ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

AUDIBILITY OF TOWER BELLS - FURTHER EXPERIMENTS AND CALCULATIONS

David E Newland

Cambridge University Engineering Department,
Trumpington Street, Cambridge, CB2 1PZ, England
den@eng.cam.ac.uk

Abstract

This paper reports the results of further experiments on tower bell audibility. It follows from the author's first paper on this subject at ICSV12. After a year's use, the new tower bells at Kettering, England, have been tested again for audibility in the ringing room. This time the experiments have included ringing some bells at different swing amplitudes, as well as repeating experiments for all the 12 bells ringing steadily at their full amplitudes. The loudness of an individual bell depends on many factors. Surprisingly, swing amplitude is not the most important. The ability of a ringer to impart additional energy, by pulling hard on a bell rope, both to accelerate and then decelerate the bell has been found to be a bigger factor. A detailed numerical simulation of all the features of full-circle ringing has not so far been completed and is part of a continuing collaborative research programme in the Cambridge University Engineering Department.

INTRODUCTION

The previous paper [1] in ICSV12 described the traditional practice of full-circle ringing with tower bells. When the ringer pulls a bell rope, the bell makes practically a full circle i.e. a complete revolution. From a starting position with the bell nearly vertical (bell-mouth facing upwards), the bell rotates through almost a full circle until it is again nearly vertical (with the bell mouth again upwards). During this revolution the bell rope unwinds from a large-diameter pulley attached to the bell, and rewinds in the opposite direction on the pulley. Therefore a further pull by the ringer causes rotation in the opposite direction, when the bell returns to its starting position, again reaching the nearly vertical position.

During this motion, the bell's clapper (or hammer) is able to swing freely within the bell. When the bell is sounding correctly, the clapper starts from a position over top dead-centre, lying against what will be the trailing edge of the rim of the bell. As the bell makes its rotation following a pull on the bell rope, the clapper swings faster than the bell, so that it leaves contact with the trailing edge and overtakes the leading edge of the bell before motion is complete. With the bell having completed about 3/4 of its full circle, the clapper collides with the leading edge of the bell and the bell "sounds".

At this point, the head of the clapper rebounds from the bell's rim, but because of the deceleration of both bell rim and clapper head, they stay in close proximity, until the full motion has been completed and both are at rest. At this point the clapper head is lying against the leading rim of the bell. On the reverse motion, the leading bell rim becomes the trailing rim, and the process repeats itself in the opposite direction, with the clapper again overtaking the bell to strike again and to end resting on the bell's rim, in its original starting position. This limit-cycle oscillation of the bell and clapper can be conveniently illustrated in the phase-plane.

PHASE-PLANE ANALYSIS OF FULL-CIRCLE RINGING

A phase-plane diagram is a graph of velocity (vertically) against displacement (horizontally). It is usual to normalise the graph by plotting non-dimensional quantities, and so, in this example, the vertical scale is angular velocity divided by

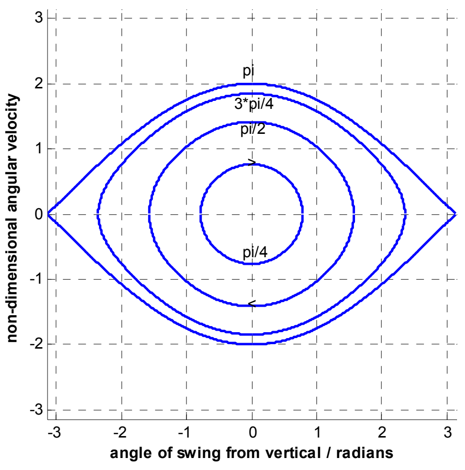

Figure 1 - Phase-plane diagrams for a pendulum swinging through amplitudes of $\pi/4$, $\pi/2$, $3\pi/4$ and π

Figure 2 - Clapper (red) swinging through an amplitude of π inside a bell (blue) swinging through an amplitude $3\pi/4$ (when the impact between clapper and bell is ignored)

a reference angular velocity and the horizontal scale is angle of rotation. The phase-plane diagram for a pendulum is well-known and is shown in figure 1. For small amplitudes of oscillation, the motion is simple harmonic, which plots as a circle in the phase plane. As the amplitude of oscillation increases, the phase plane becomes increasingly squashed until, for an amplitude of 180 degrees (360 degrees rotation), the phase-plane has the limiting shape shown in figure 1.

