Braid analysis of (low-dimensional) chaos

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We show how to calculate orbit implications (based on Nielsen-Thurston theory) for horseshoe type maps arising in chaotic time series data. This analysis is applied to data from the Belousov-Zhabotinskii reaction and allows us to (i) predict the existence of orbits of arbitrarily high periods from a finite amount of time series data, (ii) calculate a lower bound to the topological entropy, and (iii) establish a “topological model” of a system directly from an experimental time series.

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I. INTRODUCTION

Braids arise as periodic orbits in dynamical systems modeled by three-dimensional flows [1][2]. The existence of a single periodic orbit of a dynamical system can imply the coexistence of many other periodic orbits. The most well-known example of this phenomenon occurs in the field of one-dimensional dynamics and is described by Sarkovskii’s Theorem [3]. Less well-known is the fact that analogous results hold for two-dimensional systems [2]. In one-dimensional dynamics it is useful to study the period (or the permutation) of an orbit [4]. In two-dimensional systems it is useful to study the braid type of an orbit [5]. Given this specification, we can ask whether or not the existence of a given braid (periodic orbit) forces the existence of another; as in the one-dimensional case, algorithms have recently been developed for answering this question [5].

As originally observed by Auerbach et. al., unstable periodic orbits are available in abundance from a single chaotic time series using the method of close recurrence [6][7]. By a “braid analysis” we propose to analyze a chaotic time series by first extracting an (incomplete) spectrum of periodic orbits, and second ordering the extracted orbits according to their orbit forcing relationship. As shown in this paper, it is often possible to find a single periodic orbit (or a small collection of orbits) which forces many orbits in the observed spectrum. This single orbit also forces additional orbits of arbitrarily high period. This analysis is restricted to “low-dimensional” flows (roughly, flows which can be modeled by systems with one unstable Lyapunov exponent), however it has a strong predictive capability.

We would also like to point out that this analysis gives us an effective and mathematically well defined “pruning procedure” for chaotic two-dimensional diffeomorphisms [8]. Instead of asking for rules describing which orbits are missing (pruned), we instead look for those orbits which must be present. All orbits of a low enough period (say up to period 10) appear to be successfully predicted by this method. This procedure will usually miss orbits of higher period, however from an experimental viewpoint the low period orbits are the most important and accessible. Orbits of low period often force an infinity of other orbits. This is illustrated in one-dimensional dynamics by the famous statement “period three implies chaos” [9]. An analogous statement in two-dimensional dynamics is that a non-well-ordered period three braid implies chaos [10].

This paper is organized as follows. In section II we briefly review the theory of orbit forcing in one- and two-dimensional maps (three-dimensional flows). In section III we show how the braid analysis method works by applying it to times series data generated from the Rossler equations. This section also discusses some useful numerical and symbolic refinements to the method of close recurrence. In section IV we apply the braid analysis method to data from the Belousov-Zhabotinskii reaction. Our analysis builds directly on the original topological analysis of this data set due to Mindlin et. al. [15]. In section V we offer some concluding remarks by indicating how this method can be extended to low-dissipation and conservative systems. In the examples studied in this paper we do have good control of the symbolics. In principle, though, this method does not require good control of the symbolics (a good partition) and can thus overcome some of the current difficulties associated with finding good symbolic descriptions for (nonhyperbolic) strange attractors [12].

II. ORBIT FORCING THEORY

In this paper we study in detail the orbit structure of horseshoe type attractors. In particular, we will make a good deal of use of these features of one-dimensional dynamics which must always carry over to two dimensions. In our review we closely follow the point of view adopted in the Ph.D thesis of T. D. Hall [17]. Thus, none of the results in this theoretical section are new. However they are presented in such a way as to make them more useful for those wishing to apply these theoretical results to experimental data sets, as is done in the later sections of this paper. Let us begin by summarizing some well-established definitions and results pertaining...
to the periodic orbit structure of maps of the line. Let \( F : \mathbb{R} \to \mathbb{R} \) be a continuous map, and \( R = \{ x_1, \ldots, x_n \} \) be a period \( n \) orbit of \( F \) with its points labeled in such a way that \( x_1 < x_2 < \cdots < x_n \). Then there is a cyclic permutation \( \pi = \pi(R, F) \) associated to \( R \), defined by \( F(x_i) = x_{\pi(i)} \). A relation \( \leq_1 \) on the set \( C \) of all cyclic permutations can be constructed as follows: if \( \sigma, \tau \in C \), then \( \tau \leq_1 \sigma \) if and only if every map \( F : \mathbb{R} \to \mathbb{R} \) which has a periodic orbit \( R \) with \( \pi(R, F) = \sigma \) also has a periodic orbit \( S \) with \( \pi(S, F) = \tau \). If this is the case then we shall say that the permutation \( \sigma \) forces the permutation \( \tau \). The relation \( \leq_1 \) is a partial order which can be calculated, in the sense that there is a simple algorithm to determine whether or not \( \tau \leq_1 \sigma \) for any two cyclic permutations \( \tau \) and \( \sigma \): unfortunately this algorithm takes a long time to execute for orbits of high period, and it is difficult to use it to analyze the global structure of the partially ordered set \((C, \leq_1)\). There is, however, an interesting subset of \( C \) onto which the restriction of \( \leq_1 \) is well-understood. Let \( \text{UM} \subseteq C \) be the set of unimodal permutations: that is, the set of permutations of periodic orbits of the tent map (or one-dimensional horseshoe) defined well into the parameter regime where a complete horseshoe exists (a full shift on two symbols) without pruning

\[
F(x) = \begin{cases} 
3x & 0 \leq x \leq 1/2 \\
3(1-x) & 1/2 \leq x \leq 1 \\
0 & \text{otherwise}
\end{cases}
\]

