Fatigue Crack Detection on Unique Church Bells by Modal Analysis

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Abstract. Bells are musical instruments exposed to severe loading and stress conditions during ringing, when the clapper hits the bell. Thus, often fatigue cracks occur due to strong impact conditions or material insufficiencies. These cracks can only be identified, when they have already propagated through the wall of the bell to large dimensions. Then the sound of the bell in terms of individual tone shifts and damping has changed dramatically. Consequently repair such as welding or even recasting are necessary.

In this paper procedures to describe the fatigue life of bells based on simulation and strain measurements are presented based on examples from numerous bells, which were investigated in the past. From those investigations on at least more than 100 culturally and historically important bells in Europe the most important conclusion is that each bell is unique in its structure and its setup for ringing. No generally applicable conditions may be inferred from a bell with its clapper for a smooth ringing with a high quality sound.

Thus recent research aimed on a very early crack detection. Then changes of the sound are still very small, so that the musical quality of the bell may not be impaired. Still can be taken to stop the crack propagation at this early stage, by e.g. reduction of the clapper impact measures or turning the bell, so that the clapper hits on another cross section without further damaging it.

Acoustic modal analysis basically allows identifying tone shifts. However, there is no “intact” bell to which the tones of a bell may be referenced and a slight shift may allow to identify a fatigue crack. The inner harmonies of the tones of a bell differ slightly from bell to bell. Each bell has its very unique set of at least 12 tones determining for its sound. Inscriptions and pictures as well as material and structural insufficiencies lead to an individual characteristic and disturb clear harmonies.

However, a method is presented to determine a theoretically “intact” bell based on the sound measurement of a bell. Then this “intact” bell can be used as a reference to identify tone shifts due to initial fatigue cracks at a very early stage. A procedure is described, to even detect the location of such small fatigue cracks in the bell.

1. Introduction

For over 5,000 years, bells have accompanied people, especially in Europe. They are a vital expression of our culture and history. The importance for European history shows up in very different and diverse uses over the centuries to religious and secular occasions. Each time bells were silent, life, liberty and humanity were directly threatened. Thus bells are valuable cultural assets that should be preserved for future generations.

Bells are musical instruments operated like machines with necessary technical equipment engine, drive and control and exposed to severe loading conditions by the clapper. Many
especially large and famous bells were damaged by ringing over decades and centuries. With the introduction of motor driven ringing machines the intensity of fatigue loading was drastically increased, which lead to many cracked bells due to the high stress conditions under the vibrations of clapper impact and ringing. The repair or restoration requires high effort and cost and thus often valuable cultural heritage is irrecoverable destroyed.

The European competence center for bells ECC-ProBell at the University of Applied Sciences of Kempten started in 2005 and since then has performed extensive investigations on the parameters determining the life of bells and on methods to evaluate the risk for damages on bells in service. [1] These methods were applied on numerous most famous European bells e.g. the largest church bell of the world, “St. Petersglocke” in Cologne, the “Pummerin” in Vienna, St. Stephan, “Savoyarde” in Paris, Sacre Coeur, the Popes bell in Rome, St. Peter, and about 200 other bells in service.

This large variety of experience was used to develop a method for the determination of the musical fingerprint of a bell, which can be used to reliably identify fatigue cracks and other insufficiencies of a bell in a very early stage, so that repair measure can be reduced to a minimum and cultural heritage can be preserved but still the bells remain in service.

2. Bells in service

Bells are cast from bronze as a standard over centuries with about 80% copper and 20% tin. The geometry of the bell determines together with the material quality the tones of the bell; about 12 are considered as important for its sound. Bells in the western world are swinging on a well determined angularity in the belfry (Fig. 1).