If the clapper and bell could swing freely, without the clapper colliding with the bell, their phase-plane trajectories would be as shown in figure 2. During actual ringing, the bell ringers control their bells so that (usually) the bell swings through about 270 degrees (the amplitude being ± 135 degrees). However the clapper swings through a larger angle. This is because the mouth of the bell is wide and the clapper has to swing further to advance from the trailing rim to the leading rim of the bell before it strikes. Often about 90 degrees of clapper rotation is required for the clapper to make this additional rotation. So, corresponding to a bell rotation of 270 degrees, the simultaneous clapper rotation is about 360 degrees. This is illustrated in figure 2, where the bell is assumed to have an amplitude (half the angle of swing) of about $3\pi/4$ (135 degrees) while the clapper's amplitude is about π (180 degrees). Therefore the phase-plane trajectory for the clapper (shown by the red curve in figure 2) is the limiting case shown in figure 1, while the bell has the smaller-amplitude trajectory shown by the blue curve in figure 2.

During the actual motion, the clapper collides with the rim of the bell. With reference to figure 3, suppose that motion starts at point *A* in the phase-plane for the

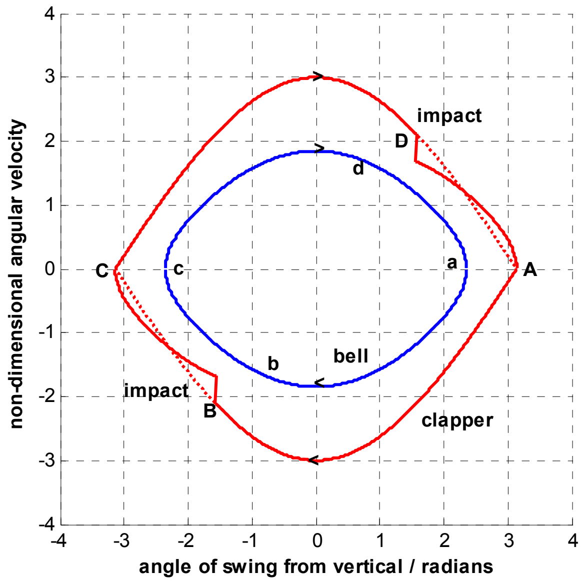

Figure 3 - Typical trajectories of bell and clapper in a phase-plane diagram during the course of steady ringing

clapper and at point *a* for the bell. Both bell and clapper are stationary with the clapper touching the trailing rim of the bell. Once motion starts, because the clapper swings faster than the bell, it overtakes the bell and strikes the bell's leading rim when the clapper is at point *B* and the bell is at *b*. The horizontal distance between *B* and *b* is then equal to that between *A* and *a*. The total angle (*A* - *a*) + (*b* - *B*) is the 90 degrees (approximately) required for the clapper to move from the trailing rim to the leading rim of the bell. When impact occurs, the angular velocity of the clapper is suddenly changed to be the same as the angular velocity of the bell (when small-amplitude bouncing of the clapper is neglected). Clapper and bell then move together with the same angular velocity (neglecting bouncing), until they come to rest together at *C* and *c* (momentarily).

This motion repeats in the reverse direction, with the clapper again overtaking the bell and striking its (new) leading rim when it is at *D*, before decelerating together to the original starting point, *A*. A full period of motion includes the bell sounding twice when the clapper is at *B* and *D*.

BELL MEASUREMENTS AT KETTERING

The previous paper reported measurements of bell loudness, recorded in 2004 in the ringing room, underneath the bells, for bells in 3 different towers. These measurements were repeated at one of the towers, Kettering, in December 2005. The sound pressure level recorded when bell number 5 (the fifth of 12 bells) was ringing at Kettering is shown if figure 4. As each blow occurs the sound rises rapidly and then decays before the next blow occurs. As described in the previous paper, unweighted dBC averages have been computed for each of four successive blows and the results averaged.

Figure 5 shows the results obtained in 2004 as the upper curve, and the repeated results obtained a year later in 2005 as the lower curve. The trend is the same. Loudness increases progressively from the treble bell (no. 1 bell) to the tenor bell (no. 12 bell), with some slight perturbations, but not as marked as had been recorded in 2004 in two other towers. However, the overall levels recorded at Kettering were generally lower in 2005 when compared with the same measurements in 2004. Possible reasons for this will be discussed briefly below, but some additional tests will be described first.

