New research developments in the assessment of the damping factor of railway bridges

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Abstract. A realistic and economical dynamic assessment of railway bridges requires accurate input parameters in mechanical. In this context, the applied damping characteristics significantly influence the accuracy of resonance effects predictions and the assessment of the compatibility between rolling stock and railway bridges. However, the EN 1991-2 standard prescribes highly conservative damping factors that do not represent reality. Consequently, in-situ measurements are frequently necessary to reclassify a bridge deemed critical in preliminary dynamic calculations. Regarding in-situ tests, measurement-based damping factors are inevitably accompanied by a scattering of the results due to the measurement method used, the individual scope of action of the person evaluating the test and the individual interpretation of the measurement data. This contribution presents a novel evaluation method for determining the damping factor based on in-situ measurements. The objective is to develop an easily applicable method that yields reliable and beneficial high damping factors while intending to reduce the scatter of the results and limit the scope of action of the person evaluating the test. The method is applied in a measurement campaign on 15 existing railway bridges, where it is shown that a clearly defined evaluation algorithm can significantly reduce the scattering of results. In addition, an approach is presented that makes it possible to determine the damping of railway bridges by calculation without the need for in-situ measurements. This first-time possible mathematical determination of damping represents an alternative to the overly conservative standard and enables a realistic assessment of the dynamic behaviour of railway bridges.

Keywords: Railway bridges, Damping, Measurements, Structural Health Monitoring, Condition Assessment.

1 Introduction

Railway bridges may experience significant vibrations during high-speed traffic, which can adversely impact both the supporting structure and the superstructure. To ensure dynamic compatibility between the rolling stock and the bridge structures, it is essential to evaluate the dynamic behaviour of railway bridges. This evaluation includes performing serviceability checks to confirm that the calculated vertical acceleration limits of the structure are within acceptable boundaries. In this regard, EN 1990/A1 [1] specifies that the vertical structural accelerations resulting from train crossings must not exceed a maximum limit of 3.5 m/s².

For dynamic calculations of railway bridges, many different mechanical models for the bridge and the crossing train with varying levels of complexity are available for practical application, which can be both two- and three-dimensional (see [2]). For a realistic and thus economical prediction of bridge vibrations and potential resonance effects, mechanical models require input parameters that correspond as closely as possible to the properties of the real structure. In this context, the bridge properties applied fundamentally influence the generated calculation results, whereby the damping characteristics, in particular, are of essential importance.

The damping properties of the bridge and all related energy dissipation mechanisms are usually summarised in a structure-related value - Lehr's damping factor ζ. Concerning the damping factor of railway bridges, EN 1991-2 [4] specifies damping factors depending on the type of construction and the span, which must be used in dynamic calculations of railway bridges. However, these normatively prescribed damping factors are regarded as the lower limit value of the damping to be expected in reality, which is why higher damping factors can almost always be generated from dynamic measurements. Fig. 1 shows a comparison between the measured damping factors for 29 steel (red diamonds), 43 concrete (green circles) and 31 filler beam (blue squares) railway bridges and the normative specifications (red and grey dashed line, see legend). The comparison in Fig. 1 illustrates the large discrepancy between normative specifications and reality. The consequence of the over-conservative approach of EN 1991-2 [4] is that railway bridges initially classified as dynamically critical can only be classified as dynamically uncritical after extensive and cost-intensive measurements of the structure and determination of the damping properties.

Further uncertainty about the realistic dynamic assessment of railway bridges lies in the measurement-based determination of the damping factor from in situ tests on the structure. In this context, the vibration excitation and test evaluation method used significantly influences the damping factor generated from measurements, with a considerable scattering of results depending on the method. Furthermore, the individual scope of action of the person analysing the in situ test is also a critical influencing factor, as this can significantly influence the result (see [5-7]).

