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Document Version
Peer reviewed version

Citation for published version (Harvard):
Kaewunruen, S, Tang, T, Ngamkhanong, C & Aikawa, A 2018, 'Dynamic properties of flooded railway ballast', Paper presented at The International Conference on Modern Practice in Stress and Vibration Analysis (MPSVA 2018), Cambridge, United Kingdom, 2/07/18 - 4/07/18.

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Dynamic Properties of Flooded Railway Ballast

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Abstract. Railway ballast is granular media derived from crushed rock-based local materials from various sources. Despite the diversity of sources, railway ballast is the main component in ballasted railway track systems. It is installed under the railway sleeper to correctly align the track geometry; absorb dynamic wheel/rail interaction forces, preventing the underlying railway track subgrade from excessive stresses; enable the interlocking of skeleton track onto the ground; and provide lateral track stability. Generally, the multi-body simulation (MBS) of train track interaction idealises ballast as a spring-dashpot system. The dynamic modelling of ballast gravels relies on the available data, which are mostly focused on the condition at a dry condition. Recent findings show that railway track could significantly experience extreme climate such as long-term flooding. This phenomenon gives rise to a concern whether the ballast may experience higher level of moisture content than anticipated in the past. On this ground, a test rig for estimating the dynamic properties of rail ballast has been devised at the University of Birmingham. A non-destructive methodology for evaluating and monitoring the dynamic properties of the rail ballast has been developed based on an instrumented hammer impact technique and an equivalent single degree-of-freedom system approximation. This investigation focuses on the dynamic model of rail ballast submerged under the flood condition. By using the impact-excitation responses, best-fitting method is used for modal parameter identification of flooded ballast in a frequency range of 0-500 Hz. This study is the world first to identify dynamic parameters of flooded ballast as the modal mass, dynamic stiffness and dynamic damping coefficient, all of which are necessary for dynamic coupling vehicle-track modelling in an extreme event.

1. Introduction

Modern railway tracks have been evolved over centuries with operational speeds and economic viability. Today, there are two types of modern railway tracks: ballasted and ballastless tracks. The use of railway ballast for rapid construction of low to medium speed tracks (< 250 km/h) has been adopted over several decades [1]. Railway ballast or granular media is a main track component used in ballasted railway tracks worldwide [2]. It is mostly manufactured from crushed rock-based local materials from various sources such as crushed igneous rocks (granite, rhyolite, decite, basalt, quartzite or latite), crushed metamorphic rocks, crushed sedimentary rocks, crushed gravel (from river, lake), or sometimes even from waste products (such as crushed slag, chitter) [3-8]. Early railways did not place ballast as being highly significant to the makeup of a successful design of the permanent way. This position gradually changed and the performance of the ballast material is now highly regarded in the design process. Ballast is required to fulfil the task of maintaining the track in good alignment both horizontally and vertically. Track geometry deterioration can be rectified and restored quickly and cost-effectively over ballast [9-15]. To gain these benefits, the railway ballast must have the following characteristics:

- Durable to be able to absorb the loads imposed by the sleepers and transmit the loads to the sub-grade without undue breakdown,
- Hard wearing with high abrasion resistance in both wet and dry conditions,
- Angular with sufficient bulk density to resist movement of the track both longitudinally and laterally, and
- Particle size to allow packing and transfer of the loads of the track but with sufficient void space to allow free draining to assist shedding of all moisture.

Both the ballast and capping layer material can be seen in Figure 1. The functions or roles expected of the ballast layer have changed with time and the evolutional development of railway technology. There is some discussion of the functions of ballast in the references, “Railroad Engineering” (Ch 21) by WW Hay, “British Rail Track” (Ch 2), by the Permanent Way Institution, “A Review of Track Design Procedures” (Vol 2, Ch 4) by Jeffs and Tew, and “Track Geotechnology and Substructure Management”, by Selig and Waters [2, 15].

Figure 1. A typical ballasted track. The capping layer or called ‘subballast’ is prepared by compacting roller prior to laying ballast. In reality, the capping layer and subgrade are non-homogenous and cannot be accurately modelled by a simple constant elastic half-space nor a continuous layer. These layers are thus designed under higher safety margin or higher factor of safety by the allowable stress design concept [16-17]. The design takes into account the accumulated strains of these layers, which are often limited over a target design period (e.g. 15-25 years). Track maintenance cost function of deteriorated ballasted tracks will increase over years.

