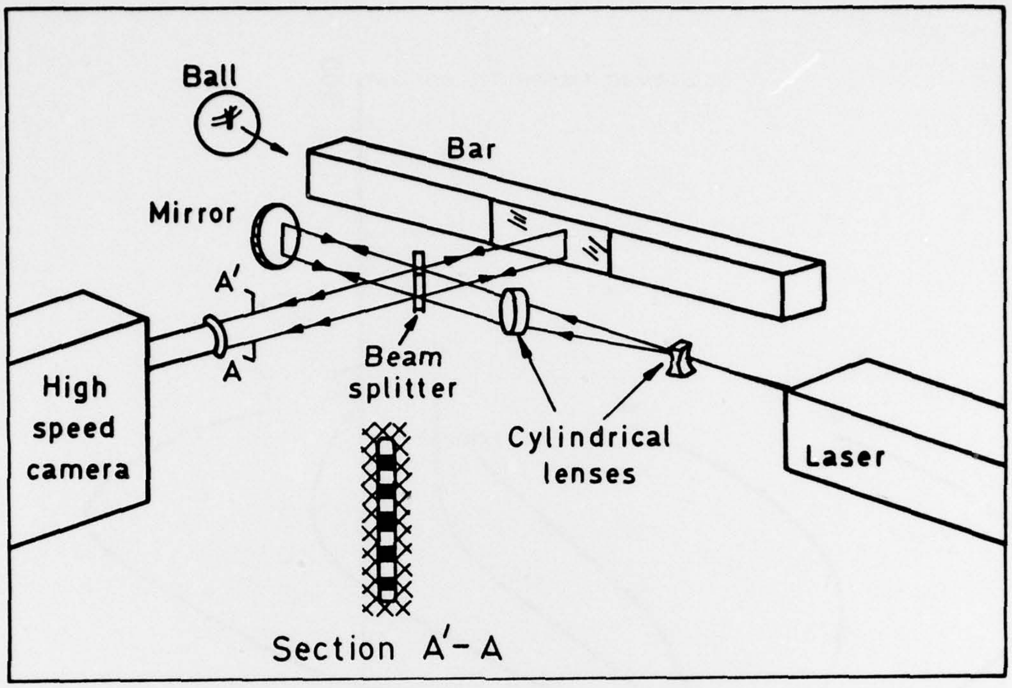

Fig 1 Experimental arrangement

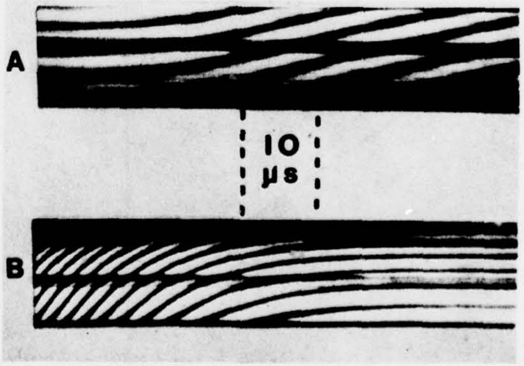

Fig 2 Records from high speed camera for A. the side and B. the end of the bar

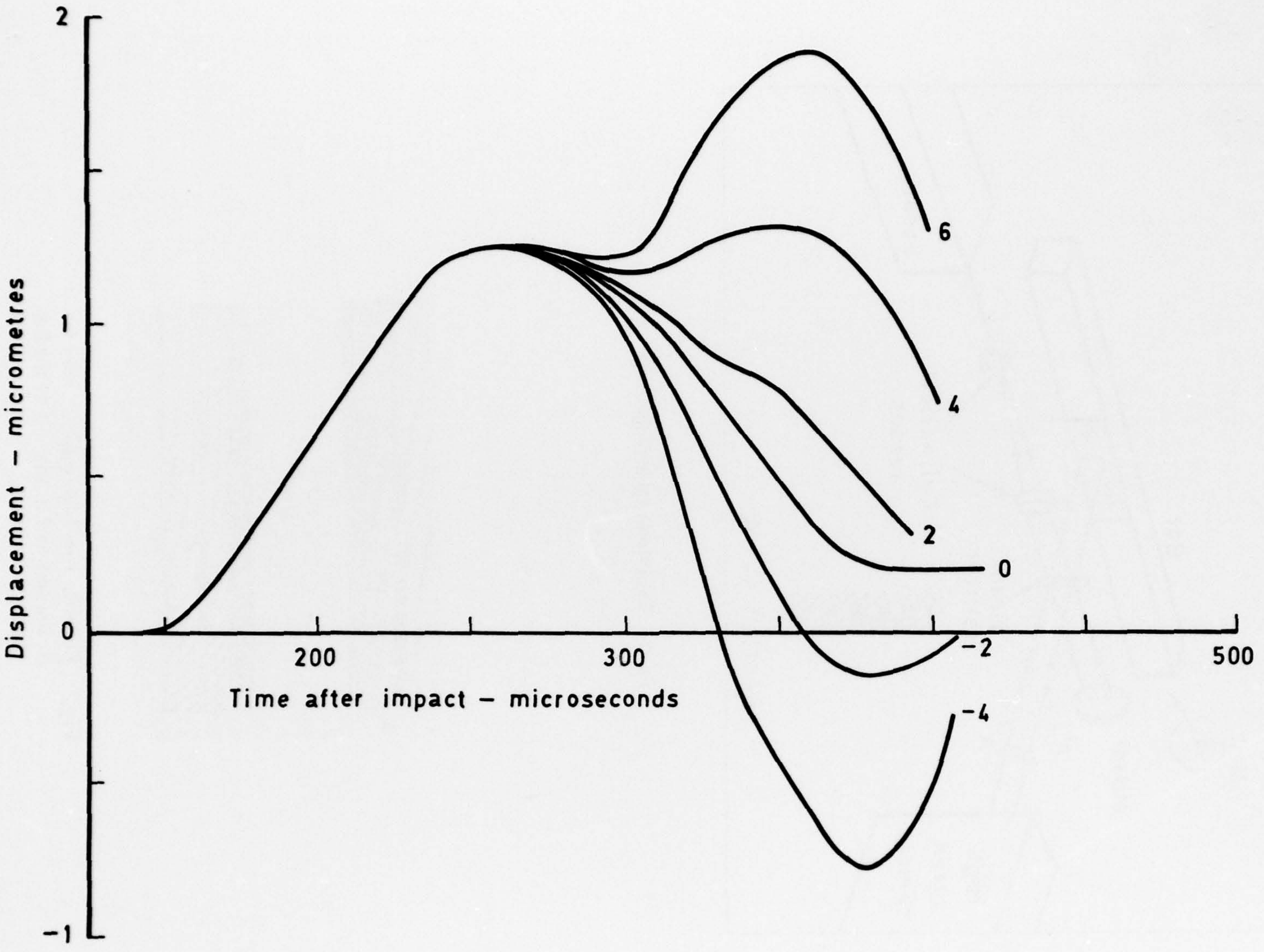

Fig 3 Displacement-time curves for a point on the side of a bar struck at one end, the point of impact being moved 2 mm through the centre between each run