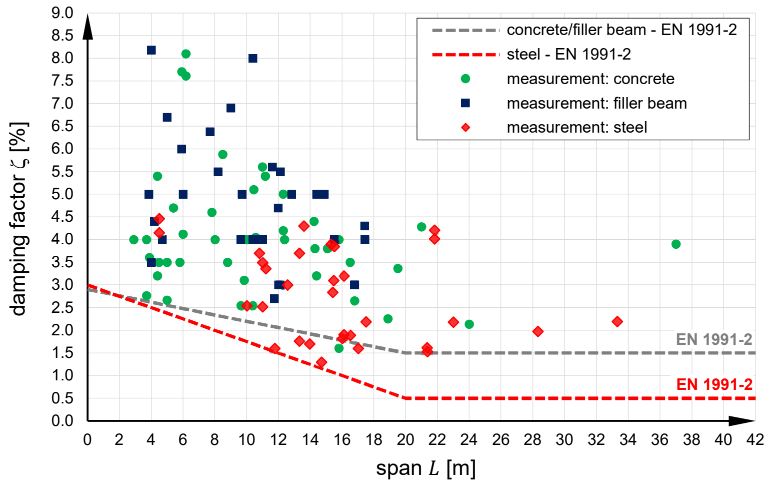

Fig. 1. Comparison between measured damping factors and specifications of EN 1991-2 [4] for steel, concrete and filler beam bridges in the Austrian rail network (source: [5], [8]).

In recent years the research activities of the Institute of Structural Engineering/Research Unit Steel Structures at TU Wien have been focused on the dynamic behaviour of railway bridges and a realistic and, at the same time, computationally efficient prediction of railway bridge vibrations. A central research focus is on the damping properties of railway bridges, with research activities including the development of novel evaluation methods for the determination of the damping factor based on measurements as well as the development of approaches for the realistic mathematical determination of the damping factor as a potential alternative to the normative specifications of EN 1991-2 [4]. This contribution presents the recent research developments in assessing the damping characteristics of railway bridges, whereby section 2 addresses measurement methods and novel evaluation procedures for the determination of realistic damping factors with low scatter of results based on in-situ measurements on the structure. Section 3 then provides an overview of an approach developed as part of the research activities for the mathematical determination of the damping factor of railway bridges with ballast superstructures.

2 Determination of the damping factor based on in situ measurements

To determine damping factors of railway bridges based on in-situ measurements of the structure, methods are available in both the frequency domain and the time domain; see [5-7]. This section presents a novel evaluation method in the frequency domain that extends the currently most commonly used standard method and its practical application (sec. 2.1). The new evaluation method aims to generate realistic high damping values with a low scatter of results while simultaneously minimising the individual scope for the person evaluating the test. Section 2.2 presents the results of a measurement campaign on 15 existing railway bridges in the Austrian rail network.

2.1 Novel evaluation method in the frequency domain

Determining the damping factor in the frequency domain is based on an amplitude-frequency response generated from measurement data, whereby the vibration amplitude of the system is determined as a function of the excitation frequency, as illustrated in Fig. 2. The standard method for determining the damping factor is the bandwidth method, where the damping factor is calculated based on the two frequencies for which the related amplitude has the value $1/\sqrt{2}$ in relation to the maximum (resonance). Strictly speaking, only three points out of all the data are used to determine the damping factor (labelled the 'point method' in this context), which entails uncertainties in the reliability and reproducibility of the results.

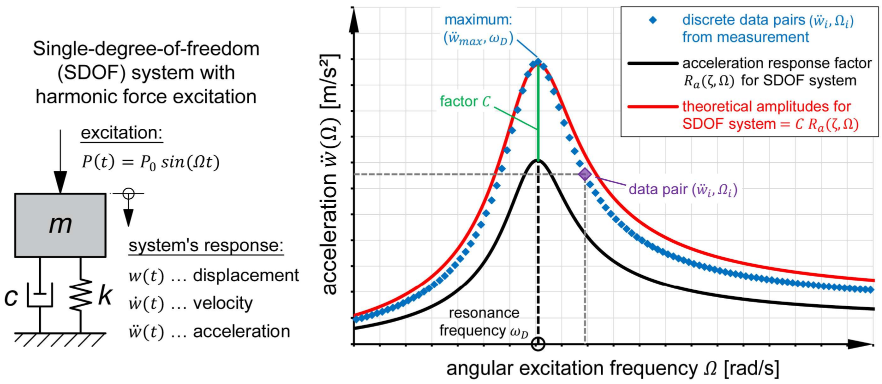

Fig. 2. Idealisation as a single-degree-of-freedom (SDOF) system with harmonic force excitation (left) and curve fitting of discrete data pairs from measurement by a continuous curve (right), see [5, 6].