The functions of ballast can be divided into two criteria:

- Primary Functions, - the original purpose of ballast; and
- Secondary Functions, - the characteristics of the material that enable the ballast to fulfil and continue to fulfil its primary function and those functions that have been added with technology improvements and community expectations.

The primary functions of the ballast are to provide a uniform elastic vertical support; to fix the track in position laterally and longitudinally; and to facilitate the correction of the track level and line enhancing constructability and maintainability of railway network [1-4]. The secondary functions of ballast are to allow surface water to drain rapidly; to inhibit the growth of vegetation; to compensate for the presence of fouling material, to reduce noise; to provide electrical insulation of one rail from the other; and, to moderate the effect of frost heave in cold climates and the movement due to climate uncertainties [3, 18-26].

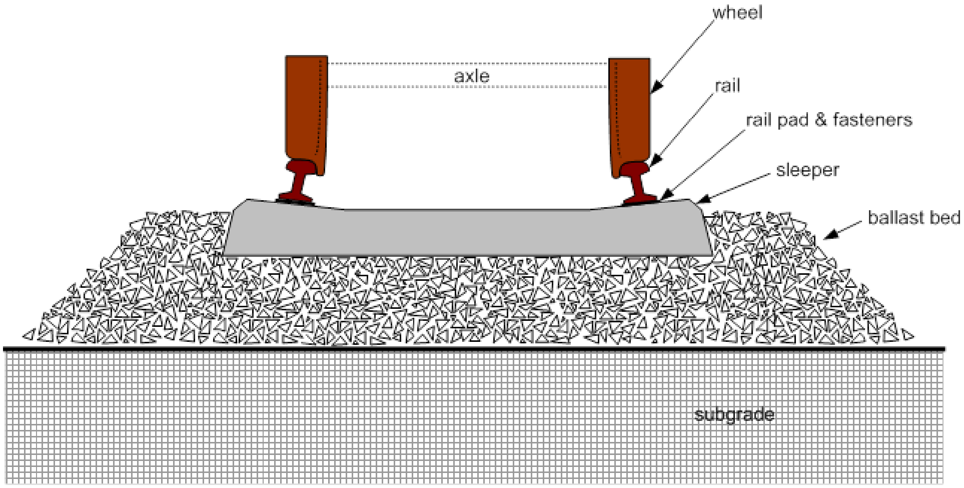


Figure 2. Ballasted track components [27].

Railway ballast is installed under railway sleepers to transfer the static and quasi-static stress (already filtered by rail pads and sleepers) from axle loads and wheel loads from both regular and irregular train movements, as shown in Figure 2. In accordance with the design and analysis, numerical models of a railway track have been employed to aid the track engineers in failure and maintenance predictions [28-31]. The current numerical models or simulations of railway tracks mostly consider the track components in perfect situation or in a normal weather condition. The effect of flooding on the dynamic behaviour of railway ballast has never been investigated, although it is evident that climate uncertainty has a significant influence on railway networks that affect the serviceability and performance of railway tracks [32]. The primary reason is due to a lack of information, either about the dynamic characteristics of railway ballast under variable flooding conditions, or about the dynamic train-track modelling to capture the flooding conditions. This paper is the world first to present dynamic modal identification of railway ballast in flooding conditions. It also highlights the experimental results obtained as part of the railway engineering research activities at the University of Birmingham (UoB) aimed at improving the dynamic performance and modelling of railway tracks globally. The proposed relationships could be incorporated into track analysis and design tools for a more realistic representation of the dynamic train-track interaction and load transfer mechanisms.

2. Dynamic coupling vehicle-track modelling

Over many decades, the dynamic coupling train-track simulations have adopted a multi-degree-of-freedom system (MDOF) approach for modelling train and track components. The MDOF system or so-called ‘multi-body simulation’ idealises the structural and mechanical components into nodes of freedom and string elements (spring and dashpot). This structural idealisation concept is very common in practice as well as in academia in order to reduce computation time and resources. The concept is to tune the component properties by vehicle and track receptances. Then, the calibrated model can be used for estimations of forces, actions, noise and vibration, and wheel/rail interface. Figure 3 illustrates the train-track simulation and Figure 2 shows the railway ballast idealisation for the numerical simulation [33-35]. The ballast component is commonly represented by a spring and a viscous damping coefficient.

