One-Year Monitoring of a Historic Bell Tower

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ABSTRACT: In 2003, people working in the San Luzi, Zuoz, bell tower reported excessive tower vibrations when ringing bells. Measurements performed in 2004 showed a maximum amplitude of 16 mm/s which is more than five times the allowable value. In 2008 the two large bells (out of four) were equipped with cranked yokes and their pendulum frequency was reduced to get a larger distance to the tower natural frequency. Measuring again in 2009 yielded the two large bells no longer exciting large tower vibrations. However, this was not true for bell No. 3. Subsequently, this bell's pendulum frequency was also reduced. In 2011, measurements showed that this last measure had negative instead of positive effects. And, disposing now of three values, the tower natural fundamental frequency was found to be somewhere in the $f = 1.43...1.50$ Hz region. It was then decided to monitor the tower dynamic behavior for one year to get reliable information on the natural frequency scatter. Monitoring started June 11, 2012, and ended October 7, 2013. Instrumentation consisted of 2D-acceleration plus air temperature sensors as well as getting weather data from a company operating a station in Zuoz, a village in the Upper Engadin Valley. Ambient vibration data was acquired every hour during 20 minutes, a time window usually free of bell action. In addition, all bell excited tower vibrations were acquired upon a trigger level having been crossed. The results: a) The tower fundamental frequency varied in an $f = 1.41...1.59$ Hz range, b) The tower is stiffer in winter than in summer, c) On a daily or weekly schedule, the tower fundamental frequency is following the temperature curve: increasing stiffness with increasing temperature and vice versa. A possible explanation for this contradiction is given. Possible measures to solve the problems with bell No. 3 are discussed.

KEY WORDS: Bell tower, ambient parameters, natural tower vibrations, non-linear structures.

1 SAN LUZI BELL TOWER

![San Luzi Church and bell tower. Total tower height: some 60 m. Cross section dimensions: 5 x 5 m. Bell arrangement unchanged since 1793. 1954: Electric bell control introduced. 1990: Tower top part rehabilitated and strengthened. 2003: Church and tower facade rehabilitated.](image)

![This inscription at the San Luzi Church in Zuoz, the "Capital" of the Upper Engadin, tells us that the lowest part of the bell tower walls stem from the year 1139. This inscription is written in Putér, one of the five idioms of Romanch Ladin, the Swiss National Language spoken by some 50'000 people in the Canton Graubünden (Grisons).](image)

Figure 1. This inscription at the San Luzi Church in Zuoz, the "Capital" of the Upper Engadin, tells us that the lowest part of the bell tower walls stem from the year 1139. This inscription is written in Putér, one of the five idioms of Romanch Ladin, the Swiss National Language spoken by some 50'000 people in the Canton Graubünden (Grisons).

The tower is equipped with four bells. No. 1: $m = 1'700$ kg, No. 2: $m = 648$ kg, No. 3: $m = 400$ kg, No. 4: $m = 260$ kg.

In about 2003, people working close to the bells reported excessive tower vibrations when ringing the bells.
LINGUISTIC BOUNDARY CONDITIONS

"Tower frequency", f1a: For the sake of simplicity, we will be talking of "tower frequency" in this paper only. The exact meaning of this expression is: The tower first fundamental natural vibration (mode) frequency as derived from (measured) vibrations excited by ambient sources like wind and micro tremors.

We will also mention the dominant modal motion direction of this mode being the same as the one of the dynamic forces exerted through bell's ringing, also called the "ringing direction", here only.

The tower second natural mode, with a frequency f2a, also being mentioned some times in this paper, exhibits a dominant modal motion perpendicular to the ringing direction. Mode f3a is in ringing direction, f4a perpendicular again. The latter two are mentioned in Figure 3 only.

"Bell frequency": A bell's dynamic motion is defined by its pendulum frequency. Since the horizontal dynamic forces generated by a bell ringing with a "usual" (±45°...80°) ringing angle are dominated by the 3rd harmonic of the pendulum frequency, "bell frequency" means here: The 3rd harmonic of the pendulum frequency.

"Bell 1": Means bell No. 1.