(equivalently, \( \text{UM} \) is the set of permutations which can be realized by periodic orbits of unimodal maps whose turning point is a maximum). The partial order \( \leq_1 \) restricts to a linear order on \( \text{UM} \) which is described by kneading theory \[1\]. Indeed, this observation leads to a statement of topological universality in the one-dimensional context: there is a universal order in which the periodic orbits are built up in families of unimodal maps of the line, and this order is calculable using kneading theory.

A periodic orbit \( R \) of a homeomorphism of the plane can be described by its braid type \[3\]; the reader who lacks the mathematical background necessary to appreciate the following definitions should simply regard the braid type as a two-dimensional analog of the permutation, and the term ‘pseudo-Anosov’ as one which, while essential for the accurate statement of theorem 1, is not essential for applying the results found in later statements. Very roughly, braids can be divided into three types, the so-called finite order braids — braids which only force the existence of a finite number of other braids (periodic orbits), — pseudo-Anosov braids — braids which must force the existence of an infinite number of other braids, and reducible braids — braids which can be decomposed into distinct components which fall into one of the first two types. Pseudo-Anosov braids play an important role in the study of chaotic three-dimensional flows since, at the topological level, they force the coexistence of an infinite number of other periodic orbits. The term pseudo-Anosov arises within the context of the Nielsen-Thurston classification of isotopy classes of surface automorphisms, which is the main tool used in the proofs of the results presented: the reader interested in this powerful theory could consult Ref. \[2\], in which there is also an extensive bibliography. An exposition of the relevance of Nielsen-Thurston theory to two-dimensional dynamics, with particular reference to braid types, can be found in Ref. \[3\].

Let \( f \) and \( g \) be orientation-preserving homeomorphisms of the plane which have periodic orbits \( R \) and \( S \) respectively. We say that \((R, f)\) and \((S, g)\) have the same braid type if there is an orientation-preserving homeomorphism \( h : \mathbb{R}^2 \setminus R \to \mathbb{R}^2 \setminus S \) such that \( h \circ f|_{\mathbb{R}^2 \setminus R} \circ h^{-1} \) is isotopic to \( g|_{\mathbb{R}^2 \setminus S} \). Having the same braid type is an equivalence relation on the set of pairs \((R, f)\), and we write \( bt(R, f) \) for the equivalence class containing \((R, f)\), the braid type of the periodic orbit \( R \) of \( f \). We say that the braid type \( bt(R, f) \) is of pseudo-Anosov, reducible, or finite order type, according to the Nielsen-Thurston type of the isotopy class of \( f : (S^2, R \cup \{ \infty \}) \to (S^2, R \cup \{ \infty \}) \) (see Ref. \[3\] for a statement of Thurston’s classification theorem for homeomorphisms relative to a finite invariant set). By analogy with the one-dimensional case, we define a relation \( \leq_2 \) on the set \( BT \) of all braid types as follows: if \( \beta, \gamma \in BT \), then \( \gamma \leq_2 \beta \) if and only if every homeomorphism of the plane which has a periodic orbit of braid type \( \beta \) also has a periodic orbit of braid type \( \gamma \). If this is the case, we shall say that the braid type \( \beta \) forces the braid type \( \gamma \). The relation \( \leq_2 \) is a partial order \[22\]: as in the one-dimensional case, there is an algorithm for calculating this order (the so-called “train track algorithm”) \[7\], but it is difficult to use it to analyze the global structure of the partially ordered set \((BT, \leq_2)\). Still, using a version of this algorithm due to Bestvina and Handel \[7\], it is possible to calculate the orbits forced by an individual braid up to say period 10 or so by hand, and we have done this for several low period pseudo-Anosov horseshoe braids in order to find their associated topological entropies (see Table \[1\]). Also, an automated version of this algorithm promises to extend these calculations to higher period orbits \[23\].

We restrict our attention to the subset \( HS \subseteq BT \) of horseshoe braid types: that is, those which are realized by periodic orbits of the horseshoe map \( f \). The determination of constraints on the order in which periodic orbits can be built up in the creation of horseshoes is tantamount to the analysis of the partially ordered set \((HS, \leq_2)\); and an important observation in discussing the topological universality of two-dimensional systems is that, unlike \((UM, \leq_1)\), the partially ordered set \((HS, \leq_2)\) is not linearly ordered.