![Fig. 1. Ringing bell with yoke and clapper](image)

The clapper is fixed inside at the top and hits the bell. The bell is fixed to the yoke which is seated rotatable in the bearing of the belfry. The double pendulum is defined by the masses, moments of inertia and centers of gravity of bell, yoke and clapper. The swinging period of the bell also depends on the angularity. The clapper inside of the bell is mostly designed to strike the bell just at the highest point of swinging, thus exiting the bell to vibrate and sound. The motor and its control ring the bell constantly on the adjusted angularity. The dynamic system is optimized, so that:
- the fixture of the clapper allows a perpendicular contact between clapper and bell;
- the clapper weight is sufficient to excite the bell properly in all tones;
- the mass distribution realizes a concentrated impact which lasts about half a millisecond;
- the stiffness and bearing of the clapper in the bell define the duration of contact;
- the clapper material strength and plastic deformation capability allows the development an adequate contact geometry;
- the ringing angle defines the impact frequency and the impact intensity;
- the masses, the contact area, the impact direction, the impact point the mass distribution of clapper define the sound and musical quality of the bell.

3. Damages on bells

Bells are severely loaded in service by the clapper strike. On many bells fatigue cracks occur mainly in the vicinity of the strike areas, due to high local stresses (Fig. 2a). Local wear occurs depending on the strike intensity, direction, materials, contact conditions (Fig. 2b). Damages may also occur due to manufacturing insufficiencies (Fig. 2c).

![Fig. 2. Fatigue cracks (a), impact wear (b) and casting defects (c) on bells](image)

Measurements of clapper strike acceleration, the sound and the local stress conditions outside the impact point (Fig. 3) were used to evaluate the fatigue loading and the wear intensity. Since each clapper stroke even under a constant ringing angle shows different intensity due to the vibrations during the half msec-contact, a statistical evaluation of the ringing over a 2min constant ringing is necessary for reliable results. Clapper impact acceleration and excited vibration intensity in terms of the local strains are strongly correlated. A fatigue load evaluation on the bell is thus possible for a 2 min ringing by accumulate damage calculation and deriving the expected life to a fatigue crack, based on material fatigue data. [2]

![Fig. 3. Measured clapper impact acceleration and local strains at the impact area of the bell](image)

Fig. 4 shows the accumulated damage of a 2 min ringing of a bell with different clappers and under certain ringing angles. An increase of the clapper mass leads to higher fatigue loads.
The material of the clapper does not influence the local stress conditions of the bell. The mass distribution of the clapper has a slight influence. A higher ringing angle leads to higher clapper impact accelerations and thus to higher damage. A method for the fatigue life evaluation of bells was developed based on computer simulations with the parameters:
- masses moments of inertia, center of gravity of bell, yoke, clapper;
- measures of bell, clapper, axes and impact point;
- measurements of the local strain, the clapper intensity and subsequently models;
- ringing angularity.

![Fig. 4. Influence of clapper mass and ringing angle on the accumulated damage and life of the bell](image)

These models and procedures were widely applied on many bells for the evaluation of their risk for fatigue damages and wear. Especially on cracked bells, the models were used to set up smooth ringing conditions after repair measures, so that new damages may not be expected in a short time. The main task of such fatigue related optimizations is to reduce the impact intensity and thus the local stress conditions in the highly loaded areas.

However, it is important to note, that the sound of the bell was quite different under the individual parameters. Even the loudness of the ringing does not only depend on the impact intensity. Thus, the setup of a bell system for a smooth ringing without high risk for fatigue damages or wear is to a certain extend independent from an optimization of the system for a good musical quality.

### 4. Damage identification

Bells are considered as cultural heritage and need to be preserved. Therefore, the ringing conditions are optimized for a smooth ringing with low risk for fatigue and wear on many bells today. Especially on old and important bells, mainly the large ones, methods are needed, to identify damages in a very early state, so that repairs may even not become necessary. If cracks can be identified in a very early stage, the bell can be rotated, so that the clapper strikes another cross section and then the initiated small crack is located in an area of low stresses and may not propagate. The ringing conditions can be set, so that the risk for further damages is strongly decreased.