3 TESTING HISTORY

3.1 Tests performed in 2004

Experimental modal analysis under ambient excitation as well as bell ringing excited tower vibration measurements were performed in May 2004.

The main results were the tower frequency being f1a = 1.43 Hz and that ringing bell 1 as well as bell 2 excited unacceptable tower vibrations (Figs. 3 to 5).

Rating of the tower vibrations is based on the Codes [1], [2] and [3]. Maximum vibration intensity reached v = 16.5 mm/s whereas the Codes allow v = 2.5...3 mm/s.

It took, however, several years until countermeasures were undertaken. In 2008, bells 1 and 2 were equipped with a cranked yoke and their frequency was decreased to get more distance to the tower frequency.

3.2 Tests performed in 2009

An analogous set of tests as in 2004 was performed in June 2009.

The main results were the tower frequency now being f1a = 1.496 Hz and that the changes applied to bells 1 and 2 were fully successful. The tower vibrations generated were less than v = 1 mm/s now.

However, probably due to the change in tower frequency, bell 3 ringing with f = 1.47 Hz now generated tower vibrations with v = 6.4 mm/s which was still unacceptable (Figs. 4, 5).

In the context of the measures taken in 2008, both belfries, one for bells 1 and 2 and a second one for bells 3 and 4, had been replaced. Since no room was available to equip bell 3 with a cranked yoke, two measures with less incidence to the belfry were taken now. To reduce the bell 3 dynamic forces, some steel plates were added at the upper yoke side and the bell frequency was reduced to f = 1.36 Hz to achieve a nice distance to the (new) tower frequency, f1a ≈ 1.5 Hz, in 2010.

3.3 Tests performed in 2011

An analogous set of tests as in 2004 and 2009 was performed in November 2011.

The main results were the fundamental natural tower frequency being f1a = 1.43 Hz again, bells 1 and 2 still producing tower vibrations with v < 1 mm/s, bell 3 such with v = 8.6 mm/s and bell 4 such with v < 2 mm/s.

In other words: The situation was worse than in 2009.

Considering the fact of the tower frequency showing clear signs of instability, meaning a non-linear tower behavior, meaning a cracked state of the tower walls, it was decided to look closer into this phenomenon before taking further measures.

Codes propose a certain "resonance distance" between tower and bell frequencies. It is however difficult to follow this prescription with the tower frequency having one value today and another one tomorrow.

3.4 Test results 2004, 2009 and 2011

The results of the three "historical" tests are summarized in Figures 3 to 5.

<table>
<thead>
<tr>
<th>May 5, 2004</th>
<th>June 15, 2009</th>
<th>Nov. 15, 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>f [Hz]</td>
<td>ζ [%]</td>
<td>f [Hz]</td>
</tr>
<tr>
<td>f1a</td>
<td>1.430</td>
<td>1.6</td>
</tr>
<tr>
<td>f2a</td>
<td>1.785</td>
<td>1.2</td>
</tr>
<tr>
<td>f3a</td>
<td>2.485</td>
<td>1.5</td>
</tr>
<tr>
<td>f4a</td>
<td>2.666</td>
<td>1.3</td>
</tr>
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</table>

Figure 3. Tower natural frequencies and damping coefficients as derived from ambient tests.

<table>
<thead>
<tr>
<th>2004</th>
<th>2009</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell 1</td>
<td>1.33</td>
<td>1.13</td>
</tr>
<tr>
<td>Bell 2</td>
<td>1.40</td>
<td>1.23</td>
</tr>
<tr>
<td>Bell 3</td>
<td>1.48</td>
<td>1.47</td>
</tr>
<tr>
<td>Bell 4</td>
<td>1.61</td>
<td>1.63</td>
</tr>
</tbody>
</table>

Figure 4. Bell frequencies.

<table>
<thead>
<tr>
<th>2004</th>
<th>2009</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell 1</td>
<td>11.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Bell 2</td>
<td>5.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Bell 3</td>
<td>3.6</td>
<td>6.4</td>
</tr>
<tr>
<td>Bell 4</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Bells 1...4</td>
<td>16.5</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Figure 5. Maximum tower vibration velocity.
4 MONITORING TEST LAYOUT

4.1 Instrumentation

The following parameters should be subject of monitoring:

- tower acceleration in both horizontal directions
- air temperature
- air relative humidity
- wind speed
- wind direction.