The connection between the ordered sets \((UM, \leq_1)\) and \((HS, \leq_2)\) is that periodic orbits of both the tent map and the horseshoe have a symbolic description. We associate to points in the non-wandering set of each map an infinite sequence of 0’s and 1’s in the usual manner, and describe a period \( n \) orbit \( R \) by its code \( c_R \), given by the first \( n \) symbols of the sequence associated to the rightmost point of \( R \). We shall identify periodic orbits of
the two maps which have the same code, using the same symbol $R$ to denote each orbit. Such an identified pair $R$ will be referred to as a horseshoe orbit (or simply as an orbit): the fact that the orbit is periodic will always be assumed. We shall write $\tilde{c}_R$ for the semi-infinite sequence $c_RC_Rc_R\ldots$ (which is associated to the rightmost point of $R$, regarded as a periodic orbit of the tent map); and $\tilde{c}_R$ for the bi-infinite sequence $\ldots c_RC_Rc_R\ldots$ (which is associated to the rightmost point $R$, regarded as a periodic orbit of the horseshoe).

It will be convenient for us to make another identification. If $R$ is a period $n$ orbit, then denote by $cR$ the code obtained by changing the last symbol of $c_R$. If $\tilde{c}_R$ is not the two-fold repetition of a sequence of length $n/2$, then it is the code of a period $n$ orbit $R'$ which can be shown to have the same permutation and braid type as $R$. We identify $R$ and $R'$ in what follows, using the same symbol $R$ to denote both, referring to them as a single orbit. The code $c_R$ of the identified pair will always be chosen to end with a zero (this is to ensure that the sequence $\tilde{c}_R$ contains the group of symbols $010\ldots$, which is necessary for the algorithms which follow). After making this identification, distinct horseshoe orbits have distinct permutations: however, it is possible for several different orbits to have the same braid type. With this in mind, we say that a function defined on the set of all horseshoe orbits is a \textit{braid type invariant} if it takes the same value on any two orbits of the same braid type.

Given two horseshoe orbits $R$ and $S$, we shall write $S \leq R$ if and only if $\pi(S, F) \leq \pi(R, F)$; and we shall write $S \leq_2 R$ if and only if $\text{bt}(S, f) \leq_2 \text{bt}(R, f)$. We refer to $\leq_1$ and $\leq_2$ as the one- and two-dimensional \textit{forcing orders} respectively. Our aim is to analyze $\leq_2$ using the well-understood properties of $\leq_1$. Notice that the orders $\leq_1$ and $\leq_2$ cannot strictly be regarded as being defined on the same set: if $R$ and $S$ are two horseshoe orbits which have the same braid type but different permutations, then they must be regarded as being equal when considering the order $\leq_2$, but as being distinct when considering the orbit $\leq_1$. For example, the orbits $f_{3x2}$ and $s_{\kappa}^2$ in Table 1 are two such orbits (for an example analogous example in the orientation-reversing Henon map see Ref. [25]).

We say that a horseshoe orbit $R$ is \textit{quasi-one-dimensional} (qod) if for all orbits $S$ we have $R \geq_1 S \Rightarrow R \geq_2 S$. As proved in Ref. [17], the following result provides a simple classification of the qod orbits which have pseudo-Anosov braid type. Let $\mathcal{Q}$ denote the set $\mathbb{Q} \cap (0, 1/2)$ of rationals lying (strictly) between 0 and 1/2. Given such a rational $q = m/n$ (in lowest terms), we write $P_q$ for the period $n+2$ orbit which has code $c_q = 10^{\kappa_1(q)}12^{\kappa_2(q)}10^2\ldots12^{\kappa_m(q)}10$, where $\kappa_1(q) = \lfloor 1/q \rfloor - 1$, and $\kappa_i(q) = \lfloor i/q \rfloor - \lfloor (i-1)/q \rfloor - 2$ for $2 \leq i \leq m$ (here $[x]$ denotes the greatest integer which does not exceed $x$). Thus, for example, $c_{2/5} = 1011010$. Then we have the following result of T. D. Hall [17]:

\textbf{Theorem 1} $q \leftrightarrow P_q$ is a one-to-one correspondence between $\mathcal{Q}$ and the set of quasi-one-dimensional horseshoe orbits which have pseudo-Anosov braid type. Moreover $P_q \geq_2 P_{q'} \iff \kappa' \geq \kappa$ for all $q, q' \in \mathcal{Q}$.

It is a consequence of quasi-one-dimensionality that $P_q \geq_2 P_{q'} \iff P_q \geq_1 P_{q'}$, and therefore the braid types of the orbits $P_q$ form a linearly ordered subset of BT. The final statement of the theorem tells us that the ordering within this subset is simply the reverse of the usual ordering on $\mathcal{Q}$.

