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SHATTERING GOBLETS WITH AMPLIFIED SINGING

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ABSTRACT

According to legend, Caruso was able to shatter a goblet with his voice. With the aid of reinforcement, this feat has now been duplicated for television commercials. Experiments and techniques will be described. Filmed and live demonstrations will be presented. Based on our data, it appears conceivable that Caruso may actually have been able to shatter a goblet with his unaided voice.

INTRODUCTION

In July of 1970, we received a telephone call from the Leo Burnett Company, an advertising agency, inquiring whether we thought it might be possible to cause a goblet to shatter by exposing it to direct or amplified singing. We were informed that this was proposed for a television commercial.

Our immediate response was to suggest a BB gun off camera. We were told, however, that it had to be a genuine demonstration. The idea was to show a goblet being shattered by a singer, while the singer was simultaneously being recorded on a Memorex cassette. The recording would then be played back to show that it could shatter a second matched goblet.

We ventured the opinion that this might be possible, and suggested a feasibility study. Thus, the project was born.

HISTORY

The story is prevalent that Enrico Caruso could shatter a goblet by singing the proper note at it. The writer remembers first hearing this story as a teenager. The article on sound in the 1958 edition of the World Book Encyclopedia contains a drawing of Caruso performing this feat.

Nevertheless, none of the half-dozen or so acoustical consultants we talked to could verify the story, and some expressed doubt that the feat could be accomplished by any unamplified voice, unless the goblet were so fragile that it could not withstand normal handling.

The attempt to pin down the truth or falsehood of the Caruso legend was not carried beyond this, but the logical next step would have been to consult historians of opera.

There was no question, however, about the possibility of breaking glass by sound, if the sound is intense enough. Supersonic airplanes and space rockets have demonstrated this amply, to the consternation of homeowners. Clay Allen, of our Cambridge office, has shattered glass funnels at a sound level of approximately 165 dB. (For reference, the threshold of pain is approximately 140 dB; 165 dB represents an intensity 300 times greater.) He has also devised, for a major company manufacturing light bulbs, a process for sonically shattering bulbs with defective glass envelopes as the bulbs come off the production line. The purpose of this process is to test the bulbs and eliminate the defective ones automatically. We have even heard reports that church windows have inadvertently been broken by very loud organ playing.

At the end of July, investigation by Dr. Eric Daniel of Memorex disclosed that in 1960 the Corning Glass Works manufactured and experimented with some special goblets designed to be easily shattered by sound, apparently for use in a motion picture. We learned that these goblets were quite large (bowl 6 1/4" diameter and 8" high), with thin walls (.032" to .036") and a "bucket" (straight-sided) shape. They were made of leaded glass with a lead oxide content of 20% or greater. A glass rod .030" to .040" in diameter was wrapped around the outside about V below the rim and sealed to the goblet (presumably by heating) to form a bead. The purpose of this bead was to concentrate the stress induced by vibration of the goblet, to make it shatter more easily. In addition, the bead and outside surface of the goblet were abraded by carborundum grit to increase the fragility.

The goblets were shattered by singing the proper note into a microphone attached to a 25-50 watt amplifier and loudspeaker. No details of the loudspeaker used were available.

We did not pursue this approach further, because it was decided by our client that the goblets to be used in the commercial should be "off-the-shelf" units purchased at a regular retail outlet, if at all possible.

GOBLETS

Several department stores selling fine glassware were visited. We looked at hundreds of glasses of various configurations and sizes, and rang dozens by snapping a fingernail against them. The principal characteristics we were looking for were thinness and a high-Q resonance (a clear ring with a long duration). It was quickly found that the goblet shape seemed to give the best ring; the tumblers we tried had a much lower Q. Among the goblets, the medium and large ones with relatively thin walls were better than the smaller wine glasses and the thicker-walled goblets. Also, those with sides that were nearly vertical near the rim generally, but not always, rang better than those with inward-sloping walls at the rim. It may be that goblets with very thin walls that are vertical at the rim are not widely manufactured because they are too fragile.