Checking the market lead to choosing GeoSIG equipment (www.geosig.com). The crucial point were the GeoDAS software capabilities to deal with the requirements:

The aim of the monitoring test was twofold: a) keeping track of the four first tower frequencies and, b) keeping track of the tower vibrations excited through the bell's ringing.

The software should therefore be capable of:

- acquiring a 20 minutes-time window of the tower ambient vibrations every hour, and
- acquiring tower vibrations excited through crossing of a trigger level when ringing bells.

This was easily covered by GeoDAS and we were lucky to not having to reinvent the wheel for this purpose. And GeoSIG also delivered an IP68-protected 1g accelerometer with sufficient dynamic and frequency ranges (AC-23).

Meteo data could be received from the local Meteomedia (www.meteocentrale.ch) station every 10 minutes (Fig. 8).

4.2 Data acquisition time schedule

Fortunately, the bell ringing schedule of San Luzi is quite simple: The clock is signalled twice an hour only. This lets open two windows to acquire time signals of enough length to perform a nice FFT-analysis. Bells ringing schedule for a normal working day is: Bell 2 at 5.01 am, bell 1 at 12.01 pm and bells 1 to 4 in the evening, with "evening" meaning a time depending on the time of the year (6...9.15 pm).

As an exception, not only bell 2 but bells 1 to 4 are operated together at 5.01am on Sundays.

Ringing duration is 1...6, rarely up to 15 minutes (services). The initially chosen time schedule for the ambient tests, once every 2 hours from hh.05 to hh.25, was changed to once every hour soon. It was noticed that not all "ambient" time windows were "bell-free". Especially when choosing the even hours, problems arose at 12 pm and at 6 pm. With the hourly schedule of the finally acquired 5'280 time windows, some 400 had to be discarded due to bells ringing inside of the ambient window.

After some pre-tests, a 0.15 mm/s² trigger level was found to being nice to acquire time windows being triggered through bell action.

4.3 Data acquisition and transfer

The GeoSIG GMS-24 electronic device (hidden in the plastic box visible in Figure 7) sampled the acceleration signals with sR = 100 Hz and a 24-bit resolution. Local storage capability was 2 GB. With the exception of data transfer facilities' problems, this was never used but to a minor extent.

The data is stored in .msd format (.msd = mini seed), a format obviously common in the earthquake but unknown to the structural dynamics communities. The good news with this format is: The resulting files are small. Per month of system operation, some 500 MB had to be transferred to our office via a G3 mobile phone connection. This is about what is possible using this technology without ending in bankruptcy, subsidizing our beloved Swiss Telephone monopolist.

4.4 Monitoring time period

Monitoring started June 11, 2012, and ended October 7, 2013. Due to problems with the G3-link, a loss of data occurred from July 14, 2012, to July 20, 2012. Besides of this, the monitoring hard- and software worked flawlessly.
5 SIGNAL PROCESSING

5.1 Dealing with the raw ambient data

We had to find out that the GeoDAS software package is well suited for the on-line data management but not for post processing purposes. Checking again the market we found a reasonable solution making use of the NI Diadem software package and relying on colleagues in Hamburg, Germany, who are using this tool on a daily basis (www baudyn.de).

As a Diadem data plug-in for .msd-Files did not exist we chose the possibility offered by GeoDAS to export the ambient files to ASCII format. Changing an existing data-plug to a minor extent (header lines) allowed easy data transfer into Diadem. The only disadvantage is the fact of the ASCII files being about ten times larger than the .msd-Files. This extended the originally 8 GB of raw data to a total of some 120 GB which is however daily routine today.

The Diadem routine written by Oliver Witter did three things with the three data streams acquired:

- extracting Min, Max and RMS values,
- calculating an FFT spectrum for the ranges f = 0.8...2 Hz and f = 2...4 Hz respectively.

