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"N Waves" from Bursting Balloons

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When a round balloon is burst "perfectly," the resulting acoustic disturbance should have the shape of the letter N. In the experiments reported here, the N wave is received by a baffled microphone, whose frequency-response characteristic is flat to about 80 kHz. The oscillogram of the microphone output is then photographed. The waveforms obtained show deviations from the idealized N shape, which are attributed to loss of spherical symmetry. Important factors determining the departure from spherical symmetry are the type of balloon and the method of bursting. By paying careful attention to experimental technique and photographing the waveforms from many balloons, it is possible to obtain good approximations of the N shape.

INTRODUCTION

When an initial spherical, uniform, static-pressure distribution is released, the acoustic disturbance that results has the shape of the letter N. The N shape (see Fig. 1) is predicted from the linear acoustic-wave equation with the appropriate boundary conditions.[1] A frequently given example of an N-wave source is a bursting round balloon.

Experience shows that balloons are actually not ideal sources of spherical N waves. There are two reasons. First, "round" ballons are rarely spherical in shape; more often they are pear shaped. Second, it is difficult to burst the balloon so that the skin gives way everywhere at once. The balloon usually tears into a few large fragments.[2] For these reasons, Watters' previous measurements of the sound from a bursting balloon showed only rough agreement with the idealized theoretical prediction.[2] By carefully controlling experimental conditions we have been able to record much-improved N waveforms.

I. APPARATUS AND METHOD

Figure 2 shows a block diagram of our instrumentation. The balloon is positioned in a reflection-free space[3] by a thin wire line. A 1-in. condenser microphone (B&K,[4] type 4132), located about 3 ft from the balloon center, triggers the oscilloscope (Tektronix, type 545B). The $\frac{1}{4}$-in microphone (B&K, type 4136), whose frequency response is flat to about 80 kHz, is used to measure the pressure waveform. This microphone is placed about 4 ft from the balloon center. At this distance the spherical wave from the balloon appears to the $\frac{1}{4}$-in. microphone to be a plane wave. A microphone amplifier (B&K, type 2604) and a microphone power supply (B&K, type 2801) are included in the system.

To avoid diffraction effects, the $\frac{1}{4}$-in. microphone is mounted in the center of a rigid baffle. The baffle consists of a 3-ft×3-ft by $\frac{1}{16}$-in. section of sheet metal bonded to a 4-ft×4-ft by $\frac{3}{4}$-in. slab of chip board. The face of the microphone is flush with the outer surface of the metal. Diffraction at the edge of the baffle produces reflections which reach the microphone after a 1.35-msec delay. The size of the baffle must be large enough that the tail of the incident wave reaches the measuring microphone before the first reflection arrives from the edge of the baffle. Pressure doubling occurs at the microphone, since the microphone–baffle combination acts as an infinite rigid surface during reception of the incident wave.

We tried several methods of bursting the balloon. The best method is to fill the balloon with

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[1] For example, see H. Lamb, *Dynamical Theory of Sound* (Dover Publications, Inc., New York, 1960), 2nd ed. pp. 211–213.

[2] B. G. Watters, Sound **2**, 8 (1963).

[3] Actually, it is only necessary that reflections from nearby objects do not reach the recording microphone until after the N wave has been received.

[4] B & K Instruments, Cleveland, Ohio.

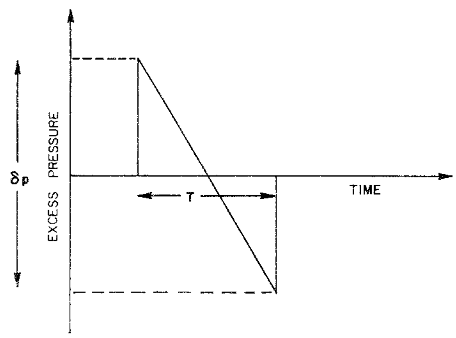

FIG. 1. Idealized N wave.

air until it ruptures spontaneously. Another method is to fill the balloon with air, seal it off just before the breaking point, and puncture it with a lighted cigarette or pin. This method always leaves three or four large pieces of rubber. Spontaneous rupture, on the other hand, tears the balloon into many small shreds, indicating a more complete disintegration of the skin. The spontaneous-rupture method thus results in a closer approximation of a pressure distribution which, at time $t=0$, is released at all points.