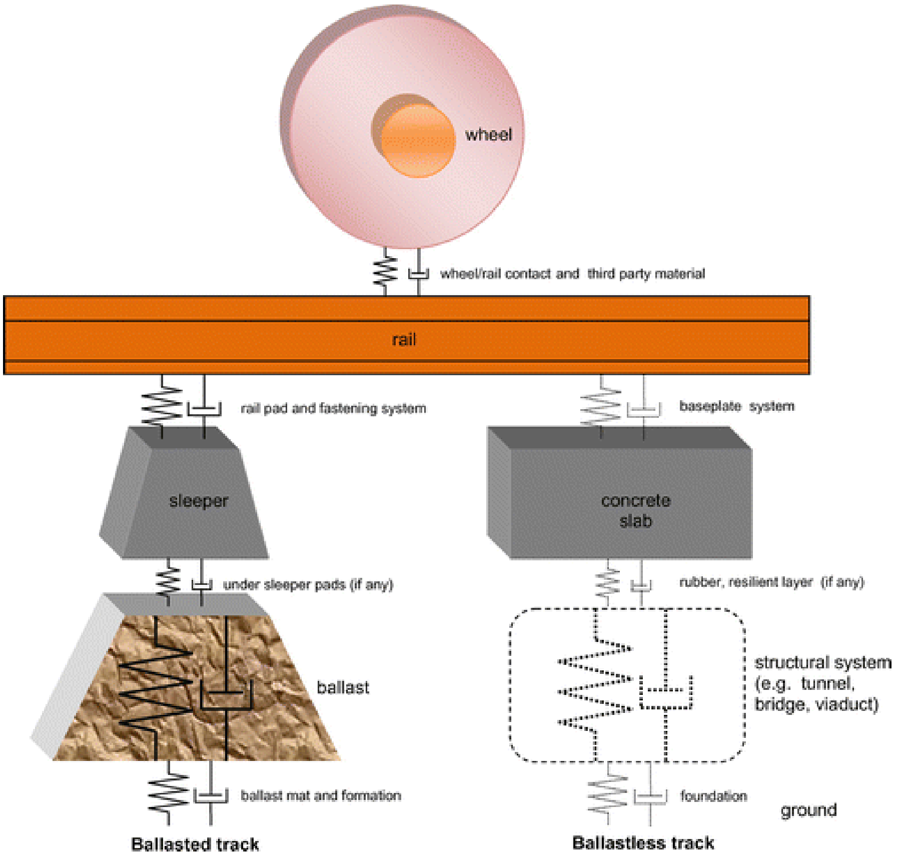


Figure 3. Coupling vehicle-track modelling

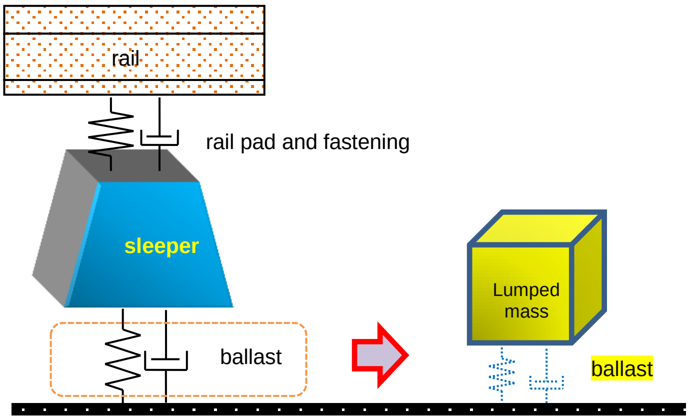


Figure 4. Ballast idealisation

3. Modal Identification

Ballasted railway tracks can be represented by either MDOF system or continuum model, depending on the specific purpose of analysis and the need for accuracy. The MDOF system is commonly used for vehicle-track interaction, wheel/rail interface, vibroacoustic analysis, and condition monitoring. The continuum model (e.g. FEM, BEM, DEM, semi-analytical methods, etc.) is generally used for component design, detailed damage investigation, contact and wave mechanics, structural dynamics, and forensic engineering. On this ground, the train-track dynamics of resilient ballasted tracks have been studied mostly based on a two-degree-of freedom (2DOF) model. This is because ballast and rail pads can be represented by series of springs and dashpots. In this study, ballast behavior is represented by the spring and dashpot. A SDOF-based method can thus be developed to help track engineers to evaluate the realistic dynamic characteristics of railway ballast required for the analysis using the numerical train-track simulation [36-37]. An analytical approach has been used to best fit the vibration responses. Considering the SDOF system in Figure 4, the dynamic behavior of ballast in the vertical direction can be described by the well-known equation of motion:

$$m\ddot{x} + c_p\dot{x} + k_p x = f(t) \tag{1}$$

$$\omega_n^2 = {}^{k_p}\!/_{m_p} \quad \text{, or} \quad 2\zeta\omega_n = {}^{c_p}\!/_{m_p} \qquad \text{(2a, b, c)}$$

$$\zeta = {}^{c_p}\!/_{2\sqrt{k_p m_p}}$$

where m_p, c_p, and k_p generally represent the effective sleeper mass, damping and stiffness of ballast, respectively. By taking the Fourier transformation of (1), the frequency response function can be determined. The magnitude of the frequency response function $H(f)$ can be represented as follows:

$$H(f) = \frac{1}{m_p}\frac{4\pi^2\beta f^2}{\sqrt{\left[1-4\pi^2\beta f^2\right]^2 + \left[4\pi^2\beta\left(\frac{c_p^2}{k_p m_p}\right)f^2\right]}} \tag{3}$$

where,

$$\beta = \frac{m_p}{k_p} \tag{4}$$

