A second common source of instability is a cusp in the Hugoniot curve such as is illustrated in fig. 2.2c. This often occurs at the point defining the onset of plastic flow or structural phase transformation of the material. Waves of amplitudes falling below the cusp are analyzed as in the previous case. Supposing the low-pressure region to be one of stable shocks, waves of intermediate amplitude corresponding to point P separate into two shocks as indicated in fig. 2.2d. One shock takes the material from the initial state to that corresponding to the cusp. Its speed is that given by the slope of the Rayleigh line $\mathscr{R}_0$. The second shock takes the material from the state at the cusp to that at point P, and propagates at the lower speed corresponding to $\mathscr{R}_P$. Stronger shocks, those of amplitude greater than that corresponding to the overdrive point (OD) where the extension of $\mathscr{R}_0$ meets the Hugoniot curve, are stable. Hugoniot curves can exhibit a variety of slopes, curvatures, discontinuities, etc., that permit various combinations of the behavior discussed above.

The shock stability problem has many facets and has been the subject of a number of investigations (see, e.g., Nunziato and Herrmann [72N2], Swan and Fowles [75S4, 75F2], and Pleshanov [76P1]).

2.3. Experimental methods

The properties of shock-compressed solids became amenable to serious scientific investigation when methods were devised for producing plane shocks of controlled amplitude and for measuring the motions they induced in material samples. Workers in this field are greatly concerned with experimental methods and interpretation of even the most routine measurement involves consideration of the limitations imposed by the method used. Misinterpretations, errors in interpretation, and differences in interpretation often rest on different assessments of the influence of experimental method.

In spite of the major role played by experimental method, no comprehensive critical review is available and one must resort to separate reviews of specific aspects of the subject. The reviews of Graham and Asay [78G5], Grady [77G2], and Murri et al. [74M3] provide critical assessments of modern methods of observing stress or particle-velocity histories. McQueen et al. [70M1] describe the methods they employ in their hydrodynamic measurements. The reviews by Fowles [73F2] and Keeler [71K1] give overall treatments of both loading methods and methods of measuring wave profiles.

Loading methods influence the control that can be achieved over the increments of pressure that can be applied, the simultaneity of the loading over the sample face, and the decompression process. The methods most frequently used include detonation of contacting explosives, impact by explosively-driven flying plates, and impact by gun-driven projectiles. Intense pulses of radiation from electron beam accelerators, lasers, and X-ray and neutron sources have also been used.

Detection methods have evolved from measurement of displacement as either a discrete or continuous function of time to direct measurement of particle velocity or stress histories. With this change, a one-hundredfold improvement in the time resolution with which these histories can be measured has been achieved. Resolutions of particle velocity histories to within a few nanoseconds are not uncommonly reported and subnanosecond resolution has been achieved under restrictive conditions [78G5]. Recent improvements in electrical shorting pins provide the capability for subnanosecond time-of-arrival measurements [79M1].

Measurement of the (U, u) *Hugoniot curve.* The most basic aspect of the study of shock compression of materials is the measurement of a Hugoniot curve. In the high-pressure regime, this involves measurement of the shock velocity U and the particle velocity jump $[u]$ at the shock transition.

There are three methods by means of which most data have been obtained: (1) the plate-impact or deceleration method, (2) the (stress-) free-surface velocity method, and (3) the impedance-mismatch or reflection method. An indication of the principles of each of these methods is given in fig. 2.3. The symmetric plate-impact method, that in which the impacting plate and the sample are of the same material, is the most basic and direct method, but the impedance-mismatch experiment is the most easily conducted and, therefore, the basis for most of the available data. The free-surface velocity method is restricted to compressions at which only moderate shock heating is encountered, but has been used extensively in this regime. These methods have been listed approximately in increasing order of the amount of material-property information that is needed either prior to interpreting a given experiment or that must be determined by iterative calculation during the interpretation process.

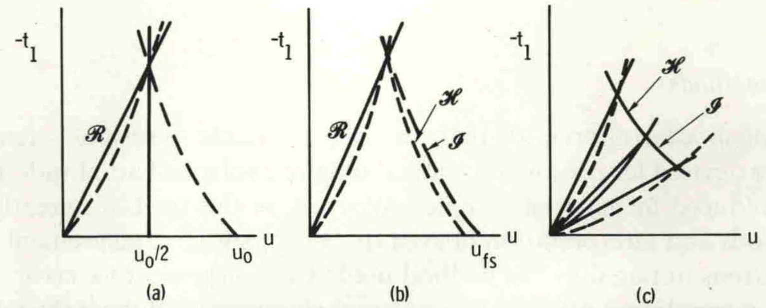

Fig. 2.3. Experimental methods of measuring Hugoniot curves are usually based on interpreting the wave interactions illustrated. In each case the solid lines represent known material properties or Rayleigh lines inferred from a measurement of the shock velocity U. The Hugoniot curve of the substance under investigation is shown dashed. The diagram (a) represents a symmetric impact in which the measured impact velocity u_0 is exactly twice the induced particle velocity. Measurement of u_0 and U suffices to determine the Hugoniot state. When the impactor is of a different material from the sample, but one having a known Hugoniot curve, measurement of u_0 and U also suffices to determine a Hugoniot state. Experiment (b) is interpreted on the basis of the approximation that the decompression isentrope ($\mathscr{I}$) differs little from the reflected Hugoniot curve ($\mathscr{H}$) so that measurement of U and the velocity, u_{fs}, of the free surface after shock reflection suffices to determine a Hugoniot state. Two cases of the impedance-mismatch experiment are shown in part (c) of the figure. The Rayleigh line and Hugoniot curve in the middle of the figure represent the known behavior of the standard base plate and the measurement of U in this base plate. When the advancing shock encounters the interface with the sample material, a shock is transmitted to the sample and either a second shock or an isentropic decompression wave is reflected back into the base plate. The Rayleigh line for the shock in the sample, as determined by measuring the velocity of this shock, can be plotted to establish the type of the reflected wave. With this information, the second-shock Hugoniot curve ($\mathscr{H}$) or the decompression isentrope ($\mathscr{I}$) plotted using the known behavior of the base plate material completes the determination of a point on the Hugoniot curve for the sample.

The Hugoniot curves and decompression isentropes of a number of materials ("*standards*") have been determined with the highest possible precision so they can be used as base plates in the determination of Hugoniot curves for other materials by the reflection method. The wave interactions encountered in these experiments have been discussed by Duvall [71D2] and others.

The actual conduct of experiments of the sort discussed above is time consuming and expensive and must be done with exacting attention to both design and execution if useful data are to be obtained. The methods by means of which these measurements are made in various laboratories will not be discussed in this review, as they have been reported elsewhere [65A2, 66J1, 70M1, 71K1, 75G2]. Measurement of electrical, magnetic, optical, and other properties involves special considerations discussed in subsequent sections of this review.