The swing amplitude can be varied by a bell ringer. By pulling on the rope early, the swing amplitude can be decreased (below the 135 degrees indicated previously). Alternatively by delaying the pull, the bell can swing higher, towards its balancing position, and the amplitude is then increased to greater than 135 degrees.

Even if the swing amplitude remains at 135 degrees, by pulling hard on the rope the bell can be given extra acceleration downwards, and this motion can be arrested by

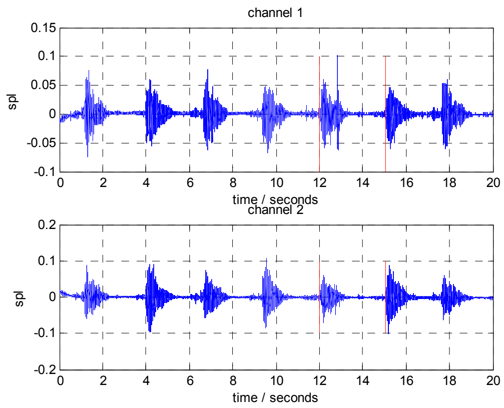

Figure 4 - Sound pressure level measurements when one bell is rung steadily

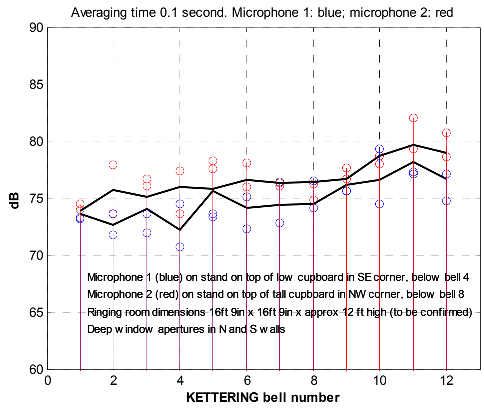

Figure 5 - Comparison between dBC levels for the 12 tower bells at Kettering, England, measured on two separate occasions, a year apart (upper curve 2004, lower curve 2005)

pulling on the rope later to decelerate the bell more than would occur naturally. This extra acceleration gives extra velocity which, in turn, leads to a more vigorous blow between clapper and bell rim, and a louder sound.

A series of measurements were made on two of the 12 bells when each bell was rung repeatedly alone, with the ringer instructed to allow the swing amplitude to gradually decrease from a full swing, taking about 2 minutes of continuous ringing for this to happen, and then gradually increase again to full amplitude over the same period. Loudness measurements were made as before and the results for the No 8 bell are shown in figure 6. The numbers along the abscissa now denote the number of the measurement (not the number of the bell, which is always the No. 8 bell). For each of these 12 different measurements, the frequency of swing of the bell is shown in figure 7. Because the natural period of a pendulum increases as its swing amplitude increases, its swing frequency decreases as the swing amplitude increases. So measurements 4 to 8 in figure 6 are for a smaller amplitude of swing than the other measurements. As expected, measurements 4 to 8 recorded less loudness than the other measurements (which were for a larger swing amplitude) but the effect is small. The dBC differences are sufficiently small to be hard to hear. However it is difficult for a ringer to keep a bell swinging steadily at constant amplitude. The impulse that a ringer has to supply to keep a bell swinging steadily has to be that to provide sufficient energy input to exactly balance the energy lost due to the natural resistance to motion of the bell and clapper assembly. If the ringer pulls too hard, the bell tends to over-swing and has to be checked by restraining it with the rope as it moves towards its stationary position. It turns out that the action of over-pulling and then checking the swing of a bell may have a significant effect on this bell's apparent loudness.