This expression contains the system parameters m_p, k_p and c_p that will later be used as the curve-fitting parameters. Equation 3 can then be used to identify dynamic properties or modal parameters of the flooded ballast. Note that these dynamic properties are the peak value at resonance, which can well inform the dynamic behaviors of the periodic system and are usually used in component design (considering the worst case scenario of resonant oscillations).

Considering Eq. (2), the fundamental frequency of railway ballast is relatively low if the track mass is significant. This implies that significant energy is required to excite the vibration of the SDOF system. By lowering the effective mass over a representative area of ballast (similar to a falling weight method with relatively small diameter of proctor, e.g. 50mm), the fundamental frequency of the SDOF system can be lifted to a higher range and it will require relatively lower energy to excite the system in order to obtain a realistic vibration response. In this study, a block of concrete (150mm x 150mm x 150mm) is used to represent the effective mass in the system. This enables the effective use of a modal hammer to excite the system [38-40].

4. Experimental Study

The experimental setup in this study is demonstrated in Figure 5. Preliminary tests (over hundreds of data sets) using a modal hammer (PROSIG) were carried out to evaluate the accuracy and precision of the vibration responses. The modal vibrations show excellent agreement between each test and it reveals that the effect of boundary condition is negligible in this test setup (relative to the size of the concrete block). The resonant frequency of the system is around 50-60 Hz, which are significantly above the minimum requirement for the calibrated, instrumented modal hammer (e.g. > 5 Hz). The boundary condition of the box is twice the side of the concrete block to avoid reflected shear wave. Since only vertical vibration is excited and measured, it was found that the boundary condition can be negligible and twisting and Rayleigh modes of vibration cannot be detected (as small-amplitude resonances). This pilot result allows further research into the effect of flooding condition on the dynamic behavior of railway ballast.