Therefore, a novel evaluation method was established at the TU Wien, which considers not just a very few selected data points but all data points of the amplitude-frequency response to determine the damping factor (referred to as the 'integral method', [5]). The basic principle is to idealise the investigated system as a single-degree-of-freedom (SDOF) system with harmonic force excitation (see Fig. 2, left) and to adjust the theoretical response of the amplitude response factor $R_a(\Omega, \zeta)$

$$R_a(\Omega,\zeta) = \frac{\left(\frac{\Omega}{\omega_0}\right)^2}{\sqrt{\left[1-\left(\frac{\Omega}{\omega_0}\right)^2\right]^2 + \left[2\zeta\left(\frac{\Omega}{\omega_0}\right)\right]^2}} = \frac{\eta^2}{\sqrt{(1-\eta^2)^2 + (2\zeta\eta)^2}} \qquad (1)$$

to the discrete measurement data by varying the damping factor and by using the method of least square error minimisation in such a way that the greatest possible agreement between the theoretical curve and the measurement data is achieved (illustrated in Fig. 2, right). The result of this curve fitting method is a damping factor that is related to the response factor scaled by the factor C (red line in Fig. 2), which approximates the discretely measured data points (blue dots in Fig. 2) as closely as possible (background, see also [5-6] and [9-10]).

The damping factor determined based on this integral method depends on the frequency range under consideration in the amplitude-frequency response, whereby Fig. 3 illustrates the practical application. Fig. 3a shows an amplitude-frequency response generated from measurement data for an exemplary single-track steel railway bridge. For analysis purposes, energy level lines are introduced, which describe the reduction of the dissipated energy in relation to the energy dissipation at the maximum (horizontal dashed lines in Fig. 3a). The damping factor is subsequently determined as a function of the frequency bandwidth Δf associated with the energy level; the result is shown in Fig. 3b. Further, the energy level line $E_{\zeta,red} = 50\ \%$ (red dotted line in Fig. 3a) is used to define a damping factor as a result. Figuratively speaking, all data points above this line (red data pairs in Fig. 3a) are used to determine the damping factor, which results in a damping factor of 1.72 % for the example shown in Fig. 3. Alternatively, the mean value between the energy level lines $E_{\zeta,red} = 50\ \%$ and $E_{\zeta,red} = 75\ \%$ can also be used, which results in a damping factor of 1.70 % (area marked in green in Fig. 3b).

To determine a concrete damping factor related to the test, the damping factor ζ_{50} is defined as the result. In section 2.2, the damping factor for 15 railway bridges in the existing Austrian network is determined using this standardised procedure.

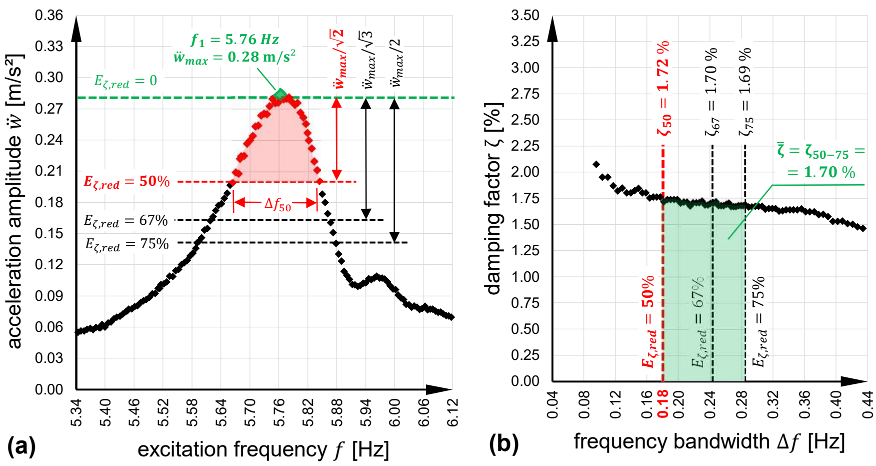

Fig. 3. Determination of the damping factor in the frequency domain based on discrete data pairs for one example bridge: (a) amplitude frequency response and (b) damping factor depending on the considered frequency bandwidth [6].