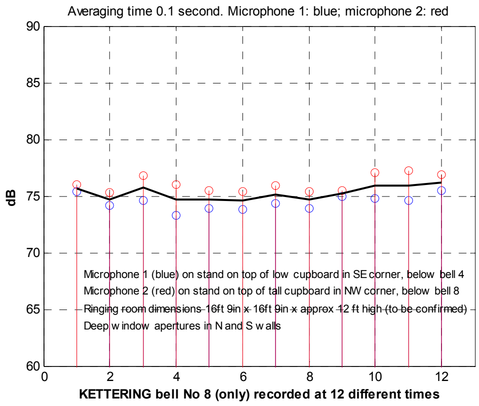

Figure 6 - Loudness of 4 successive blows (averaged) of the No. 8 bell at Kettering recorded at 20 second intervals over 4 minutes

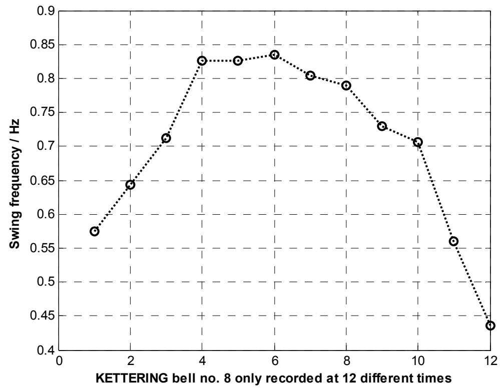

Figure 7 - Calculated swing frequency for each of the 12 measurements shown in figure 6 (this is the frequency of blows which is twice the frequency of a full phase-plane cycle in figure 3)

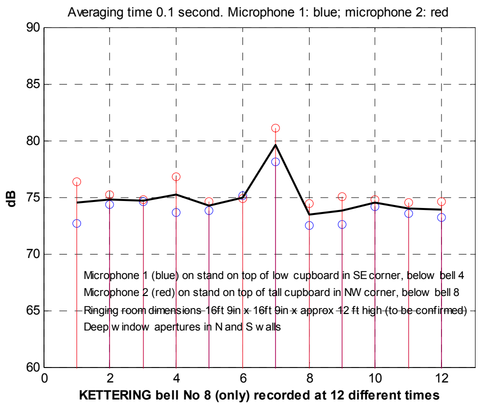

Figure 8 - Loudness of each of 12 successive blows on the No. 8 bell at Kettering

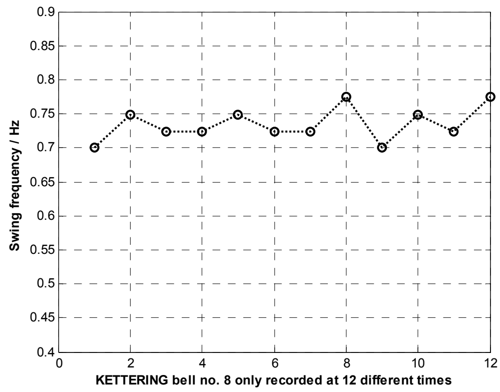

Figure 9 - Swing frequency for each of the 12 blows whose loudness is recorded in figure 8

Figure 8 shows the result of measuring the loudness of 12 successive blows of the No. 8 bell at Kettering. These have been selected from the 4 minute period of ringing described earlier when the ringer had been instructed to allow the swing amplitude to decrease gradually and then return to full amplitude. It can be seen that there is a significant variation in loudness between adjacent blows, and that one blow in particular is clearly louder than the adjacent blows. Although the same ringer rang all the bells for the 2005 tests shown in Figure 5, several other (different) ringers rang the bells for the 2004 tests. The different bell handling of different people is believed to be one reason why the loudness figures recorded in 2005 are different from those measured in 2004. For these experiments, only 4 blows of each bell were recorded after "steady ringing" had apparently been established and no attempt was made to look for and eliminate unexpectedly loud or quiet blows. Of course there are other possible explanations, including the calibration and positioning of the microphones and sound level meters (although the same equipment was used on both occasions and with microphones located in approximately the same positions), and the "running in" of the new bells at Kettering after a year's use. They may now swing more easily and require less input from the ringers to keep them swinging steadily. Also the clapper-to-bell contact area is likely to have changed, as the bells have bedded-in, although how much this would affect loudness, if at all, is not known.