The wear at the strike areas can be inspected and evaluated visually. The identification of material insufficiencies due to manufacturing and early fatigue cracks require non-destructive testing methods. Ultrasonic, X-ray, Eddy current method or color penetration requires high effort, is not reliable and probably lacks on good references. Acoustic resonance testing is considered as the most adequate test method.

The sound of the bell is determined by the tones, of which up to 12 are considered as important for evaluation. They depend on the geometry and the material of the bell only. The sound and respectively the mixture of the tones and their damping is strongly determined by the strike excitation. Additionally the swinging of the bell in the belfry strongly influences
the sound due to dynamic effects. A non-destructive testing method therefore can rely on noise measurements with a microphone and analysis of the frequencies. Analysis of damping and sound are not useful due to the influence of many ringing parameters. The bell must not swing to avoid dynamic effects. The actual natural frequencies of a bell depend on its geometrical shape, which is designed to meet musical requirements for the 12 important tones. Inscriptions and ornaments as well as insufficiencies of the material lead to tone shifting or several frequencies in close vicinity. Fig. 5 shows the eigenmodes of the 12 most important tones of a bell. Also the musical intervals with respect to the principal, the main tone of the bell are given. All bells are aiming to sound in this or similar musical regimes and are designed for a required principal in the chimes of a bell tower. By the colours in Fig. 5 the number nodal rings and meridians is indicated. This numbers of rings and meridians describe the areas of main vibrations. A damage or insufficiency or asymmetry located in an area of large vibration of a tone will lead to a shift of that tone; located in a node, the tone will not be influenced.

Fig. 5. Modes of the 12 important tones of a bell (left) and frequency splitting of a Terz (right)

At lower right side of Fig. 5 the phenomena of tone splitting is demonstrated for the tone Terz. Each tone occurs in the bell due to its rotational symmetry 2 times shifted by half the angle of the meridian. If the bell is ideally symmetrical, the frequencies of the split tone in the bell are exactly the same. Any crack, wear insufficiency will lead to an asymmetry resulting in a difference between the two frequencies of the split tone. All tones are affected, which show a maximum in vibration at the area of asymmetry. It thus can be concluded, that asymmetries in different areas of a bell result in quite different changes of tones and sound.

Mass and size of the bell determine the principal tone of a bell; the geometry and shapes results in tones in required musical intervals. Thus bells of any size are very much similar in terms of intervals of the many tones with respect to the principal tone. However each bell has its specific shape resulting in more or less slight deviations from the defined intervals, leading to its unique sound. Thus there is no exact set of tones, which describe the intact bell, but each bell has its very unique natural frequencies.
Splitting of tones will occur due to asymmetries in areas with large vibrations of these tones:  
- inscription, ornament or relief, 
- material insufficiency due to manufacturing, 
- fatigue cracks or wear.

Fig. 6. Tone fading after impact with beating waves due to tone splitting

Fig. 6 shows the sound pressure of a bell after a clapper strike for about 10 sec. The upper time history shows the total pressure, the lower ones show the pressure of the individual tones Unterton, Prime and Terz. The bell under investigation had heavy wear at the sound bow. By this diagram the different damping behaviour of the individual tones becomes obvious. However, more important is the beat frequency on the Prime and the Terz, which occurs due to 2 tones in the bell with small difference in frequency.