Theorem 1 allows us to quickly identify a very useful subset of pseudo-Anosov braids and a program is easily written to quickly generate all the horseshoe qod orbits of any desired period. Moreover, Theorem 1 can be used to define an invariant of horseshoe braid type: the \textit{height} $q(R)$ of a horseshoe orbit $R$ is the unique element of $[0, 1/2]$ with the property that for all $q \in \mathcal{Q}$ we have $q < q(R) \Rightarrow P_q \geq_1 R$ and $q > q(R) \Rightarrow P_q \not\geq_1 R$ (thus $q(R) = \sup\{q \in \mathcal{Q} : P_q \geq_1 R\}$). Because the orbits $P_q$ are qod, it follows immediately that $q < q(R) \Rightarrow P_q \geq_2 R$. In fact, it can be shown that the second property in the definition of height also holds for the two-dimensional forcing order: that is \cite{17}.

\textbf{Theorem 2} Let $R$ be a horseshoe orbit and $q \in \mathcal{Q}$. Then $q < q(R) \Rightarrow P_q \geq_2 R$ and $q > q(R) \Rightarrow P_q \not\geq_2 R$. In particular, height is a braid type invariant.

We can also find the finite order braids because the finite order braids of the horseshoe are exactly those whose period equals the denominator of the height \cite{17,20}. Because the height is defined in terms of the one-dimensional order, it can be calculated using kneading theory. We first define the height $q(c) \in [0, 1/2]$ of a semi-infinite sequence which begins $c = 10\ldots$, and which contains the group of symbols $010\ldots$. To do this, write $c$ in the form $c = 10^{\kappa_11^{m_1}10^{\kappa_21^{m_2}}10^{\kappa_31^{m_3}}10\ldots}$, where $\kappa_i \geq 0$ and $\mu_i$ is either 1 or 2 for each $i$, with $\mu_1 = 1$ only if $\kappa_{i+1} > 0$ (thus the $\kappa_i$ and $\mu_i$ are uniquely determined by $c$, and the fact that $c$ contains the group $\ldots010\ldots$ means that $\mu_s = 1$ for some $s$). Let

$$I_s(c) = \left(\frac{r}{2r + \sum_{i=1}^{s-1} \kappa_i}, \frac{r}{2r - 1 + \sum_{i=1}^{s-1} \kappa_i}\right)$$

for each $r \geq 1$, and let $s$ be the least positive integer such that either $\mu_s = 1$ or $\cap_{i=1}^{s+1} I_s(c) = \emptyset$. Then $\cap_{i=1}^{s+1} I_i(c) = (x, y)$ for some $x$ and $y$: we define $q(c) = y$ if $\mu_s = 1$ or $I_{s+1}(c) > \cap_{i=1}^{s} I_i(c)$, and $q(c) = x$ if $\mu_s = 2$ and $I_{s+1}(c) < \cap_{i=1}^{s} I_i(c)$.

\textbf{Theorem 3} $q(R) = q(c_R^{\infty})$: in particular, $q(R)$ is positive and rational \cite{17}.

For example, let $R$ be the period 20 orbit with code $c_R = 1000011000110001100$. We have $\kappa_1 = 4$, $\mu_1 = 2$, $\kappa_2 = 2$, $\mu_2 = 2$, $\kappa_3 = 4$, $\mu_3 = 2$, $\kappa_4 = 2$, and $\mu_4 = 1$. Thus
\[I_1 = (1/6, 1/5), ~ I_2 = (2/11, 2/10), ~ I_3 = (3/17, 3/16), \]
\[and ~ I_4 = (4/21, 4/20). ~ Since ~ 4/21 > 3/16 \text{ we have} \]
\[I_1 \cap I_2 \cap I_3 \cap I_4 = 0, \text{ and } I_4 > I_1 \cap I_2 \cap I_3. \]
Therefore, \[q(R) = \max(I_1 \cap I_2 \cap I_3) = 3/16. \]

There is a relationship between height and a well-established braid type invariant: the height of a horseshoe is equal to the left hand endpoint of its rotation interval. A proof of this is given in Ref. [43], where a practical algorithm for determining the rotation interval of a horseshoe is described. It can also be shown using the algorithm for determining the height that for each \( q = m/n \) (in lowest terms), \( P_q \) is the only period \( n \) + 2 orbit of height \( q \); thus it is the only orbit of its braid type. This observation enables us to determine exactly which of the orbits \( P_q \) are forced by a given orbit \( R \) in the two-dimensional order: we now present an algorithm for this purpose. If \( R \) is a horseshoe orbit then we define the depth \( r(R) \in [0, 1/2] \ni Q \) of \( R \) as follows: consider all groups of the form \( \ldots 01110 \ldots \) or \( \ldots 01010 \ldots \) in the sequence \( \sim c_{qR} \); suppose that there are \( l \) such groups \( g_1, \ldots, g_l \) contained in one period of \( \sim c_{qR} \). If \( l = 0 \) then \( r(R) = 1/2 \). Otherwise, for each \( i \leq l \) let \( f_i \) be the code obtained by starting at the last \( 1 \) in \( g_i \) and moving forwards through \( \sim c_{qR} \), and \( b_i \) be that obtained by starting at the first \( 1 \) and moving backwards. Then \( r(R) = \min_{1 \leq i \leq l} \max(q(f_i), q(b_i)). \)

**Theorem 4** \( r(R) \) is the unique element of \( [0, 1/2] \) with the property that for all \( q \in Q \) we have \( r(R) < q \implies R \geq P_q \) and \( r(R) > q \implies R \not\geq P_q \). In particular, depth is a braid type invariant [17].

