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Case studies of structural natural frequencies assessment and application in SHM and the calibration of FEM models

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Abstract

In this paper, we will present the equipment and method by which we assess the natural frequencies on site. The data motivated us to start estimating the eigenfrequencies of structures and apply the results to calibrate FEM models. Several case studies will be presented in which the calibration method of FEM models via structural natural frequencies identified onsite were applied. The application of this method is very useful during the assessment of the safety of existing buildings and the design of their renovation, reinforcement or rehabilitation. FEM programs with very high possibilities of static and dynamic analysis of structures in the linear and nonlinear field are in use now. We can expect reliable analysis results from a well-calibrated model. Calibration is required to make the model, which includes, at least indirectly, any imperfection that exists in the structure, and which cannot be registered in any other way. Our experience with low-rise structures with great stiffness will be compared with the published experience of other authors. The possibilities of structural health monitoring will be shown also, by comparing the natural frequencies obtained by measurements at different times: before, during and after the structural rehabilitation. This method is not omnipotent, therefore, except for the advantages, we shall show limitations of method related to the type of structure, weather conditions and other. In second part we shall present some case studies from the literature. In order to motivate the owners, as well as the fellow designers, at the end some accidents that may have been avoided if this or other SHM methods had been used will be shown.

Key words: microtremors, natural frequencies, structural health monitoring, FEM, calibration

1 Introduction

The dynamic properties of structures are possible to evaluate by measurements on the structure excited by shaker or impulse hammer; or on the structure, which is excited by microtremors. Ambient vibrations or seismic noise (microtremors) are the results of processes and phenomena in nature as well as human activity, spreading in soil and transmitted to the structure. Buildings, as well as soil, vibrate in all three directions NS, EW and vertical.

1.1 Motivation

During 2003 and 2004, we worked on the structural design for a business complex in Zagreb later called the Eurotower. Measurements on it were done in the first half of 2007 by prof. Herak et al within the NATO SfP 980857 Project [1]. Comparing the measurement and calculation results, we were very surprised by the 100 % match of the first tone as well as the drastic differences in the higher tones. This made us even more motivated to check and adopt, if it is possible, this method for the analysis and assessment of existing structures as well as to better understand the results of our calculations.

Table 1. Comparison of measured and calculated values

Mode	**Measured f** [Hz] **[1]**	**Calculated f**[Hz]	**Difference Δf** [Hz]	**Percentage**
1	0.44	0.44	0.00	0
2	0.73	0.47	0.26	55,3
3	1.95	0.88	1.07	121.6
4	3.83	/	/	/

For this structure, we checked only the three first frequencies. Later we calculated up to fifty. Table 1 shows the measured and calculated values and their comparison. On the other hand, we use very powerful programs for the analysis of structures by the finite element method. Without quality input data and results control, accurate results cannot be expected, which also directs us to other methods of testing structures.

1.2 HVSR Technique

By analysing strong motions, records in Japan found the H/V spectral ratio. On soft soils, horizontal displacement components are larger than on vertical ones, while on hard soils they are approximately equal in shape and intensity. Over the H/V spectral ratio, it is possible to estimate the dominant frequency [1]. Although this method has been known from earlier, after the Nakamuras article from 1989 it is an accepted practice of seismic micro zonation.

Following wide applications in seismic micro zoning, it is later applied for the evaluation of natural frequencies of structures, especially after research carried out in the framework of the SESAME project [1]. In order to apply this method to the structures, the

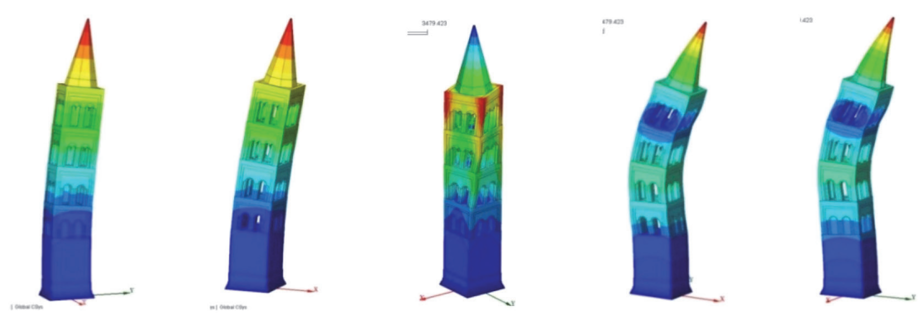
following hypothesis should be adopted: the structure is a single-degree-of-freedom model and the vertical component does not change during the propagation in the structure. Besides the natural frequencies, the value of modal damping, amplification and modal shape can be assessed too.
In relation to the other methods for estimating natural frequencies of structures, this technique has the following advantages: NDT, quick and simple (cheap) measurements, no time dependence, so one can perform a series of measurements on the structure with only one device. We use the TROMINO device for collecting data. The sampling frequency is 512 Hz with a sampling period from 10 to 20 minutes. For the analysis of collected data, we use GRILLA software [2].