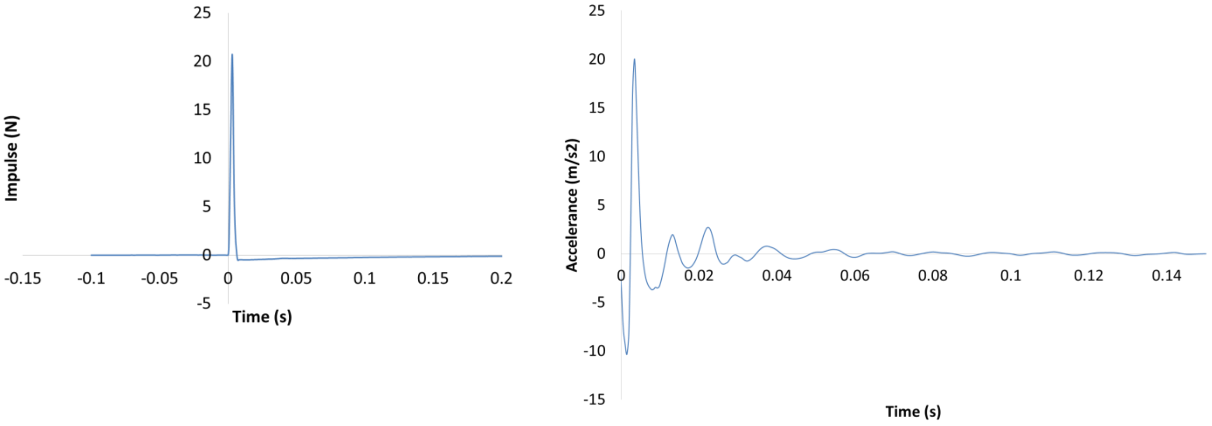
Figure 5. Experimental Setup

To obtain the receptance of the ballast, an accelerometer was mounted on the top surface of the concrete block, as illustrated in Figure 5. The mass of the concrete block is 8.2kg. It should be noted that the test box is set on a “strong” or “isolated” floor, the frequency responses of which are significantly higher than those of interest for the ballast. During the tests, the floor also isolates ground vibration from surrounding sources. To impart an excitation on the upper mass, an impact hammer was employed within a capable frequency range of 0–3,500 Hz. The frequency response function (FRF) could then be measured by using the PCB accelerometer connected to the PROSIG modal testing system, and to a computer. Measurement records also included the impact forcing functions and the coherence functions. As aforementioned, the FRFs describe the modal parameters of the vibrating system. The coherence function represents the quality of FRF measurements and should be close to unity.

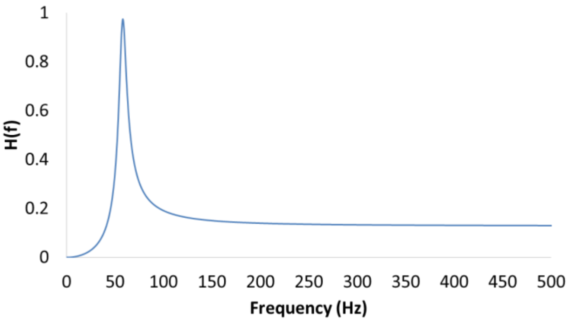
5. Results and discussion

It is important to note that railway operators do not commonly operate a train over a flooded railway track, to assure the safety of passengers and goods. This is due to the fact that the condition and integrity of railway tracks under flood condition cannot be inspected or assessed. In many cases, the flood water washes away railway ballast and also undermines the condition and load bearing capacity of subgrade and formation. Running a train on unstable track formation can cause train derailment, damage to assets and infrastructure, and failure of signalling system (e.g. switches and crossings). In addition, the track circuits and signalling could be malfunctioned and it is impossible to detect the location of the train. These issues are dangerous for train operations. The aim of this study is to establish a better insight into the dynamic characteristics of railway ballast in flooding condition. The insight will help track engineers to develop appropriate models of flooded railway ballast. Also, the dynamic model can be used for condition monitoring of railway tracks so that the track integrity can be adequately assessed in both normal and flooding conditions.

An example of the impulse, dynamic response and FRF of railway ballast in the experiments can be seen in Figure 6. It is found that the level of water slightly reduces the natural frequency of ballast system since the stagnant water fills the pore of gravels or clogs the ballast. Figure 7 also confirms the insight into the dynamic behavior of the ballast in flooding conditions. It can be observed from the variation bands that the use of natural frequency alone cannot be effective in determining the integrity of railway ballast. Note that the flooding condition tends to shift the natural frequency of the ballast layer (of the SDOF system). Considering that the representative mass is relatively constant, it implies that the water level tends to reduce the stiffness of the system



a) impulse **b)** accelerance



c) FRF

Figure 6. A test result (based on the average of 10 data sets)

Table 1 demonstrates the effect of flood level on the dynamic modal parameters of railway ballast. It can be observed that the increment of flood water level will reduce stiffness of ballast, whilst increase the damping coefficient. The quality of experimental result and the best-fitting can be seen from the correlation coefficient. The error of modal parameter identification is less than 3%. However, the influence of flood water on stiffness is relatively moderate with around 30% change observed. In contrast, it is apparent that the flood water can affect the damping significantly since the change in damping can be over 70%. This insight informs that the dynamic modeling of ballast needs to be updated. Based on the experimental results, it is proposed that a model of state-dependent properties (e.g. with additional dashpot) should be adopted for flooded ballast.