The following corollaries from theorems 2 and 4 will be very useful in our braid analysis since they allow us to apply one-dimensional theory to calculate two-dimensional orbit forcings.

**Corollary 1** Let \( R \) and \( S \) be horseshoe orbits. If \( r(R) < q(S) \) then \( R \geq S \). On the other hand, if \( q(R) < q(S) \) and \( r(S) < r(R) \) then \( R \not\geq S \) and \( S \not\geq R \): thus orbits of the braids types \( R \) and \( S \) can exist independently of each other.

In fact, a much stronger result can be proved: if \( r(R) < q(S) \) then every homeomorphism of the plane which has a periodic orbit of braided type \( R \) has at least as many periodic orbits of the braided type \( S \) as does the horseshoe (the corollary only says that every such homeomorphism has at least one such orbit). Thus all of the periodic orbits of the braided type \( S \) must be created before any of the periodic orbits of braided type \( R \) in any family of homeomorphisms leading to the creation of a horseshoe. We can use the following corollary to locate some of these orbits.

**Corollary 2** If a homeomorphism of the disc has a qod orbit \( P_q \), and \( R \) is another orbit which is forced by \( P_q \) in the one-dimensional order (which means that its height is \( \geq q \)), then the homeomorphism must have at least one orbit of the braided type of \( R \). If in addition the height of \( R \) is strictly greater than \( q \), then the homeomorphism must have at least as many orbits of the braided type of \( R \) as does the horseshoe [27].

For example, if a period 7 orbit with the braided type of 1011010 (height 2/5) is extracted, then there must be at least one orbit of the braided type of 10110 (since this braided type has height 2/5), and at least as many of the braided type of 1011100 as in the horseshoe (i.e., 2) need exist (since the height of these orbits is also 2/5). On the other hand, both of the orbits in the period 6 pair 101110 need exist since the height of these orbits are 1/2. A listing of the low period qod orbits and some of the low period orbits which they force is found in Table 1.

Since the qod orbits essentially inherit the one-dimensional forcing order we can use one-dimensional methods to calculate their topological entropies. This information can be used to obtain lower bounds for the topological entropy of a partially-formed horseshoe. More precisely, given a horseshoe orbit \( R \), let \( h(R) \) denote the smallest possible entropy of a homeomorphism having an orbit of the same braided type as \( R \). Now we know that for all \( q > r(R) \) we have \( R \geq P_q \), and hence the topological entropy \( h(R) \geq h(P_q) \). However, since \( P_q \) is a qod orbit, it can be shown that \( h(P_q) \) is equal to the entropy of \( P_q \) regarded as an orbit in one dimension: this can be calculated using standard transition matrix techniques. A Mathematica program based on the method of Block et al. [28] is available from T. D. Hall which allows us to calculate the topological entropies of the qod orbits. A graph of the function \( (q, h(P_q)) \) appears in Ref. [17]: it is monotonic and discontinuous everywhere. Thus, we can go directly from a qod orbit to a lower bound for the topological entropy. For example, the orbit \( R \) with code \( c_R = 10011010 \) has \( r(R) = 1/3 \): any partially formed horseshoe which includes an orbit of the braided type of \( R \) has entropy greater than \( h(P_{2/3}) \approx 0.442 \). By taking rational closers and closer to 1/3 we get better and better estimates (e.g., 5/14 gives 0.481). We can also use the pseudo-Anosov orbits which are not qod to get estimates (e.g., the orbit \( s_3 \) mentioned above has \( h \approx 0.498 \), however in this instance we must compute the entropy from a train track and this can be a difficult calculation.

In Table 1 we collect together some useful facts about braids in the horseshoe up to period eight. All the reducible orbits up to period nine only have finite order components. This is because the lowest period with a pseudo-Anosov orbit is five, and numbers less than or equal to nine do not have proper factors greater than or equal to five. As mentioned previously, the topological entropy for the pseudo-Anosov orbits which are not quasi-one-dimensional is calculated by finding the "train track" using the method of Bestvina and Handel [25]. This method results not only in a topological entropy, but also an explicit Markov partition (a "topological model") and
associated Perron-Frobenius matrix which is useful for locating in phase space where the predicted periodic orbits are to be found.

III. ROSSLER BRAID ANALYSIS

A braid analysis of a low dimensional chaotic time series consists of four steps once an appropriate three-dimensional space is created $\mathbb{R}^3$: (i) the periodic orbits are extracted by the method of close recurrence $\mathbb{R}^3$, (ii) the braid type of each periodic orbit is identified and the orbits are ordered by their two-dimensional forcing relationship $\mathbb{R}^2$ (iii) a subset of braids are selected which have maximal forcing and which force the orbits extracted in step (i), and (iv) if possible, an attempt is made to verify that some of the predicted orbits (not originally extracted in step (i)) are found in the system.