2 Case Studies

We shall present a few case studies in which we used this technique for structural natural frequencies assessment. Each of them has something specific that is interesting to be presented as follows:

2.1 St. Anastasia Cathedral Bell Tower in Zadar

The bell tower of the cathedral in Zadar was built in two phases. The ground floor and the first floor (height of 16.6 m) were built in the 15th century; while the rest (height 38.3 m - in total 54.9 m) was upgraded in 1885. The bell tower was built with carved stones of limestone, the older part from the local quarries, while the newer part mainly from Vrnik Quarry near the island of Korčula. Five years after the construction was completed, cracks appeared in the 15th century parts of the bell tower [3]. The natural frequencies assessment was performed as part of very extensive examination works on the bell tower structure.



a) The 1st mode Y direction | b) The 2nd mode X direction | c) The 3rd mode torsional | d) The 4th mode Y direction | e) The 5th mode X direction

Figure 1. Modes

We used the results for the calibration of the FEM model. During the multi-step calibration process of the FEM model, it is necessary to change and adapt boundary conditions, geometric properties, material properties. The model was calibrated in more than a few steps and modal analyses were performed (Fig. 1) whereby we have well matching between measured and calculated frequencies, differences from 0 to 10.7 % (Table 2). The same table compares our measurements with those performed by Herak et al which also match well, with differences ranging from 2.9 to 4.7 %. The monitoring of the cracks in the bell tower is ongoing. Upon completion of the monitoring, we plan to repeat the measurements to determine whether there are differences in relation to the first results of natural frequencies.

Table 2. Comparison of natural frequencies

Mode	**Calculated after calibrating f** [Hz]	**Measured f** [Hz]	**Difference Δf** [Hz]	**Percentage** [%]	**Measured by Herak et al [4] f (Hz)**	**Difference Δf** [Hz]	**Percentage** [%]
1	1.69	1.7	0.01	0.6	1.78	-0.08	4.7
2	1.70	1.7	0	0	1.78	-0.08	4.7
3	4.98	4.5	-0.48	10.7	4.71	-0.21	4.7
4	6.53	6.9	0.37	5.4	6,7	0.2	2.9
5	6.81	6.9	0.09	1.3	6,7	0.2	2.9

2.2 Peristyle of Diocletian's Palace in Split

The Peristyle is the central square of the palace, surrounded by the protiron and porches. Throughout history, many buildings were constructed inside and beside the Peristyle. Some of them are still preserved on the west colonnade. The eastern colonnade was set free from the attachments in the second half of the nineteenth century. Very complex boundary conditions were given to the original structure of the Peristyle. The present aggregate consists of five parts: St. Rocco Chapel, East colonnade, Vestibule with protiron, building block 1 and building block 2 (Fig. 2). Data for natural frequencies assessment, were registered on 104 sites, for a period of 20 minutes each, and grouped in 31 verticals. The FEM model was calibrated by these results. We needed to make many changes in the FEM model to calibrate it. The results of modal analyses of the calibrated model and assessed natural frequencies are shown in the diagram (Fig. 3). By comparing the registered natural frequencies with those obtained by modal analyses, it is evident that we have a very good match. Differences generally occur in the higher tones, which is not surprising considering the very complex structure. We did not recognize the oscillations of roof and floor structures, but that was not our point of interest. In the first 14 modes, only one frequency was not recognized by measuring. A few modes are shown on Fig. 4, 5 and 6.