Eight or nine different kinds of goblets were finally purchased. Bowl diameters ranged between 2-7/8" and 6-5/8", wall thicknesses between 0.024" and 0.050", ring frequencies between 330 and 1540 Hz, and prices between $1.25 and $12.50. Most had relatively straight sides with rounded bottoms; two had more spherical shapes with inward-curving rims, and one was funnel-shaped. Two had designs cut into the sides that we felt might increase the fragility.

INITIAL EXPERIMENTS

In our laboratory, initial experiments were conducted using a heavy-duty 6" x 9" loudspeaker in a closed-box enclosure, driven by a 50-watt amplifier. The signal was a pure tone of variable frequency provided by a sine-wave oscillator. The goblet under test was set on the laboratory bench immediately in front of the loudspeaker. Sometimes the goblet was held by the foot and moved slowly through various orientations and positions in the vicinity of the loudspeaker.

In these initial experiments, two methods were used to tune the oscillator to the goblet ring frequency. In the first method, the oscillator tone was played softly while the goblet was snapped by the fingernail. The goblet ringing produced audible beats with the oscillator tone, and the latter was tuned to reduce the beat rate to as close to zero as possible. The second method was to play the oscillator tone as loudly as possible while holding the goblet by the stem, and tune the oscillator for maximum feelable vibration of the stem.

Each of three different goblets used in the first experiments was subjected to the maximum output of the sound source at the ring frequency. The frequency and output were held constant while the goblet was moved about in front of the loudspeaker. The sound pressure level in the vicinity of the goblet was measured with a sound level meter and was found to be approximately 122 dB. None of the goblets broke, although their vibration was very evident.

Although a goblet when struck rings predominantly at one particular pitch or frequency, any such object has many resonantfrequencies. Thus, it was conceivable that a goblet might break more easily at some frequency other than the most obvious ring frequency. Consequently, in addition to the foregoing test at the ring frequency, each goblet was subjected to the full audio range by slowly sweeping the oscillator from 20 Hz to 20,000 Hz. No breakage resulted.

We then substituted a medium-sized horn loudspeaker for the 6" x 9" cone loudspeaker and repeated the tests. The higher efficiency of this loudspeaker enabled us to reach sound levels of approximately 132 dB at the ring frequencies of the smaller goblets. Again none of the goblets broke.

Early in the project, two professional singers were brought to our laboratory for experiments. One of these was a male operatic tenor; the other was a female popular singer with a wide range. Tape recordings of their voices were made for later analysis. The analysis showed that in her soprano range, at least, the strongest harmonic of the woman's voice was the fundamental; thus she would have the best chance of shattering a goblet by singing the same note as the goblet's ring frequency. The man's voice, on the other hand, had somewhat greater power in the second harmonic than in the fundamental, so he would be expected to shatter a goblet more easily by singing one octave below the ring frequency.

Both singers attempted to shatter several goblets by singing the proper note with their lips close to the side of the goblet; neither was successful.

The writer and a representative of the Leo Burnett Company also made attempts, with the same lack of results, even though we could generate levels up to about 140 dB at the lips.

We next obtained a large horn loudspeaker. We found that in spite of the relatively high efficiency of this unit, we could not obtain significantly higher sound levels near the mouth because the sound energy was spread out more than with the smaller horn. Consequently, we removed the horn and tried the driver alone. This enabled us to reach somewhat higher sound levels. ,

We tuned the oscillator to the 810 Hz ring frequency of one of the goblets and moved the goblet very slowly toward the driver. As the distance between them decreased from about 1 1/2" to about 3/4", the vibration of the rim of the goblet closest to the driver became so violent that it blurred like an image going out of focus, and the goblet suddenly shattered. The sound level meter was placed where the goblet had been, and gave a reading of 136 dB.

The test was later repeated with other goblets of the same kind, and gave similar results. Other kinds of goblets were also tried, but did not shatter as easily as the first kind. This kind was used in most of the subsequent experiments, and in the commercial. It was manufactured in West Germany. The bowl is 3-3/8" in diameter and 4" high. The wall thickness is approximately 0.035" near the rim, tapering to about 1/4" at the bottom. There is no bead at the rim. The sides are vertical near and at the rim. The overall height of the goblet is 6-1/4", and the foot diameter is 2-7/8". Ring frequencies fall in the range of about 600 to 900 Hz.