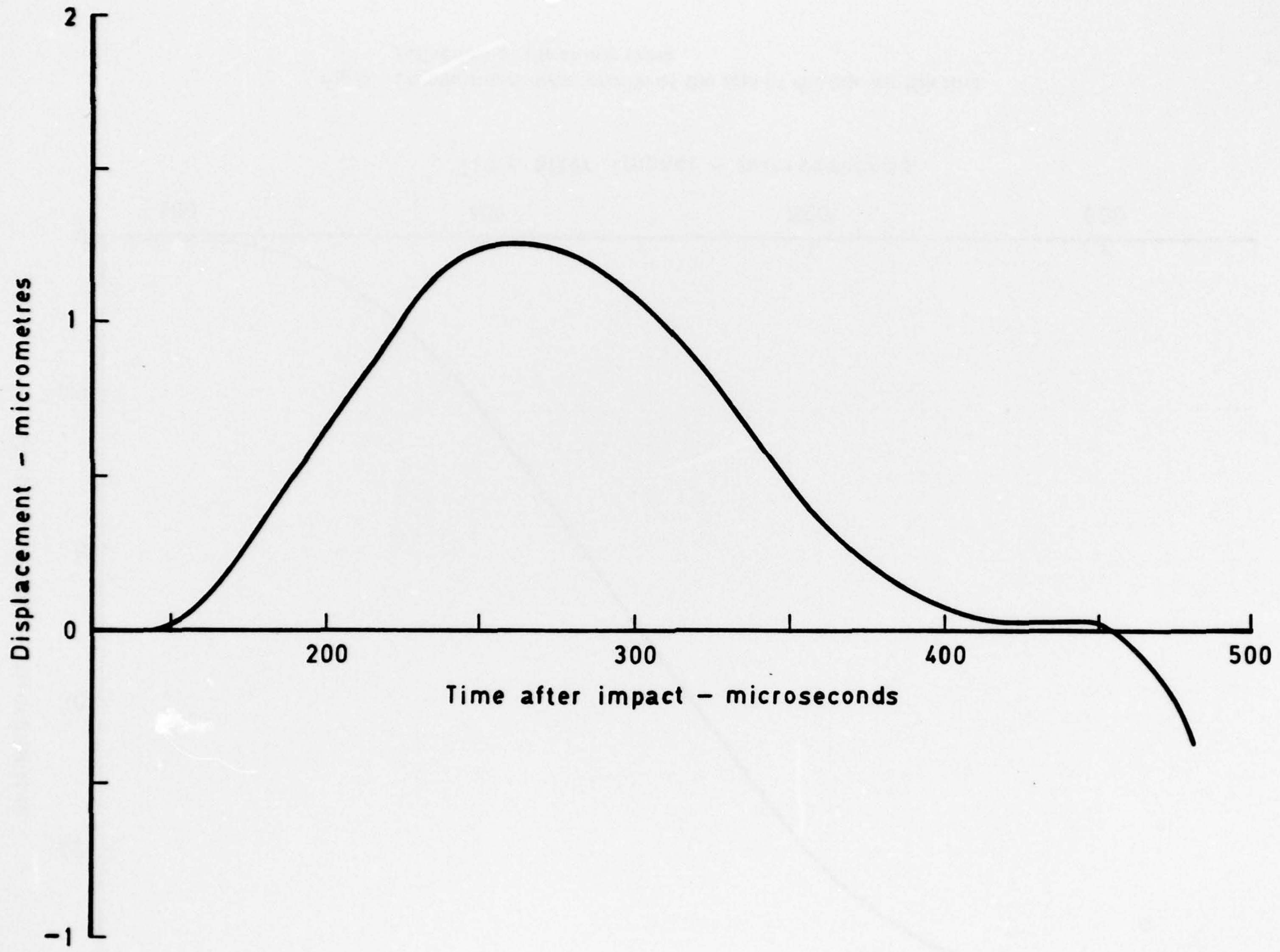

Fig 4 Out-of-plane displacement for a point on the side of a bar (impact central on one end)