Figure 2 Situation

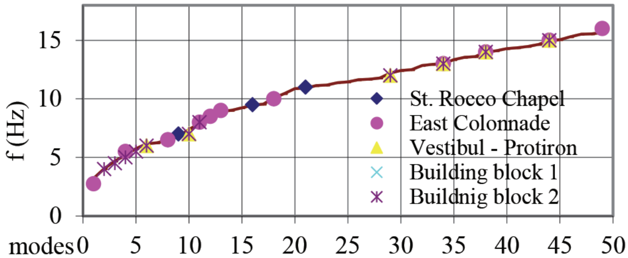


Figure 3 Comparison of frequencies

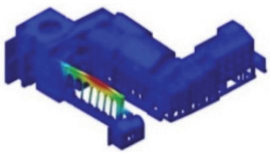


Figure 4 1st mode

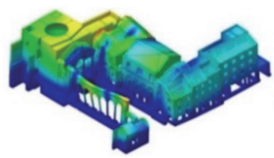


Figure 5 10th mode

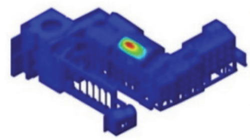


Figure 6 30th mode

2.3 St. Krševan (Chrysogonus) Church in Zadar

The church of St. Krševan is a Romanesque three-nave basilica with semicircular apses. It was built of ashlar masonry in lime mortar. In the early twentieth century, it was thoroughly reconstructed under the direction of Ć. Iveković. After a century, it was necessary to rehabilitate the church. Part of the remediation plan was to increase the seismic resistance of the structure. Static and modal analyses were conducted. The structure was analysed in two FEM models, one with a complete roof structure (Fig. 7) and another without roof structure above the main nave. Measurements were carried out in three phases: prior to commencing the rehabilitation works, during the repair works (without roof structure above the main nave) and after the completion of the structural repair. Besides the calibration of the FEM structural model, we wanted to check the influence of interventions on the change of natural frequencies. The calibration of models satisfied only the first tones (Table 3). Matching higher tones failed for two reasons: the specific structure and relatively simple model with plate and shell elements. Changing the natural frequencies through three test phases were the lowest during reconstruction, greater before reconstruction and the highest after reconstruction. Natural frequencies after removing the roof fell by 27.5 to 10.2 %, an average of 18 %. After the reconstruction the first (42.9 %) and fourth (21.4 %) increased extremely (Fig. 8).

Table 3. Comparison of calculated and measured 1st natural frequency

Model	**Calculated f** [Hz]	**Measured f** [Hz]	**Difference Δf** [Hz]	**Percentage** [%]
Model 1	4.124	4	0.124	3.1
Model 2	2.44	2.5	-0.060	2.4

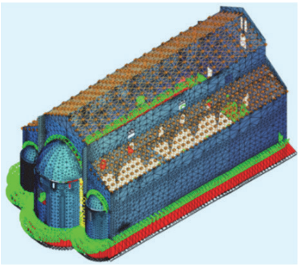


Figure 7. FEM model 1

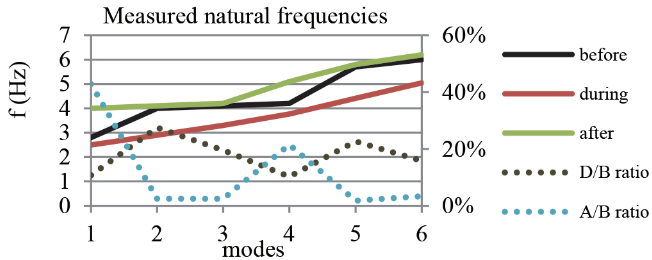


Figure 8. Comparison of natural frequencies

2.4 The Ex Puppet Theatre in Zadar

The building of the former puppet theatre was built between the two world wars as part of GIL centre. The floor number of the building is GF+2. The basic structure consists of RC columns and beams in longitudinal facades, semi-prefabricated RC ceiling with brick infill, and infill brick walls at the ends of the building. There are no beams between the columns in traverse direction, so one cannot speak about the framework behaviour in this direction. In the longitudinal direction, the framework behaviour of the structure is also questionable.