BREAKAGE PATTERN

Most goblets broke into relatively few pieces. It was soon discovered that the mode of vibration of the goblet bowls was such as to tend to break them into four approximately equal pieces, much as though they were sliced vertically into quadrants by two knives at right angles to each other. However, since the bowl cannot easily break at the bottom where it is thickest and where the stem is attached, the actual breakage pattern is a little more complicated. Typically, one of the "imaginary knives"

slicing down through the bowl divides into two near the bottom, passing on opposite sides of the stem and leaving a crescent-shaped section attached to the latter. At 90° to this, the other "imaginary knife" at the same time is deflected to one side or the other of the stem but does not divide into two; this "knife" thus slices off one of the two horns of the crescent, leaving the other attached to the stem.

Thus, the fundamental breakage pattern leaves six pieces: the four large, quadrants, a small crescent horn, and the remainder of the crescent attached to the stem (Figure 1).

In most cases, at least one of the four quadrants broke further. On rare occasions, the bowl broke into only two pieces.

The general breakage pattern is a logical consequence of the vibration pattern of the goblet at its ring frequency. Vibration is maximum at the rim. If the motion were slowed down, it would look as though invisible fingers at opposite sides of the rim were alternately squeezing and stretching it out of its circular shape. This results in maximum movement (antinodes) at four points on the rim 90° apart, one of which is the point closest to the loudspeaker sound source (Figure 2). The four points midway between these antinodes are nodes and do not move. At a sound level nearly strong enough to shatter the goblet, the blurring of the rim at and near the four antinodes can be clearly seen.

GOBLET MODIFICATIONS

It seemed conceivable that there might be some simple modification of the goblet which, by weakening it or by concentrating the stress, might cause it to shatter at a substantially lower sound level.

We tried nicking the rim of a goblet with a file at four points spaced 90° apart. This did not have a significant effect (the goblet did not break at a sound level of approximately 130 dB). With a glass cutter, we made four vertical scratches down the sides of the goblet, beginning at the nicks. The goblet did break at a sound level a few dB lower than the undoctored goblets, but it broke into only two pieces.

We glued brass nuts to opposite sides of the rim of a goblet, but this had no apparent effect other than to produce a double ring (two notes) when the goblet was struck.

We filled one goblet with enough water to lower its ring frequency slightly. When this was subjected to a high sound level at its ring frequency, the water surface became so agitated that it changed the ring frequency, detuning the goblet and causing the vibration to die down. When the water surface settled down, it brought the goblet back into resonance with the sound source and the vibration built up again. This action repeated itself several times per second, with the water performing an entertaining choreographic display. We are certain that a water-filled goblet would withstand a considerably higher sound level before shattering than an empty one, because of the detuning action of the dancing water surface.

Efforts to weaken the goblets were discontinued at this point, because the client expressed the desire that the goblets to be used in the commercial should not be "doctored" in any way.

FURTHER EXPERIMENTS

Later, we replaced the horn driver with a more efficient unit and replaced the 50-watt amplifier with a 100-watt unit. With this combination we were successful in shattering goblets repeatedly, using the writer's amplified voice as the signal source. The sound level required was found to be 5 to 10 dB higher than when using the sine-wave oscillator. This can be explained partly by the fact that only a fraction of the power of the voice is in the second harmonic that the goblet responds to, and partly by the inability of the voice to hit and maintain the proper pitch with the same precision as the oscillator. (Because of its extremely high Q, the goblet does not shatter the instant the sound is applied; the vibration must build up for a second or more before it becomes intense enough to rupture the glass.)

At this point in the project, at the request of the client, we investigated the possibility of duplicating the experiment with a cone loudspeaker instead of a horn driver. We obtained an efficient 12" cone loudspeaker capable of withstanding a continuous sine-wave power input of 100 watts. We were at first delighted to find that we could generate a level of 152 dB at the face of the loudspeaker, and then disappointed to learn that this would not shatter a goblet, even when the signal source was the oscillator.