In practice, steps (i) and (ii) are greatly simplified if the template or knot-holder organizing the flow can be identified using the procedure described by Mindlin and co-workers $\mathbb{R}^2$ $\mathbb{R}^2$. Knowledge of the template helps in obtaining the symbolic names of the periodic orbits and in calculating the forcing relationship for the specific braids in that template. For instance, if the template is identified as a two-branch horseshoe knot holder (as are all the examples studied in this paper), then the theory of qod orbits of section II can be applied to simplify the analysis.

Although template identification is very valuable, it is not essential for a braid analysis. Nor is the symbolic identification of the extracted orbits. In the worst case a braid analysis does require that the braid conjugacy class of each extracted periodic orbit is identified (see Elrifai and Morton $\mathbb{R}^2$, or Jaquemard $\mathbb{R}^2$ for algorithms), and that the minimal Markov model (a ‘train track’ in the language of Thurston) can be constructed for each braid (see Bestvina and Handel $\mathbb{R}^2$, Los $\mathbb{R}^2$, and Franks and Misiurewicz $\mathbb{R}^2$ for algorithms). Algorithms exist for both of these steps, although the most computationally efficient version of the braid conjugacy algorithm is probably not an effective solution beyond $\mathbb{R}^8$.

To illustrate the braid analysis we consider a chaotic attractor of the Rossler equations,

\[
\begin{align*}
\dot{x} &= -(y + z) \\
\dot{y} &= x + ey \\
\dot{z} &= f + xz - \mu z
\end{align*}
\]

with $e = 0.17$, $f = 0.4$ and $\mu = 0.85$. The Rossler equations are integrated through $10^5$ cycles and the return map is examined at the half plane $\Sigma = \{(x,y,z) : x < 0 \text{ and } y = 0\}$. The template is easily identified as a horseshoe with zero global torsion. This template identification is verified by calculating the relative rotation rates and linking numbers of the extracted periodic orbits as described by Mindlin et. al. $\mathbb{R}^2$ $\mathbb{R}^2$.

To extract the (surrogate) periodic orbits by the method of close recurrence we first convert the return map from the sequence of values $(x_n,y_n)$ directly into the symbol sequence of 0’s and 1’s. In this particular instance, since the map is close to one-dimensional, a good symbolic partition is obtained by examining the maximum value of the next return map formed from the projection on the $x$-coordinate $\left( -x_n, -x_{n+1} \right)$ at the surface of section. Orbits passing to the left of the maximum are labeled zero, and those to the right are labeled one. Next we search this symbolic encoding for each and every periodic symbol string. Every time a periodic symbol string is found we calculate its recurrence and then save the instance of the orbit with the best recurrence. For instance, in searching for the period three orbit ‘100’ we search the symbolic encoding of the return map for any instance of ‘100’ and its cyclic permutations ‘010’ and ‘001’, and every time this symbol string is found, we next calculate its recurrence, which for this period three orbit is $\epsilon_{y=0} = (x_{n+3} - x_n)^2 + (z_{n+3} - z_n)^2$, and then save the orbit with the minimal $\epsilon$. The advantage of this procedure of orbit extraction is that it is exhaustive. We search for every possible orbit up to a given period. In these studies we searched for all orbits between periods 1 and 16.

The resulting spectrum of periodic orbits up to period eight is shown in Table I. The orbits which are present in (the full shift) complete hyperbolic system, and not present in Table III, are said to be pruned. Our goal is to predict as best as possible the pruned spectrum from the chaotic time series.

Before we discuss the braid analysis, though, it is interesting to consider the number of orbits extracted as a function of the number of points in the return map. As expected, we find that the number of orbits that can be extracted increases with the number of points in the return map. More importantly, our numerical results strongly suggest that using the method of close recurrence it is possible to obtain all the low period periodic orbits embedded within the strange attractor after examining only a finite number of data points, in this instance $10^5$. For instance, after $10^4$ points are examined our numerical results show that no new periodic orbits are found below period six. Similarly, after examining $10^5$ points we believe we have found all orbits up to period eight. These results also caution us when working with small data sets — the extracted orbit spectrum is expected to miss orbits either because the orbit is pruned (it is not in the strange set) or because the sample of the strange set we are examining fails in providing a close enough coverage over the whole attractor.

Using the results in section II, the finite-order and quasi-one-dimensional orbits in the extracted spectrum are easily identified from their orbit codes (see Table III). Not unexpectedly, we see a sequence of quasi-one-dimensional orbits of increasing entropy (decreasing height) — the maximal qod orbit is the period 16 orbit $10110111011011010$ with entropy $h \approx 0.480804$. All orbits
forced by this period 16 orbit up to period 8 are present, and none are missing. So this period 16 qod orbit already gives us a very good hyperbolic set with which to approximate to our (possibly nonhyperbolic) chaotic attractor. Can we do better? Doing better in this instance means identifying a pseudo-Anosov orbit which is not qod, but perhaps implies the maximal qod orbit found. Indeed, in this data set there is such an orbit, it is the period 8 orbit 10010100 with entropy \( h \approx 0.498093 \). Again, the spectrum of orbits forced by this maximal pA orbit are consistent with the extracted spectrum which was examined up to period 16.