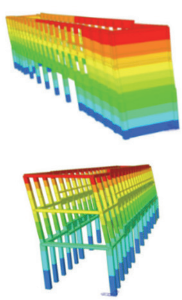


Figure 9. FEM model 1
and FEM model 2

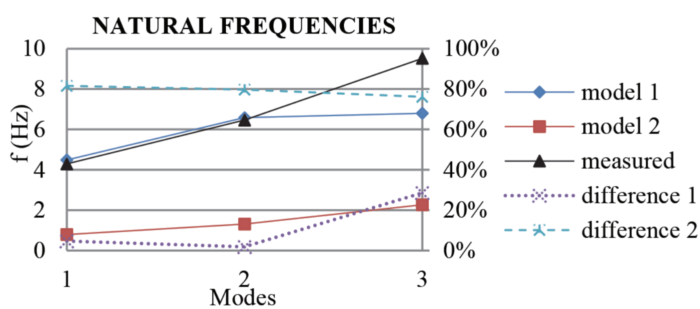


Figure 10 .Comparison of natural frequencies

Within the structural safety assessment, it was necessary to determine the structure behaviour between the two options, including infill walls with or without them (Fig. 9). So two FEM models defined in accordance with these options were made on which modal analyses were conducted. The results obtained by assessment of natural frequencies showed a high degree of matching with the model with included infill walls (Fig. 10).

2.5 St. John of Capistrano Monastery in Ilok

The monastery of St. John of Capistrano in Ilok is a complex building with centuries-old history. During that period, it was built, upgraded and reconstructed until it reached the current layout, which includes part of the city walls with a round tower. It consists of three wings and a tower. The floor number of the building is GF +1. The walls are built of solid brick in lime mortar. Above the ground floor, there are brick vaults, above the first floor, there is a wooden structure, and the roof structure is wooden. The assessment of natural frequencies was carried out as part of extensive testing of the mechanical properties of the structure. We performed the measurements in two phases. In the first phase, we measured at 30 points. In the second phase, we performed 41 measurements. Repeated measurements in the second phase were prompted by doubts about the accuracy of the first phase. From the results of the first analysis, it was not possible to estimate the natural frequencies of the structure. The reason for this is the structure of low height and high stiffness. Similar problems appeared when natural frequencies of low-rising building schools in Canada were assessed (Tischer et al [5]). With additional analyses, results were obtained that could be used to calibrate the FEM model. Comparing the natural frequencies, we can conclude that from 50 tones obtained with modal analysis (Fig. 11 and 12) by measuring on the structure, we identified 31 of them (Fig. 13).

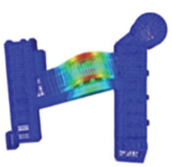


Figure 11. 1st mode

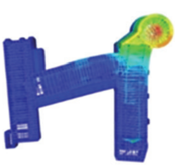


Figure 12. 2nd mode

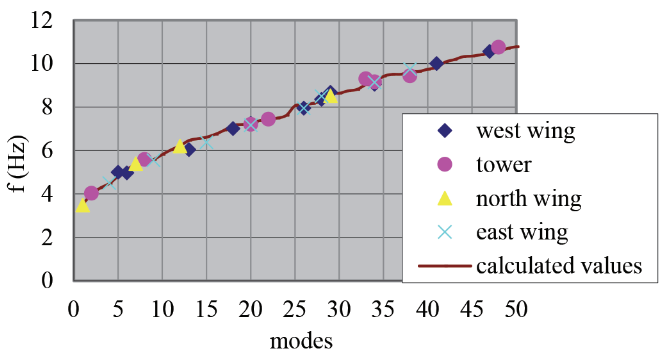


Figure 13. Comparison of calculated and measured frequencies

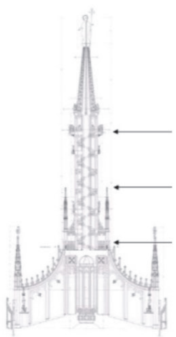
3 Experiences of other authors

3.1 Passive characterization of low rising School Buildings in Canada [5]

In 16 schools, 101 buildings, located in Montreal were studied, determining their dynamic properties using ambient vibration testing. These tests were conducted with regard to the particularly significant purpose of schools during regular use and after earthquakes. Lessons learned from the earthquake have shown that school buildings are especially vulnerable. In the low rise building there is the problem of estimating natural frequencies. In 77 buildings it was possible to evaluate natural frequencies; of which in 22 it was possible to estimate only the first three modes.