The first frequency range aimed at the tower frequencies f1a and f2a, the latter at f3a and f4a (see Fig. 3). The respective values were stored in two .xls-Files covering 24 rows per day and 35 columns per hour monitored.

In addition, this software also produced the .png-Files shown in Figures 9 and 10, presenting the time and spectrum data dealt with. The PSD-spectra shown were determined through transforming one single 20-minute-time-window, Hanning weighted, into the frequency domain.

Including the .xls-meteo-data-file delivered by Meteomedia, we finally disposed of three .xls-data-files per day covering all raw data necessary to get information on the tower behavior over a total of 477 days, 68 weeks or 16 months.

5.2 Putting the raw ambient data into graphics form

Again, we had to find out that standard software packages like, in this case, Microsoft Excel, do not fulfill more than basic requirements. Do not try to present more than three columns of data in the same diagram! Here, help arrived from Holzer Informatik, a company we found through an internet search (www.holzer-informatik.ch).

In three steps, Christian Holzer wrote a Visual Basic routine allowing graphic presentation of up to nine parameters on the Y-axis versus time on the X-axis. And: These parameters can be scaled individually and they can be filtered based on a second and on a third parameter. To illustrate this strategy: We can, e.g., present the tower frequency together with air temperature, X-acceleration-PSD-spectral density and wind, the latter for wind speeds W ≤ 4 km/h and for wind in the ringing direction only. Distinguishing between wind in ringing direction and perpendicular means: Separating wind directions 0...90 and 180...270 degrees from 90...180 and 270...360 degrees (Fig. 8).

5.3 Dealing with bell excited tower acceleration data

Here, GeoDAS proved to be feasible again. Manually separating the half and full hour bell activities from real bell ringing based on the file storage time and file length was somehow lengthy. However, high-pass filtering with a cut-off frequency at fc = 0.2 Hz and subsequent integration of the files of interest was easily possible.

It came as a surprise that, based on the trigger level crossing, 103 files were acquired and stored without any relation to bell activities. Checking these files in detail yielded the reason for this being what we subsequently called "strong-wind"-excited tower vibrations.

Figure 9. Tower acceleration and air temperature signals acquired May 15, 2013, 12.05 pm to 12.25 pm.

Figure 10. Tower acceleration PSD-spectra for f = 0.8...4 Hz for the X- and Y-directions derived from the time signals shown in Figure 9.
RESULTS: 16 MONTH'S ANGLE OF SIGHT

6.1 Tower frequencies f1a and f2a as a function of time

The tower fundamental frequency varied in the range f1a = 1.42...1.59 Hz in the 16 months monitored (Fig. 11). The second tower frequency with the dominant modal motion being perpendicular to that of the fundamental mode, varied in the range f2a = 1.78...1.96 Hz (Fig. 12).

6.2 Fundamental tower frequency as a function of time and meteo parameters

Figure 13 shows the tower frequency f1a being higher in winter than in summer. This indicates the tower generally being stiffer in winter than in summer. It may be mentioned here that the temperature range valid for the 16-month's-period monitored is T = +28°C...-27°C (Fig. 13). Zuoz is located at a height of about 1'750 m above sea level.

The average wind speed is lower in winter than in summer. However, the highest peaks observed, W ≈ 30 km/h, occur in winter as well as in summer (Fig. 14).

Relative air humidity scatters in a smaller range in winter than in summer (Fig. 15).

Limiting wind speed to W ≤ 2 km/h yields the tower frequency scatter becoming noticeably smaller than for all wind speeds (Fig. 16; compare to Fig. 11). However, the f1a frequency range reduces to f1a = 1.44...1.58 Hz only. For f2a, the numbers are now: f2a = 1.83...1.96 Hz.

Trying to isolate an air humidity effect on f1a through splitting rel.H. into the ranges rel.H. = 0...85% and rel.H. = 85...100% yields, that this is not possible: The respective diagrams for f1a as a function of time look the same.

Figure 11. Tower frequency f1a as a function of time.

Figure 12. Tower frequency f2a as a function of time.

Figure 13. Tower frequency f1a and air temperature T as a function of time.

Figure 14. Tower frequency f1a and wind speed W as a function of time.