TIME-FREQUENCY ANALYSIS

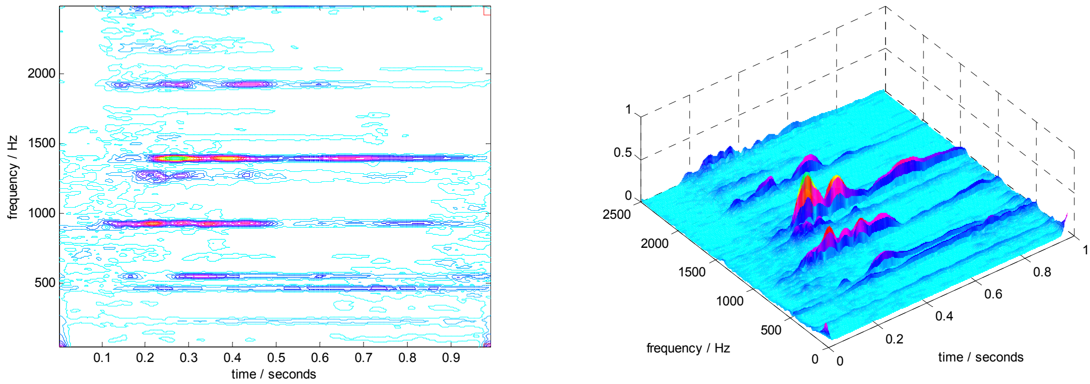

Figure 10 - Time-frequency analysis of one bell sounding: contour plot left and corresponding mesh plot right. Analysis by using the harmonic wavelet transform.

The changing contact between bell clapper and bell rim, as the bells bed-in, is expected to have some effect on the harmonic content of the bell sounds. The spectrum that is measured is complicated and varies with time during each swing of the bell. Figure 10 shows time-frequency plots when No. 8 bell strikes once. They show how the frequency content changes with time. As explained previously [1], the spectrum of an English tower bell consist of octaves of the bell's principal note, accompanied (usually) by a selection of minor thirds and perfect fifths. The nominal octave and the minor third above it are the dominant features in figure 10, but their onsets, after the bell strikes, are not simultaneous and each varies with time.

The two diagrams in figure 10 have been derived by plotting the magnitude of the amplitude of the harmonic wavelet transform of the recorded sound. The left-hand view is a contour plot and the right-hand view its corresponding 3D mesh plot.

CLAPPER DYNAMICS

The bell note sounds when the bell's clapper collides with its bell rim. A typical clapper (the bell hammer) is made of wrought iron and consists of a heavy ball on a rigid shaft. The shaft is pivoted to swing freely about the end opposite the ball, with its hinge point inside the bell and slightly lower than the axis of rotation of the bell. The offset, the distance from the swing axis of the bell to the swing axis of the clapper, is important and there are empirical rules for determining this if the bell is to be capable of the desired limit-cycle oscillation described above. The moment-of-inertia of the clapper about its hinge axis is also important, for the same reason, and it is usual for the clapper shaft to protrude past the ball to increase the moment-of-inertia.

When the ball of the clapper strikes the rim of the bell (at points B and D in the phase plane, figure 3), there is a natural tendency for the ball to bounce on the rim. It does not rebound a large distance because both the rim of the bell and the clapper are experiencing substantial deceleration at this time and the deceleration acts to hold them together until motion has come to rest. Typically the linear deceleration (tangential to the path of motion) is about 5g when impact occurs. But small amplitude bounces do occur and cause intermittent contact between the clapper ball and the bell rim after the first impact.

This phenomenon of bouncing has been measured by Woodhouse and Rene [2] and they have shown that bouncing always occurs, but usually at rapid intervals of less than 0.2 seconds. However for some bell/clapper combinations, the initial bounce is sufficiently large that the time interval before there is a second impact is greater than 0.2 seconds and then it is possible for a listener to hear what may appear to be a second blow. This of course is undesirable and a well-proportioned bell system keeps clapper bouncing sufficiently small in amplitude that there is no impression of multiple hits when a bell sounds.

The role of clapper dynamics in generating the complicated time-varying spectrum shown in Figure 10 is not yet understood, nor is the role of bouncing in reducing the naturally deadening effect on sound that would be produced if the clapper rested continuously against the bell rim after striking it. These are the subjects of further research.

REFERENCES

[1] Newland David E., "Audibility of tower bells in change-ringing", Proc. ICSV12, Lisbon (2005).

[2] Rene, James C., "The sound and vibration of church bells", 4th year undergraduate project report (supervised by Prof. J. Woodhouse), Cambridge University Engineering Department (2005).