One problem with the spontaneous-rupture method is that the air hose must remain attached to the balloon. When rupture occurs, the pressure in the hose is released, causing distortion of the N wave. To minimize this distortion, the air hose is constricted close to the balloon so that during rupture the mass flow out of the air hose is very small.

II. RESULTS

Figure 3(a) shows two waveforms recorded simultaneously from one balloon burst. The top trace was obtained from an unbaffled $\frac{1}{4}$-in. microphone and the bottom trace from a baffled $\frac{1}{4}$-in. microphone. The unbaffled microphone was mounted as close to the axis of the baffled microphone as possible so that the sound received by each would be approximately the same. Although a sharp initial rise occurs on each trace, the waveform from the unbaffled microphone exhibits large oscillations which are quickly damped out. Use of the baffle delays these undesirable diffraction effects until after the incident N wave has been received. The baffled microphone was used for all the measurements reported below.

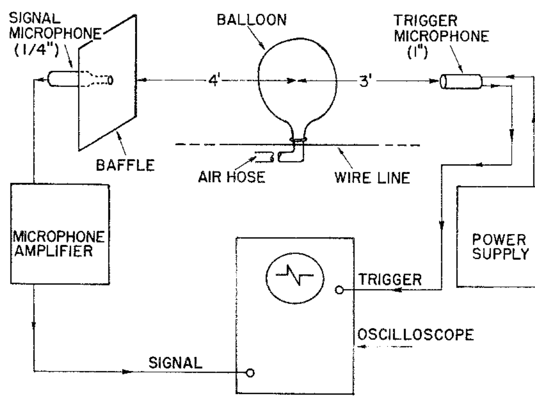

FIG. 2. Block diagram of instrumentation.

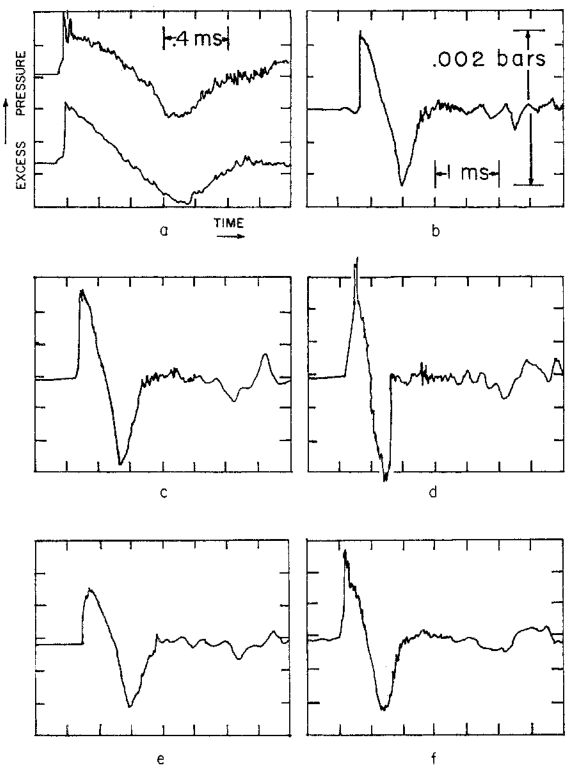

FIG. 3. In (b)–(f) the sweep rate (0.5 msec/cm) and sensitivity (0.2 V/cm) are the same and the microphone is baffled: (a) comparison between output from an unbaffled microphone (top) and output from a baffled microphone (bottom), for one balloon burst; (b) and (c) waveforms with sharp leading edges; (d) waveform with a sharp trailing edge; (e) and (f) typical waveforms.

Acoustic waveforms from bursting balloons are influenced by the brand and shape of the balloons. Truly round, 8–12-in. balloons would probably work best, but we could find no such balloons on the local market. "Playmate" brand,[5] 8–12-in. pear-shaped balloons gave the best results of those tested. Larger (greater than 16 in.) and smaller (4–6 in.) balloons gave generally poor results.

Balloons with printing on them apparently disintegrated unevenly. After rupture, the largest piece of rubber usually had most of the printing on it. Balloons with no printing consistently ruptured into small pieces of rubber. For some reason, the color of the ballons was also an important factor. We found that red and orange balloons yielded the best N waves.