Figure 15. Tower frequency f1a and air relative humidity rel.H. as a function of time.

Figure 16. Tower frequency f1a for wind speeds W ≤ 2 km/h as a function of time.
7 RESULTS: 1 MONTH'S ANGLE OF SIGHT

Out of the 16 months observed two months delivering a distinct message are shown in Figures 17 and 18.

In summer, the mean values of f1a and air temperature T are changing in parallel: high temperature means high frequency f1a (Fig. 17).

Although not appearing in the same simple form, the same is true in winter (Fig. 18).

This is a straightforward contradiction to what was found using a 16 month's angle of view. This needs further discussion.

No simple relationship between the monthly development of the mean values of f1a versus wind speed as well as air humidity can be observed.

8 RESULTS: 1 WEEK'S ANGLE OF SIGHT

Checking the graphs for all 68 weeks monitored yields that for the case with the air temperature exhibiting large daily amplitudes between 0°C and about +20°C the tower frequency shows a similar behavior over time as temperature: Increase in temperature also means increase in frequency (Figs. 19, 20). This result is similar to the one found in the last Paragraph.

9 RESULTS: A COUPLE OF HOUR'S ANGLE OF SIGHT

Whereas the tower frequencies as well as the meteorological parameters generally change with a rhythm of days, weeks, months or seasons, wind is a parameter changing with a rhythm of hours, minutes or seconds.

This became clear when checking the graphs for the 68 weeks monitored, now including tower frequency, air temperature, wind speed WX in X-direction and Xrms-value of the tower acceleration. As an example, such a diagram for week 30/2012 is presented in Figure 21.

Going into the details of this graph yields the tower frequency decreasing from f1a = 1.505 Hz to f1a = 1.445 Hz and increasing back to the original value within a time window of one to two hours (Fig. 22).

Going into details even further yielded the tower vibrational velocity reaching values of v = 4.6 mm/s and v = 1.52 mm/s in the two orthogonal directions X and Y respectively.

A second example for a case of a wind generated drop in tower frequency is given in Figure 23. Here, f1a drops from f1a = 1.48 Hz to f1a = 1.415 Hz and recovers within one to two hours.
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BELL RINGING EXCITED TOWER VIBRATIONS

10.1 General
San Luzi Bell Tower bell ringing schedule is discussed above. In a first attempt, bells 1 and 2 were not included in the investigation. They both produce less than $v = 1$ mm/s tower vibrations.

At the beginning, we also did not concentrate on bell 4. However, since this bell produced vibrations with a maximum in X-direction $v = 1.8...2.1$ mm/s an eye was kept on this.

The primary subject of investigation was, however, bell 3. It has to be mentioned here that this bell has been taken out of service from August 15, 2012, to January 27, 2013. This happened subsequently to a visual inspection of the tower state of health by a specialist for "old stones". After discussing the situation with all people involved in this project it was decided to take the risk of further operating this bell. Otherwise, a very important piece of information would have been lost: Is there a relationship between bell 3 excited vibrations and the tower frequency?

10.2 Ringing Bell 3
Bell 3 is operated as a single once a week at the Saturday 6.01 pm schedule only. Figure 24 gives the maximum tower velocity values for these events having occurred in the 16-month's monitoring period.
To include more values, Figure 25 shows the maximum tower velocity for all cases where bell 3 has been included in the ringing. In addition to the 6.01 pm single ringings shown in Figure 24, this includes the 5.01 am multiple bell ringings and those related to probable funerals in some afternoons.

The result is disappointing: No relationship between the maximum tower vibration and its frequency can be established. The tower velocity is always more or less the same, showing signs of increase with time. Telling us that something should be done with bell 3 as soon as possible.

10.3 Ringing bells 2 and 4

To check, whether or not San Luzi Bell Tower is following some rules of basic (linear) physics, tower vibrations excited through bell 2 were subsequently investigated into. Because bell 2 is single activated in the daily 5.01 am schedule except on Sundays, much more values are available than for bell 3.

And: The results are encouraging (Fig. 26). With the bell frequency being $f = 1.23\, \text{Hz}$, tower vibrations are larger for $f_{1a} < 1.5\, \text{Hz}$ (in summer) than for $f_{1a} > 1.5\, \text{Hz}$ (in winter).