2.2 Measurement campaign on 15 railway bridges

This subsection presents the results of a measurement campaign on 15 existing railway bridges in the context of the measurement-based determination of the damping factor. The measurement campaign is part of a recently concluded research project and includes the measurement-based determination of the damping factor for 15 single-track steel railway bridges in the Austrian rail network. Fig. 4 exemplarily shows two selected bridges (designation B2 and B4) that are part of the measurement campaign. For all 15 bridges (labelled B1 to B15), dynamic measurements were carried out using force-excited vibration excitation and the damping factor was determined using the method described in section 2.1. The bandwidth method was also used to determine the damping factor as a direct comparison. Further details and background information on the measurement campaign, as well as the results and analyses of the damping factor, can be found in [6], to which reference is made here.

Fig. 4. Exemplary overview of two bridges of the measurement campaign (B2 and B4).

Fig. 5 illustrates the damping factors determined for all 15 bridges based on the methods in the frequency domain. The bridges are sorted by their increasing resonance frequency (first natural bending frequency f_1) along the abscissa, which lies between 4.27 Hz (B1) and 13.68 Hz (B15). For each bridge, several tests were carried out, with the results in Fig. 5 containing the damping factors based on the bandwidth method ('point method': ζ_{BW} – in grey) and the newly presented curve fitting method ('integral method': ζ_{50} – in red). Furthermore, the mean values of the damping factors for each bridge, including the standard deviation (expressed by the whiskers) are also depicted. The normative prescribed damping factors according to EN 1991-2 [4] are illustrated for comparison as well (horizontal black dashed lines, see legend).

Fig. 5 shows that the new integral method always yields higher damping factors than the bandwidth method. Notably, both values are based on the same amplitude-frequency responses. The standard deviation related to the mean values for individual bridges is slightly higher when the integral method is used. This is due to nonlinearities in the system behaviour, which lead to a higher standard deviation. The nonlinear behaviour can also be identified in Fig. 3b in the damping factor, which decreases with increasing frequency bandwidth. If the system properties were constant, the damping factors would be at the same level, independently of the frequency bandwidth. The qualitative trend in Fig. 3b is thus an indicator of non-linearities in the damping behaviour.

Another correlation that can be seen in Fig. 5 is that the measured damping factors are always and sometimes substantially higher than those in EN 1991-2 [4]. This shows great potential for revising the current normative specifications, with the new evaluation method providing reliable and realistically high damping factors as a possible basis.

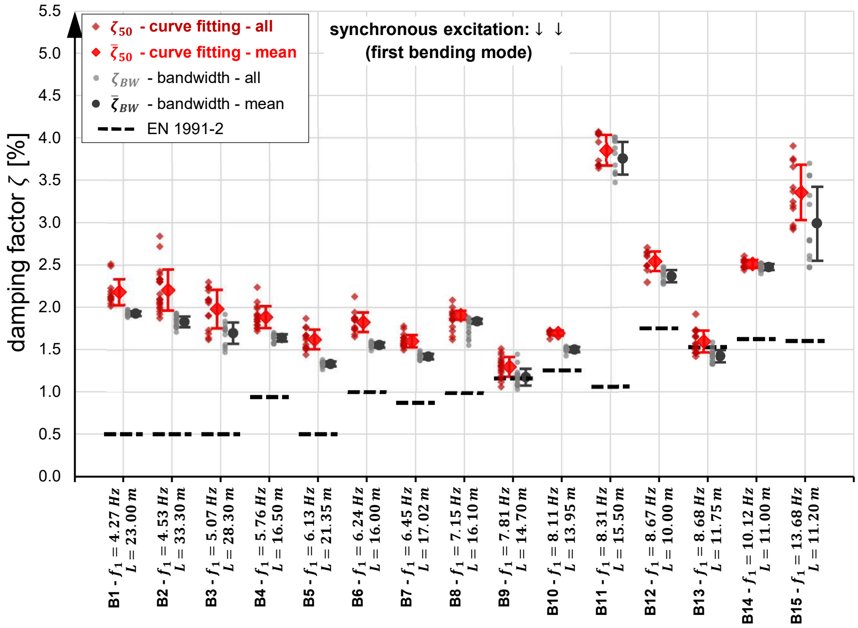

Fig. 5. Damping factors identified from measurements in the frequency domain (forced vibration) based on the curve fitting method and the bandwidth method for all 15 bridges.