The theoretical prediction for the period T of the N wave is[1]

$$T = d/c, \tag{1}$$

where d is the balloon diameter, and c is the speed of sound in air. The diameter of our balloons at the time of rupture was 9.0 ± 0.5 in., from which we calculate a period of 0.68 ± 0.04 msec. Figure 3(b) shows an N wave with a period of 0.70 ± 0.05 msec. Within the experimental error, then, the measured period agrees quite nicely with the theoretical prediction. Watters did not obtain such close agreement.[2]

Because the head and tail of an ideal N wave are really shock fronts, traveling at speeds slightly different from c, we expect the measured period of the N wave to be about 0.04 msec larger than the period given by Eq. (1).[6] Since 0.04 msec is less than our measurement error, we neglect this increase.

For the balloon of Fig. 3(b) the peak-to-peak pressure δp at the observation point r was 0.0018 ± 0.0001 bar,[7] which implies a sound pressure level of about 128 dB (re. 0.0002 μbar). According to linear theory, the peak-to-peak pressure at $r = r_0$ is

$$\delta p_0 = (r/r_0)\,\delta p, \tag{2}$$

where r_0 is the balloon's mean radius and δp_0 is the peak-to-peak pressure at r_0. With $r = 48$ in. and $r_0 = 4.5$ in., we find that δp_0 is 0.019 ± 0.001 bar. Hence the excess static pressure inside the balloon just before bursting was about 1/50 atm.

The sharp rise time of the waveforms in Figs. 3(b) and 3(c) gives an indication of the system's response, which is limited by the response of the $\frac{1}{4}$-in. microphone. The frequency characteristic of the B&K $\frac{1}{4}$-in. microphone is flat within 1 dB from 20 Hz to about 80 kHz. Because the most important maximum in the frequency spectrum of our N waves is at 1 kHz, this response is adequate to record the fast rise times of our waveforms.

The measured waveforms shown in Figs. 3(b)–(f) deviate slightly from the theoretically predicted N shape. In Fig. 3(b), the middle portion of the N is concave down and the trailing edge does not rise sharply. Figure 3(d) shows a waveform with a sharp trailing edge and a poorly defined leading edge. The most common waveform has neither a sharp leading edge nor a sharp trailing edge [see Figs. 3(e) and 3(f)].

The major cause of these deviations appears to be the manner in which the pressure distribution is released. The balloon initially tears from an arbitrary point on the skin instead of disintegrating at all points simultaneously. The initial tear propagates around the balloon until disintegration is complete. Because of the finite time required for rupture, loss of spherical symmetry results. Therefore, one would expect asymmetric waveforms like those in Fig. 3.

The sharpness of the leading and trailing edges of the N is probably determined by the place of origin of the initial rupture. If rupture starts on the side of the balloon facing away from the microphone, the waveform will have a sharp trailing edge and a distorted leading edge. In order to see this more clearly, imagine that the rip has just started to propagate around the balloon. The pressure discontinuity at the back of the balloon is free to propagate, while that at the front is still being held by the balloon's skin. By the time the rip travels around the balloon to the front, pressure discontinuities already released will, if the tearing takes place slowly enough, precede the predicted pressure front and destroy the sharp rise time of the leading edge. However, the pressure discontinuity originating from the back of the

[5] The balloons were made by the Eagle Rubber Co., Ashland, Ohio.

[6] For example, see D. T. Blackstock, J. Acoust. Soc. Am. **36**, 1032(A) (1964); also D. T. Blackstock, J. L. McKittrick, and W. M. Wright, Am. J. Phys. **35**, 679(A) (1967).

[7] Because of pressure doubling, the peak-to-peak pressure actually received by the microphone was 0.0036 ± 0.0002 bar.

balloon propagates as predicted, resulting in a sharp trailing edge. If the conditions of initial rupture are reversed and the tear starts on the side of the balloon facing the microphone, one can easily see that the front of the N wave will be sharp. But as before, the pressure discontinuity on the other side of the balloon (this time the back) will be held until the rip propagates completely around, and the trailing edge will be distorted. Most initial ruptures, of course, occur neither at the front of the balloon nor at the back, but at random points over the skin. Therefore most of the waveforms photographed have neither a sharp leading edge nor a sharp trailing edge; many balloons must be exploded before a waveform with a sharp leading or trailing edge is photographed. For example, Fig. 3(b) shows the "best" waveform from a set of 10 photographs.

In conclusion we have demonstrated that although the waveforms vary from balloon to balloon, good N waves such as those of Fig. 3(b)–(f) can be obtained if careful attention is given to experimental procedure.

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