A similar check was performed for bell 4. Not very many values are disposable here again because bell 4 is operated in the Saturday's 6.01 pm schedule only.

But again: The candidate "theoretical (linear) physics" gets 100 points: With the bell frequency being $f = 1.63\, \text{Hz}$, tower vibrations are smaller for $f_{1a} < 1.5\, \text{Hz}$ (in summer) than for $f_{1a} > 1.5\, \text{Hz}$ (in winter) (Fig. 27).

11 SUMMARY, RESULTS, DISCUSSION

11.1 General

San Luzi Bell Tower vibrations under ambient as well as bell operation excitation were monitored together with the meteorological boundary conditions from June 11, 2012, to October 7, 2013. This sums up to about 477 days, 68 weeks or 16 months. Continuous vibration and temperature monitoring was performed during 20 minutes every hour. Bell operation excited tower vibrations were acquired upon crossing of a 0.15 mm/s² trigger value. Meteo values were determined every 10 minutes.

Monitored data was transferred via 3G-link to our office. Meteorological values were determined and delivered by Metoemedia Schweiz.

8 GB raw data in .msd-format was acquired primarily. The final project file was of a 120 GB size. This is mainly due to the need of transforming the raw data into ASCII-format.

Data processing included the GeoDAS, NI Diadem and Holzer Informatik software packages.

11.2 Tower fundamental frequency $f_{1a}$

The fundamental tower frequency varied in the range $f_{1a} = 1.42\ldots1.59\, \text{Hz}$. This corresponds to a change of system stiffness for the tower of 22\ldots23% between the two extremes.

Frequency variation has two sources:

- change in air temperature,
- change in wind activity.

In more detail:

- The system "tower" is stiffer in winter than in summer.
- With temperature changes on a monthly, weekly or daily schedule, the system "tower" is stiffer for high temperatures than for low ones.

- Strong wind results in a sudden decrease of the tower frequency.

11.3 Bell excited tower vibrations

Bells 1 and 2 produce tower vibrations $v < 1\, \text{mm/s}$. This is definitely non-critical.

Bell 4 produces tower vibrations up to $v = 1.8\ldots2.1\, \text{mm/s}$. This is not critical but worth to keep an eye on.

Bell 3 produces tower vibrations up to $v = 11.4\, \text{mm/s}$. This is not acceptable.

It is not possible to establish a simple relationship between bell 3 excited vibrations and the tower frequency.

Strong wind produces tower vibrations up to $v = 4.6\, \text{mm/s}$. This is more than the Codes allow.

11.4 Discussion

The scatter in tower frequencies is much larger than expected. Obviously, the tower is significantly cracked. What may happen: Upon exciting the tower with forces with $f < f_{1a}$ (including wind!), the cracks open. For $f > f_{1a}$, they don't.

It might therefore be a good idea to distinguish the two cases when discussing resonance distances for old (cracked) bell towers in Codes like [1].

The influence of air temperature on the tower frequency is ambivalent. Based on a one-year scale, the tower is stiffer for low than for high temperatures. Based on a monthly, weekly or daily scale, the contrary is true.

The first behavior is known: In winter, a structural system including its foundation freezes and its stiffness increases.

The second behavior has been mentioned (to our knowledge) once in the literature only. The explanation presented by Saisi and Gentile in [4] is: Due to increasing temperature the single stones expand, the cracks close and, as a result, the system is better "compacted" and therefore stiffer.

12 PROBLEM SOLUTION

The problem with bell 3 cannot be solved through moving the bell frequency far enough from the tower frequency range. We cannot go low enough (to $f = 1.23\, \text{Hz}$, e.g., where bell 2 is). And we cannot go high enough (higher than $f = 1.63\, \text{Hz}$, e.g., where bell 4 is). There are technical limits with changing bell frequencies. Solutions with using TMD's or cracked yokes for bells 3 and 4 are looked for, now. The problem with cracked yokes is finding a solution not killing the bell's sound.

ACKNOWLEDGMENTS

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