This data set is close to one-dimensional so kneading theory also does quite well for predicting the low period orbits. For instance, we could consider the period 3 orbit 100, and this orbit (based on one-dimensional unimodal theory) also accurately predicts most of the extracted spectrum. However, this period 3 orbit is finite order, and we know from the results of Holmes and Whitley that spectrum. However, this period 3 orbit is finite order, and we know from the results of Holmes and Whitley that there will be many (possibly high period) orbits which are forced by \( \leq 1 \) but not by \( \leq 2 \) (in fact, we know that in 2-dimensions 100 forces only itself and a fixed point, and in 1-dimension it forces orbits of arbitrarily high period). Thus, although one-dimensional theory is a useful guide in this instance to the low period orbits, it can not be safely applied to make predictions about high period orbits.

### IV. BELOUSOV-ZHABOTINSKII REACTION
#### BRAID ANALYSIS

To further illustrate the braid analysis method we obtained data from the Belousov-Zhabotinskii chemical reaction [36]. This is the same data set analyzed by Mindlin et. al. and consists of 65,000 equally spaced points which measure the time dependence of the bromide ion concentration in the stirred chemical reactor. Following the techniques described by Mindlin et. al. we also embedded the scalar time series \( x(i), i = 1, 2, \ldots, N \) in \( \mathbb{R}^3 \) via a differential phase space embedding described by

\[
\begin{align*}
y_1(i) &= x(i) + \lambda \cdot y_1(i-1), \quad \lambda = 0.995 \\
y_2(i) &= x(i) \\
y_3(i) &= x(i) - x(i-1)
\end{align*}
\]

from which we reproduced the 3-dimensional attractor and return map shown in Figs. 5 and 6(a) of Ref. [15]. The attractor is a zero global torsion horseshoe. There are approximately 125 points per cycle so the return map consists of about 520 points.

Our technique for extracting (surrogate) periodic orbits from this time series differs somewhat from that described in Ref. [15]. We use the same procedure described for the Rossler data: first the return map data is converted into a symbol sequence of 0’s and 1’s depending on whether the orbit passes to the left or right of the maximum value of the return map, and second an exhaustive search is performed for all possible periodic orbits between periods 1 and 15. Again, this data set is almost one-dimensional and the simple symbolic prescription just described leads to a unique and consistent encoding of all the periodic orbits we are able to extract. Since the data set (at the return map) is small, we choose not to pick an arbitrary cut off for \( \epsilon \), the close return criterion. Rather, we report the best \( \epsilon \) we are able to extract for a given periodic orbit (see Table IV). By including this additional piece of information we can make a more selective judgement about which close returns are, and are not, good surrogates for periodic orbits. In this way we are able to locate a few more periodic orbits than were originally reported in Ref. [15]. Also, one perhaps surprising result comes out of this extraction method. It is not uncommon to find orbits of high period with very small recurrences. For example the period 13 orbit 1011011011110 has a recurrence of \( \epsilon = 0.000712 \) which is significantly better than almost all of the lower period orbits.

A list of the extracted orbits and their Thurston types is presented in Table IV. As expected, there is a sequence of quasi-one-dimensional orbits of increasing entropy, the largest of which is the period 16 orbit 1011011011011011 with entropy \( h \approx 0.48084. \) In this particular instance, the period 16 qod orbit is in fact the maximal pseudo-Anosov orbit in the data set and it forces all the extracted orbits in this data set except for the finite order period three orbit 101. Indeed, a careful analysis of this data set suggests that the signal is subject to a small parametric drift which carries it between the strange attractor and a stable period 3 orbit (whose 1-dimensional entropy is \( h \approx 0.4812 \)).

Table IV shows the number of predicted and extracted orbits as a function of period. The number of forced orbits which are not in the extracted data set increases with the period. As with the Rossler data set, we believe the forced orbits which are missing could actually be extracted from the data set if we were given a longer time series which provides a better coverage of the entire attractor.

### V. CONCLUSION

In retrospect, we find it remarkable that such a small subset of periodic orbits (which are easier to get from experiments) contain so much topological and dynamical information about a (low-dimensional) flow. As previously demonstrated, a few low period orbits are sufficient to determine the template describing the stretching and folding of the strange set [15]. The template provides an upper bound to the topological entropy and is, in a sense, a maximally (i.e., a full shift) hyperbolic set which we formally associate to a (possibly nonhyperbolic) strange set [29]. In this paper we show how a sequence of periodic orbits (and their associated hy-
perbolic sets) can be used to obtain a collection of finer and finer approximations to a strange set which is probably not hyperbolic. Formally, we might say that the hyperbolic set associated with each pseudo-Anosov braid is embedded within the strange attractor we are trying to describe in the sense that the (possibly nonhyperbolic) strange set must contain at least all the orbits forced by the extracted pseudo-Anosov braid. We indirectly discussed two measures of the goodness of this approximation — the difference in the topological entropy, and the difference between the forced and extracted low period orbits. Using either measure, we have seen that it is possible to select moderate period orbits (say < period 20) which provide good hyperbolic sets with which we can approximate a (possibly nonhyperbolic) strange set.