Fig. 7. PSD over time of last 50 ringing hours up to fatigue crack

Fig. 7 presents the power spectral densities of a bell, drawn over the time. The sound was recorded each hour during a continuous ringing of a bell of about 355h and the FFTs were plotted over each other; the colour indicates the power of the recorded noise at the frequencies. In the diagram the last 50h of the life of the bell are drawn, when a fatigue crack of some 20cm could be detected with colour penetration method. At the end of the life after about 340h of ringing a splitting of the certain tones, a shifting and a fading away can be observed. The splitting of a certain tone leads to the beat as presented in Fig. 6. It is concluded, that the phenomenon of tone splitting can be used to identify any asymmetry in a bell.
From these analysis the following conclusions can be drawn, which lead to a procedure for the identification of bell failures. The phenomena of tone splitting occurs on bells as soon as any asymmetry is apparent. If there are very small asymmetries the tone splitting results in beating frequencies. According to the location of any local deviation of rotary symmetry of a bell, different tones are affected by the splitting. The absolute frequency of a tone is not of interest, but only the occurrence of split modes and the frequency difference. Thus the actual unique quality of a bell is not a matter of the observed phenomena. The analysis can be performed for any bell, without having to define a reference, since the reference is always the first of the split tones itself and the second if apparent describes the asymmetry. If each tone is analysed for splitting, from the combination of tones on which splitting occurred, the type and location of the failure can be identified based on the nodes and antinodes of the individual tones.

5. Procedure for determination of musical fingerprint for failure detection

By the described phenomena on bells the following procedure was derived, to determine the musical fingerprint of a bell. The musical fingerprint does not indicate any musical quality of the bell and thus takes into account the unique bell in its present condition. The analysis is based on the frequencies of the mode shapes and is not influenced by ringing conditions. The evaluation of the tone splitting phenomena of 12 tones respectively the different mode shapes allows to identify specific types of asymmetries and failures. The phenomena can be investigated by frequency analysis with FEM models and be verified by measurements on bells with well-defined cracks and failures.

A microphone is placed in the center under the bell or outside above the crown.

The bell is struck by the clapper or a hammer from inside at the sound bow in the direction of the clapper strike. The mass of the hammer should be close to that of the clapper to ensure that all relevant tones are excited. The strikes are introduced at the sound bow in steps of 15° around the bell starting from one impact cross section to ensure that a possible failure cross section is excited properly.

The noise is recorded for about 10 sec during the fading sound of one strike. From the FFT analysis all relevant 12 tones are identified and most important any splitting frequency of these tones. The resulting frequencies, in terms of the first and the second splitting frequency, are inserted to a star diagram according to Fig. 8. The colors of the sections are selected according to the mode shapes presented in Fig. 5. On the radial axis the difference of the split frequencies are given in cent. 1 cent is 1 percent of a half tone step (1 cent = 1/100 *21/12 *f). The threshold for identification such frequency difference by hearing is about 6 cent. By the graphs in Fig. 8 for each relevant tone, the differences of the tone splitting can be identified. A circular graph for all tones at 0 means, that the bell is ideally rotational symmetric in all areas. Any deviation from 0 at a tone indicates an asymmetry in a specific area of a certain intensity.

In Finite element models the following failures were introduced and frequency analysis was performed accompanied by measurements on actual bells with well-defined failures:
- comparison of actual bell and ideal bell (Fig. 8a)
- a thick relief on the waist (Fig. 8b)
- material insufficiencies due to manufacturing
- horizontal shrinking crack inside the sound bow
- wear at the strike area (Fig. 8c)
- fatigue crack at the sound bow (Fig. 8d)
The graphs in Fig. 8 demonstrate the specific tone split code of selected insufficiencies, wear and cracks on a bell. By such diagrams it is possible to distinguish between the different reasons for split tones. The observed tone splitting is very sensitive and indicates cracks in a very early state. By repeatedly performing such analysis, e.g. once each year, which may correspond to about 30h ringing on a large bell, crack propagation may be observed. Fig. 8d shows the analysis of a welded 22to bell; it can clearly be stated, that the welding is insufficient. This method will be used to monitor bells for identification of initiating cracks to then introduce optimized ringing conditions and other measures to stop crack growth and still ring the bell in its unique sound. Then the bell is turned, so that an identified crack is located in an area of low stresses and then the clapper strikes a cross section with nodes of the relevant tones. Thus the impact of a failure is reduced to a minimum and may not even be heard.

References