3 Approach for mathematical calculation of the damping factor

The previous section 2 addresses the determination of the damping factor on the basis of in-situ measurements on the supporting structure. As part of the further research activities of the Institute of Structural Engineering at TU Wien in relation to the damping characteristics of railway bridges with ballast superstructures, an approach was developed that enables the mathematical determination of the damping factor of railway bridges (discussed in detail in [8] and [11-13]). The basis for this approach is provided by two-dimensional mechanical models of the bridge with varying degrees of complexity, as shown in Fig. 6.

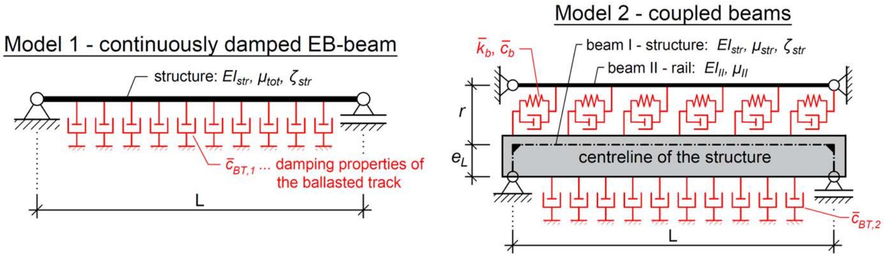

Fig. 6. Mechanical models with different levels of detail.

The mechanical models in Fig. 6 are a continuously damped Euler-Bernoulli beam (model 1) and a coupling beam model (model 2), which consists of two beams coupled via horizontal spring-damper elements. In both models, the red spring-damper or damper elements represent the stiffness and damping properties of the ballast superstructure. The basic principle in the model-related calculation of the damping factor is to separately determine the dissipative contributions of the supporting structure and the ballast superstructure and to superpose them as follows:

$$\zeta_{tot,i} = \zeta_{str} + \Delta\zeta_{bt,i} \qquad i = 1,2 \tag{2}$$

The calculated damping factor of the bridge $\zeta_{tot,i}$ is thus determined by a proportion of the supporting structure ζ_{str} and a proportion of the ballast superstructure $\Delta\zeta_{bt,i}$ according to Eq. (2). About the damping factor of the supporting structure ζ_{str}, reference values can be used, depending on the structure under consideration, which are given in [9] and [11], for example. The dissipative contribution of the ballast superstructure $\Delta\zeta_{bt,i}$ depends on the considered model (model 1 or model 2, Fig. 6). For model 1 it is defined as

$$\Delta\zeta_{bt,1} = \frac{\bar{c}_{BT,1}}{2\,\Omega_1\,\mu_{tot}} \tag{3}$$

depending on the damping coefficient $\bar{c}_{BT,1}$, the fundamental frequency Ω_1 and the mass distribution μ_{tot} (see Fig. 6). Model 2 also takes in two account the horizontal track-bridge interaction (damping coefficient $\bar{c}_b$) with the ballast superstructure's damping factor defined as:

$$\Delta\zeta_{bt,2} = \frac{\bar{c}_{BT,2}}{2\,\Omega_1\,\mu_{tot}} + \frac{\bar{c}_b\,\pi^2}{\Omega_1\,\mu_{tot}\,L^2}\left(e_b^2 + \frac{r^2}{2}\right) \tag{4}$$

Eq. (4) also includes geometric parameters such as span L, bearing eccentricity e and centreline distance r (see Fig. 6). As part of the research activities at the Institute of Structural Engineering/Research Unit Steel Structures at the TU Wien, the dynamic behaviour of the ballasted superstructure is investigated in a targeted and isolated way using special large-scale test facilities (see Fig. 7), which enables the precise determination of the damping parameters of the ballasted superstructure and the identification of their dependencies. Using the special test facilities, it is thus possible to specifically analyse the energy dissipation mechanisms occurring in the ballast superstructure under dynamic excitation and further derive model-related stiffness and damping parameters as a basis for the approach formulated in Eqs. (2) to (4), published e.g. in [14-15]. Initial comparative analyses between mathematically determined damping factors according to Eq. (2) and damping factors identified from measurements (see [12-13]) show that the mathematical approach provides realistic damping factors. Current and future research work is dedicated to further verifying and validating this novel approach for the mathematical determination of the damping factor based on comprehensive in-situ measurements of existing structures.