3.2 Dynamic properties of the Guglia Maggiore of the Duomo in Milan [6]

Guglia Maggiore is a carved stone bell tower structure on the roof of the cathedral in Milan. Overall, the structure extends to 40 meters in height. On Fig. 14 are marked the places where accelerometers were placed. The results of the research conducted by Busca et al [6] inter alia show the changing of natural frequencies depending on the wind speed and time of day: day or night (Fig. 15). The changes of day (high traffic) and night (low traffic) and the wind speed significantly affect the changing of natural frequencies.



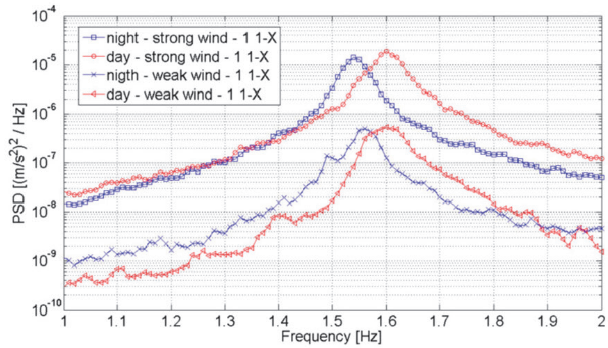


Figure 14. Guglia maggiore [6] **Figure 15. Changes of natural frequencies [6]**

3.3 Dynamic monitoring analysis of Mallorca Cathedral [7]

Headed by Prof Roca from Universidad Politécnica de Catalunya [7], an extensive multi-year static (cracks, relative displacements or convergences, piers inclination, environmental parameters: temperature, relative humidity, wind direction and velocity) and dynamic monitoring of the cathedral in Mallorca was conducted. We chose the results which show changes of natural frequencies during the year due to changes in temperature (Fig. 16) and surface of multiple regression for temperature, humidity and natural frequencies (Fig. 17). These studies have shown that the temperature and relative humidity had significantly affected the dynamic properties of the building so that the values of natural frequencies changed up to 3 %.

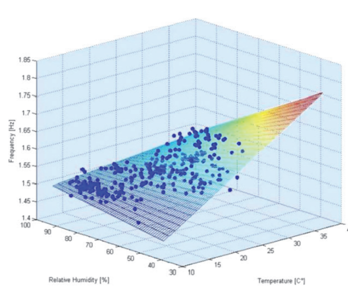


Figure 16. Changes of natural frequencies [7] **Figure 17. Regression surface [7]**

3.4 Wooden structure testing [8]

A series of testings was carried out on the timber building by shaking table in 2011 in EUCENTRE laboratories in Pavia. At the founding assembly of ISI on May 18th, 2011 the third test with accelogramme MONTENEGRO 15/4/1979 scaled to PGA 0.5 g was carried out, which we attended. After processing, the test results were presented, including changes in natural frequencies of the intact structure to the state after the third trial [8]. Although there were no visible damages on the structure, the first natural frequency decreased by 7.14 % due to loosening fasteners. It is interesting to note that partial reduction after each test was approximately the same with an average value of 2.44 % (Table 4).

Table 4. Changes of the 1st natural frequency

The 1st mode	**f** [Hz] **[8]**	**Period** [s] **[8]**	**Reduction** [%]	
prior to 0.07 g	5.250	0.191	Partial	Total
prior to 0.25 g	5.125	0.195	2.38	2.38
prior to 0.50 g	5.000	0.200	2.44	4.76
later on 0.50 g	4.875	0.210	2.50	7.14

3.5 Seismic surveillance of Cologne Cathedral [9]

Hinzen at al analysed data collected by five accelerometer stations mounted at Cologne Cathedral (Fig .18). They, as others, found that natural frequencies change depending on changes of external influences, but they also found two very interesting things. In periods when temperatures drop below 0° C, some natural frequencies change slightly but very clearly. They associated this with the freezing of moisture in the porous sandstones from which the cathedral was partially built. This is not surprising given the proportion of sandstone (marked as ***e*** and ***f*** on Fig. 19) in the walls of the cathedral. Analysing the effect of wind speed on the structure, they found that the spectral amplitudes increase exponentially with increasing wind speed (Fig. 20). With such shifts, it is possible for broken pieces of stone to fall from the cathedral, so they determined the wind speeds at which access to the cathedral is closed, in order to prevent injuries to pedestrians.