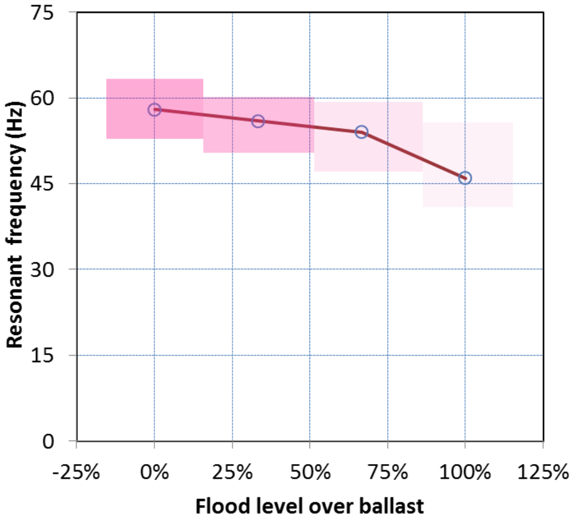


Figure 7. Natural frequency of ballast in flood conditions

Table 1. Dynamic properties of ballast in flood conditions (water temperature at 20°C).

	Stiffness (kN/m)	% ΔK	Damping (kNs/m)	% Δc	Correlation Coefficient (%)
Dry	1,036	0	0.3721	0	99.85
33%	1,009	3	0.5736	54	98.16
66%	986.2	5	0.6131	65	98.94
100%	708.4	31	0.6364	71	97.81

6. Conclusion

Modern railway tracks have widely adopted railway ballast, which is granular media from crushed rocks, as one of their critical components over centuries. The railway ballast is generally installed under the railway sleeper to align track geometry; absorb dynamic wheel/rail interaction forces; preventing the underlying railway track subgrade from excessive stresses; and, enable the interlocking of skeleton track onto the ground providing lateral track stability. Current practices in dynamic coupling vehicle-track simulations idealise track components into MDOF systems. However, up to day, only dynamic parameters of dry ballast condition have been investigated. Recent findings show that railway track could significantly experience extreme climate such as long-term flooding. Therefore, it is necessary to identify modal parameters of railway ballast exposed to flooding conditions. This study is the world first to highlight such critical conditions. Analytical and experimental studies have been conducted to address such the pressing issue. The modal experimental studies reveal an unprecedented insight into the dynamic properties of the flooded ballast. The flood condition can reduce the stiffness of the track system, whilst also increase the damping or energy dissipation of the track. It is important to note that this study considered a flash flood case only. In reality, the flood condition can also reduce the load carrying capacity and stiffness of the subgrade layer. In addition, the experiments in this study reveal that frequency-based condition monitoring technique might have certain limitation in practice. Future work will highlight the development of new

SDOF model that is more realistic and more capable to define state-dependent characteristics of the railway tracks submerged under flood conditions. The influence of impulse energy as well as the track mass will also be investigated in the near future.

Acknowledgement

The first author wishes to gratefully acknowledge the Japan Society for Promotion of Science (JSPS) for his JSPS Invitation Research Fellowship (Long-term), Grant No L15701, at Track Dynamics Laboratory, Railway Technical Research Institute and at Concrete Laboratory, the Universi-ty of Tokyo, Tokyo, Japan. The JSPS financially supports this work as part of the research project, entitled "Smart and reliable railway infrastructure". Special thanks to European Commission for H2020-MSCA-RISE Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Net-work" (www.risen2rail.eu) [41]. In addition, the sponsorships and assistance from CEMEX, Network Rail, RSSB (Rail Safety and Standard Board, UK) are highly appreciated. Financial support from BRIDGE Grant (Collaboration between University of Birmingham and University of Illinois at Urbana Champaign) is also grate-fully acknowledged.

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