A little thought revealed the reason for this seeming contradiction of our earlier results. To cause the goblet to vibrate in the proper way, there must be a differential force acting on its opposite sides. In other words, when the side of the goblet nearest the loudspeaker is moving in one direction, the side away from the loudspeaker must be moving in the opposite direction. If the same force is applied in the same direction to both sides, the goblet may be moved as a whole but the glass is not appreciably bent. The horn driver was successful in shattering goblets because its mouth is small compared to the goblet, so the force acting on the near side was much stronger than that acting on the far side. With the large cone loudspeaker, on the other hand, the sound dispersed so gradually as a function of distance that the sound level at the far edge of the goblet was practically the same as at the near edge.

One way of overcoming this problem might be to use a goblet that is approximately a half wavelength in diameter at its ring frequency; then the sound at the far edge would act in the opposite direction to that at the near edge. Such a goblet, however, would probably have to be fairly thick, making it difficult to break.

The simpler solution is to use a small opening in front of the loudspeaker, thereby causing the sound to disperse rapidly as it leaves the opening. We found that when the loudspeaker was mounted on a baffle with a 2" opening, the same sound level could be achieved at the opening, and goblets could be shattered as easily as with the horn driver.

We also found that for maximum loudspeaker output at the ring frequencies of these goblets, the enclosure volume behind the loudspeaker should be small. Best results were obtained by completely closing the openings in the loudspeaker basket.

FILMING OF THE COMMERCIALS

Three television commercials have been made. The first was with operatic tenor Enrico Di Giuseppi, the second with operatic soprano Nancy Shade, and the third with Ella Fitzgerald.

Prior to each filming, the ring frequencies of several dozen goblets were determined by striking each goblet, picking up the tone with a microphone, and reading the frequency with an electronic frequency counter. The goblets were then grouped in pairs matched within approximately 1 Hz.

For the first part of the commercial, a goblet was set immediately in front of the loudspeaker such that the rim of the goblet was approximately level with the top of the 2" opening in the loudspeaker baffle. The singer was given the proper pitch by means of an oscillator, frequency counter, and monitor loudspeaker. He or she then sang a short musical sequence of notes, ending with the ring frequency (or, in the case of the tenor, an octave below the ring frequency). The sound was picked up by a microphone held by the singer, amplified, and fed to the loudspeaker. A meter across the power amplifier output monitored the voltage delivered to the loudspeaker. The microphone preamplifier output was also fed to a cassette deck and recorded on a Memorex cassette.

After the shattering of the goblet by the amplified live singing had been filmed, the cassette was rewound and the matching goblet was placed in front of the loudspeaker. For the second part of the commercial, the cassette recording was played back through the loudspeaker at the same level as the original live program, and caused the second goblet to shatter. After the filming, the recording was played back once more and a sound level meter was placed where the goblets had been, in order to measure the sound level that had shattered the goblets. In the three commercials, the respective readings were 141, 151, and 148 1/2 dB.

The soundtrack of the singing for the first part of the commercial was taken from the microphone preamplifier. For the second part of the commercial, the soundtrack of the singing was taken from the cassette deck. In the Ella Fitzgerald commercial, there is instrumental accompaniment which was picked up with separate microphones and recorded on a separate synchronized recorder. This was then added later to the commercial soundtrack. Thus, the accompaniment was not reproduced by the loudspeaker and played no role in the goblet shattering.

The sound of goblets shattering was dubbed onto the commercial soundtrack, since the actual shatter sound was relatively weak compared to the loudspeaker level.

As might well be expected, not every trial was successful in breaking a goblet. Sometimes the singer's pitch was very slightly off. Sometimes, especially during the first trials with each singer, there was too much vibrato. Professional singers, it seems, are not used to singing without any vibrato and find it hard and/or distasteful to do. Sometimes the singer was successful in breaking the first goblet but the recording failed to break the second one. When this happened, repeating the trial with the same goblet was almost never successful. The probable reasons for this occasional failure to break the second goblet are a slight difference in ring frequency or a sturdier goblet. We did find that some goblets were harder to break than others. Incidentally, the goblets with ring frequencies above about 850 Hz were extremely difficult or impossible to break. They probably had thicker walls.