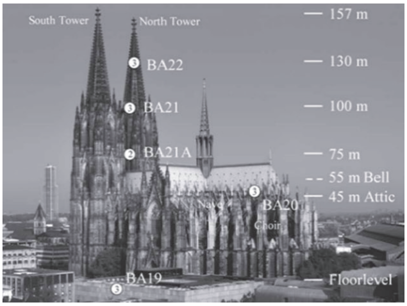


Figure 18. Cologne Cathedral with locations of five permanent accelerometer stations [9]

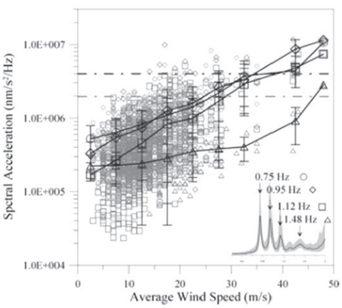


Figure 20. Correlation between wind speed and logarithm of the spectral acceleration [9]

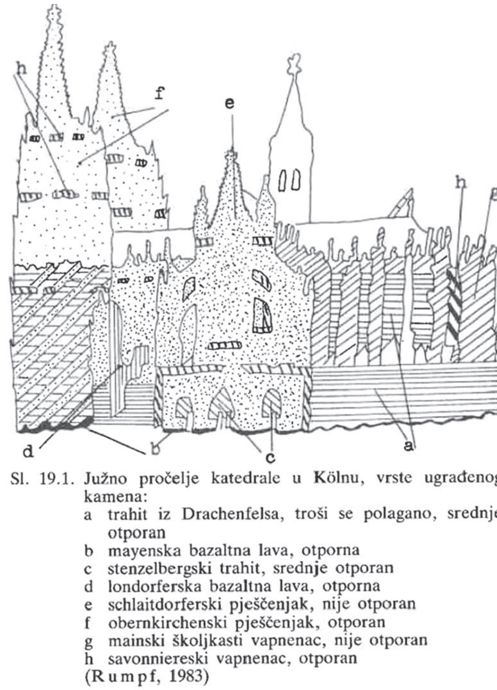


Figure 19. The southern façade of Cologne Cathedral, types of built-in stone [10]

4. Before concluding, the question

Would it have been possible to prevent the collapse of the following buildings if continuous or periodical dynamic monitoring had been implemented, parallel with, of course, other types of monitoring?

- Torre Civica in Pavia, Italy (March 17th 1989) - four killed (Fig 21)
- The bell tower of St. Magdalene church in Goch, Germany (May 24th 1993)
- Cathedral of St. Nicholas in Noto, Sicily (March 13th 1996)
- Bell tower of St. George church in Pleškovec, Croatia (June 4th 2008) (Fig. 22).

Figure 21. Remains of Torre Civica in Pavia today

Figure 22. St. George church Pleškovec [11]

5 Conclusions

FEM programs, with very high possibilities of static and dynamic analysis of structures in the linear and nonlinear field are in use now. Highly accurate and reliable results are expected of such programs. The quality of the results depends on the accuracy and reliability of the input data. The issue of the accuracy of input data appears for the existing buildings. With various testing methods (DT, SDT, LDT, NDT), it is possible to determine material properties and stress states. Boundary conditions, the influence of infill walls, imperfections and possible structural damage cannot be determined without an evaluation of natural frequencies and comparing the results with the structural analysis results. The problem is especially great in the cultural heritage, in which sometimes any one method of testing except non-destructive is to be used. The global behaviour of the structure is possible to determine on the basis of natural frequencies estimates. As the presented researches have shown, the natural frequencies change depending on the atmospheric changes. Therefore, it would be ideal to ensure continuous monitoring of significant buildings. It is often not possible to enable continuous monitoring, whereby periodical measurements should be carried out at certain time intervals in order to collect as much data as possible on the behaviour of the structure. By comparing the results of measurements after an earthquake or other event with previously collected data, the degree of damage to the structure can be determined.

Structural natural frequencies are good references for the calibration of the FEM model of structures. Natural frequencies of structures, combined with the results of other testing techniques, are a powerful tool for assessing the condition of the building and structural health monitoring.

Acknowledgements

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