Fig. 7. Large-scale test facilities for isolated research of energy dissipation in the ballast superstructure: facility for investigation of longitudinal track-bridge interaction (top) and facility for investigation of vertical track-bridge interaction (bottom)

4 Conclusions

This contribution has presented a compact overview of the research work at the Institute of Structural Engineering at TU Wien in the context of assessing the damping properties of railway bridges, focusing on a reliable data-based determination of damping factors based on in-situ measurements and, in addition, on a mathematical determination of the damping factor in an amount corresponding to reality as an alternative to the overly-conservative and thus disadvantageous specifications of EN 1991-2 [4]. The approaches and methods presented provide a significant contribution to the realistic assessment of damping characteristics of railway bridges based on the combination of measurements and mathematical prediction and thus enable an economic dynamic assessment of railway bridges and the compatibility between rolling stock and infrastructure.

References

1. EN 1990/A1:2013 05 15 Eurocode: Basis of Structural Design – Amendment 1: Application for Bridges (consolidated version). Austrian Standard International, Vienna.
2. Zhai W, Han Z, Chen Z, Ling L, Zhu S (2019) Train-track-bridge dynamic interaction: a state-of-the-art review. Vehicle System Dynamics 57(7):984-1027. https://doi.org/10.1080/00423114.2019.1605085
3. Arvidsson T, Karoumi R (2014) Train-bridge interaction – a review and discussion of key model parameters. International Journal of Rail Transportation 2(3):147-186. https://doi.org/10.1080/23248378.2014.897790
4. EN 1991-2:2012 03 15 Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges (consolidated version). Austrian Standard International, Vienna.
5. Stollwitzer A, Bettinelli L, Loidl S, Vospernig M, Schellander J, Fink J (2025): Novel evaluation methods for data-based determination of damping factors in the frequency and time domain with application to railway bridges. Railway Engineering Science. https://doi.org/10.1007/s.40534-024-00373-1
6. Stollwitzer A, Fink J, Mohamed E (2022) Methods for reducing the output scatter of results for determining realistic damping factors of railway bridges – Part 1: method in the frequency range. Bauingenieur 97(5):153-164. https://doi.org/10.37544/0005-6650-2022-05-55
7. Stollwitzer A, Fink J (2022) Methods for reducing the output scatter of results for determining realistic damping factors of railway bridges – Part 2: method in the time range. Bauingenieur 97(10):341-352. https://doi.org/10.37544/0005-6650-2022-10-79
8. Stollwitzer A (2021) Developing an Approach for the Mathematical Calculation of the Damping Value of Railway Bridges with Ballasted Track. Dissertation, TU Wien. https://doi.org/10.34726/hss.2021.92244
9. Petersen C, Werkle H (2018) Dynamik der Baukonstruktionen. 2nd edn. Springer, Wiesbaden.
10. Chopra AK (2020) Dynamics of Structures: Theory and Application to Earthquake Engineering. 5th edn. Person Education Limited, London.
11. Stollwitzer A, Fink J (2021) Mathematical calculation of the damping value of steel railway bridges – part I: theoretical background. Stahlbau 90(4):305-315. https://doi.org/10.1002/stab.202100009
12. Stollwitzer A, Fink J (2021) Mathematical calculation of the damping value of steel railway bridges – part II: verification on the basis of existing bridges. Stahlbau 90(6):449-462. https://doi.org/10.1002/stab.202100013
13. Stollwitzer A, Loidl S, Bettinelli L, Fink J (2025) Approach for redefining the damping factor of railway bridges with ballast superstructure: model validation and guidelines for practical application. Railway Engineering Science. https://doi.org/10.1007/s40534-024-00373-1
14. Stollwitzer A, Bettinelli L, Fink J (2023) The longitudinal track-bridge interaction of ballasted track in railway bridges: Experimental analysis of dynamic stiffness and damping characteristics. Engineering Structures 274. https://doi.org/10.1016/j.engstruct.2022.115115
15. Stollwitzer A, Bettinelli L, Fink J (2024) Vertical track-bridge interaction in railway bridges with ballast superstructure: experimental analysis of dynamic stiffness and damping behavior. International Journal of Structural Stability and Dynamics, 2540008. https://doi.org/10.1142/S0219455425400085