FEASIBILITY OF THE CARUSO LEGEND

The human mouth is similar in dimensions to the loudspeaker baffle opening used in the commercials. Some of our goblets shattered with amplified voice levels as low as 141 dB. The writer, who is not a singer, is able to produce a voice level of 140 dB at his lips. When these facts are put together, it is not difficult to believe that Caruso may indeed have shattered one or more goblets with his voice, if he held them very close to his mouth and used the right goblets. If any reader can document the legend, the writer would appreciate hearing about it.

ACKNOWLEDGEMENT

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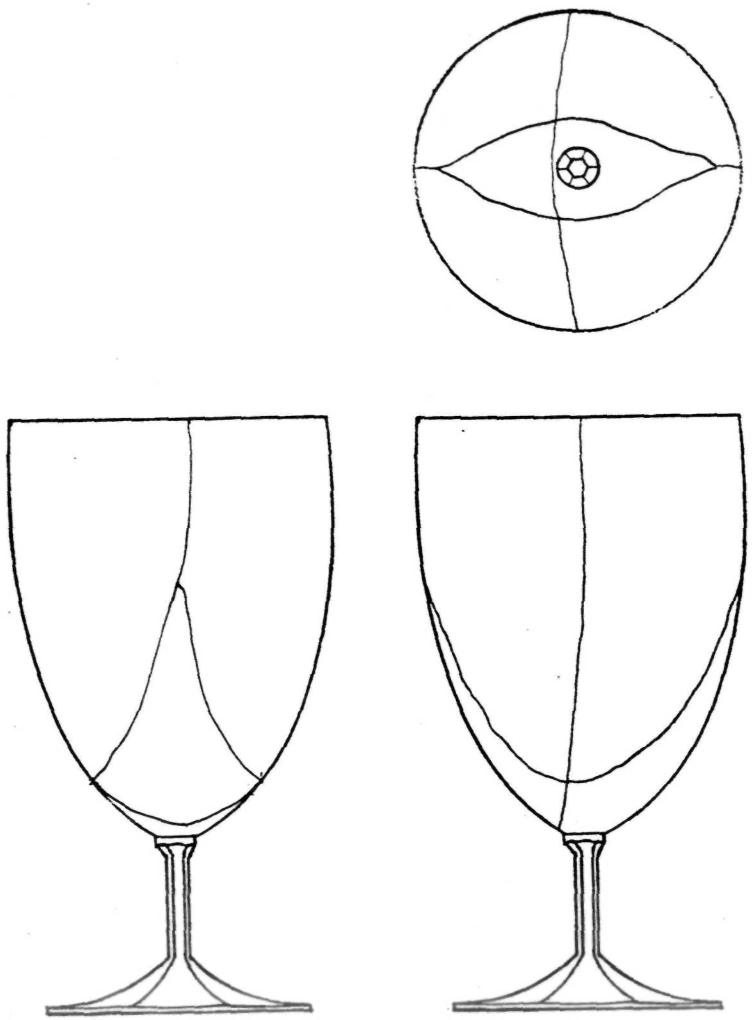

FIGURE 1. BASIC BREAK PATTERN

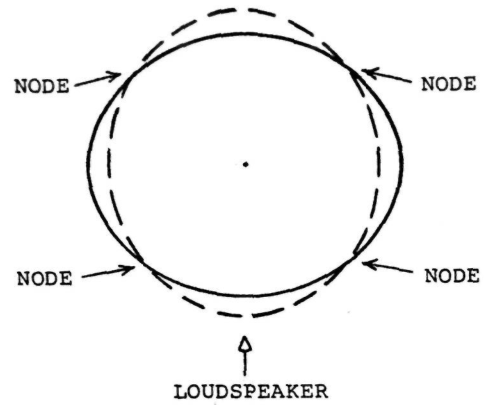

FIGURE 2. VIBRATION PATTERN OF GOBLET RIM AS SEEN FROM ABOVE