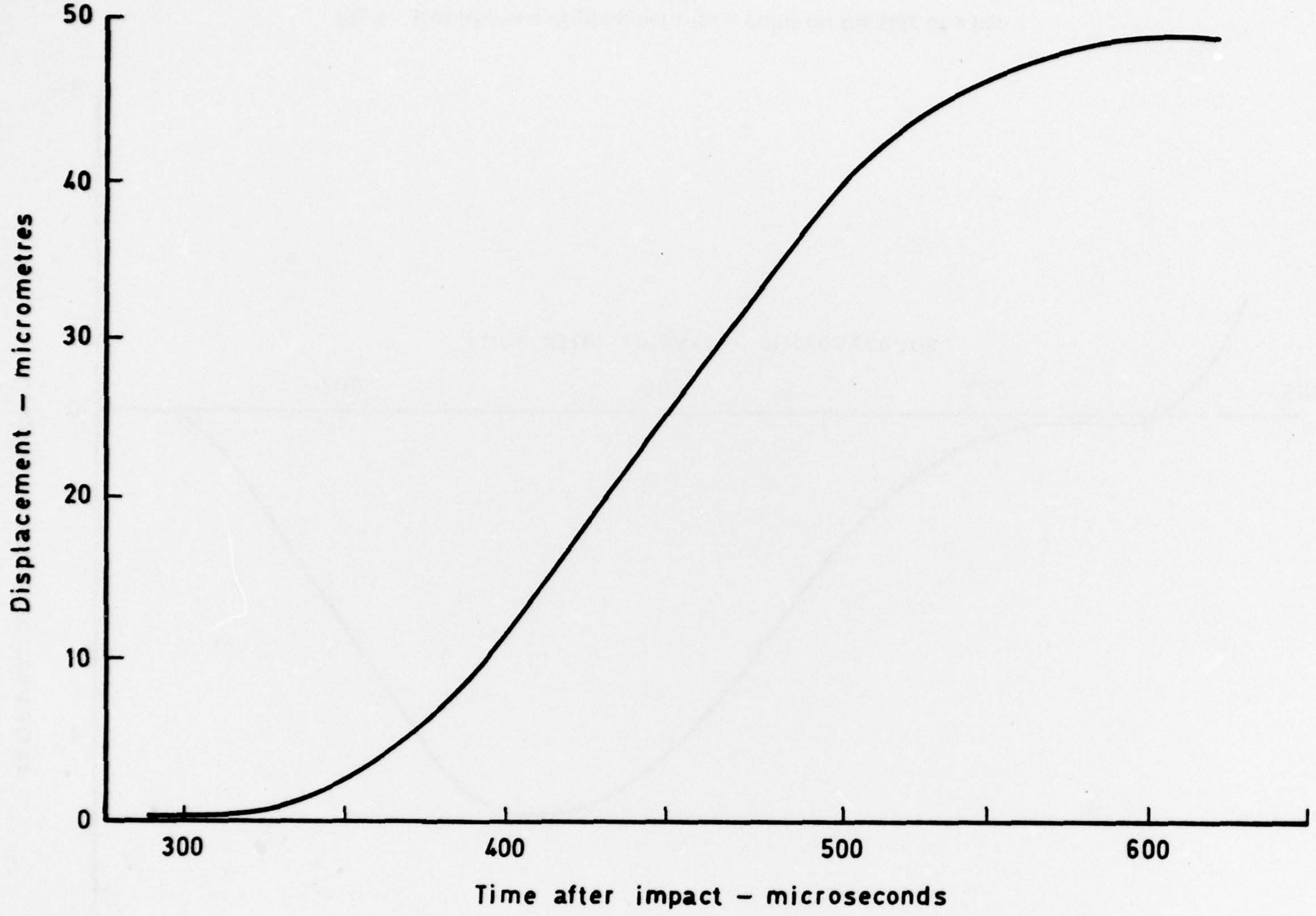

Fig 5 Displacement-time profile of the end of the bar for the first reflection of the shock wave