The dynamical information derived from an orbit depends only on its braid type. As mentioned in section III, the braid type of an orbit can be determined without obtaining a good symbolic description of the orbits in the flow. We will illustrate these techniques in a future paper in which we consider a braid analysis of the bouncing ball system in a low-dissipation regime [8]. Our strategy for handling the cases where a good symbolic description is not easy to obtain is to find a complete set of braid invariants on the small set of braids of interest. For instance, as mentioned in Table 1, the exponent sum (simply the sum of the crossings) is a complete braiding invariant for horseshoe braids up to period 8.

We would also like to point out that it is common for a collection of finite order braids to be pseudo-Anosov. This suggests an alternative strategy: instead finding a single orbit with maximal implications, it should also be possible to find a collection of orbits (possibly with very low period) which force all the observed orbits and provides yet another hyperbolic approximating set. This is also the subject of future investigations.

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TABLE I. Low period horseshoe orbits. The exponent sum is a complete braid type invariant for all horseshoe orbits up to period eight (see Ref. [17] for the explicit conjugacy). The braid name notation is from Ref. [35]. Thurston braid types: finite order (fo), reducible (red), and pseudo-Anosov (pA), and quasi-one-dimensional (qod). The “red, fo” orbits are reducible Thurston types with finite order components.

| $P$ | $\phi_P$ | $\pi_P$ | Type | $q(P)$ | $h$ |
|-----|----------|----------|------|--------|-----|
| $s_1$ | 1 | (1) | fo | 0 | 1/2 | 0 |
| $s_2$ | 10 | (12) | fo | 2 | 1/3 | 0 |
| $s_3$ | 1011 | (1324) | red, fo | 5 | 1/2 | 0 |
| $s_4$ | 1001 | (1234) | fo | 3 | 1/4 | 0 |
| $s_5$ | 10111 | (13425) | fo | 8 | 2/5 | 0 |
| $s_6$ | 100101 | (12354) | pA, qod | 6 | 1/3 | 0.543535 |
| $s_7$ | 1000101 | (12345) | fo | 4 | 1/5 | 0 |
| $s_8$ | 101111 | (143526) | red, fo | 13 | 1/2 | 0 |
| $f_{2 \times 2}$ | 101111 | (1453627) | fo | 18 | 3/7 | 0 |
| $f_{3 \times 2}$ | 100101 | (1325467) | pA, qod | 16 | 2/5 | 0.442138 |
| $s_9$ | 1001101 | (1245367) | pA | 14 | 1/3 | 0.476818 |
| $s_{10}$ | 1000100 | (1235467) | pA, qod | 10 | 1/4 | 0.632974 |
| $s_{11}$ | 1000110 | (1234567) | fo | 5 | 1/6 | 0 |
| $s_{12}$ | 1011110 | (1453627) | fo | 18 | 3/7 | 0 |
| $s_{13}$ | 1101101 | (1462537) | pA, qod | 16 | 2/5 | 0.476818 |
| $s_{14}$ | 1001010 | (1245367) | pA | 14 | 1/3 | 0.476818 |
| $s_{15}$ | 1001100 | (1235467) | pA, qod | 10 | 1/4 | 0.382245 |
| $s_{16}$ | 1000100 | (1234567) | pA | 10 | 1/4 | 0.382245 |
| $s_{17}$ | 1000110 | (1234567) | pA | 10 | 1/4 | 0.666213 |
| $s_{18}$ | 1000010 | (1234567) | fo | 6 | 1/7 | 0 |

The table continues with similar entries for other $P$. The notation for $\phi_P$, $\pi_P$, Type, $q(P)$, and $h$ follows the same pattern.
TABLE II. A sequence of quasi-one-dimensional (qod) orbits with increasing forcing implications (entropy). Thus, every orbited forced by the period 7 qod orbit is also forced by the period 10 orbit, and so on. The notation “(*)” after an orbit indicates that one (but perhaps not both) of the saddle-node pair is forced. Both saddle-node partners will be forced by the next orbit in the qod sequence.

| Period | Forced by (7) | Forced by (10) | Forced by (13) |
|--------|--------------|----------------|----------------|
|        | 101101^0    | 10110101^0     | 10110110101^0   |
| 1      |              |                |                |
| 2      | 10           |                |                |
| 3      |              |                |                |
| 4      | 1011         |                |                |
| 5      | 1011_1(*)    |                |                |
| 6      | 10111_1      |                |                |
| 7      | 101111_1(*)  | 101101*        |                |
| 8      | 10111010     | 101101(*)      |                |
| 9      | 10111111_1(*)| 10110111_1(*)  | 10110111_1(*)   |
| 10     | 10111111_1(*)| 10110101(*)    |                |
| 11     | 10111111_1(*)| 101101111_1(*)| 101101111_1(*)*|
|        |              | 101110101(*)   | 10110111_1(*)   |

...
TABLE III. Periodic orbits extracted from time series data of the Rossler equations. All extracted orbits up to period 8 are shown. Between periods 9 and 16 only the extracted quasi-one-dimensional (qod) are shown. The maximal pseudo-Anosov orbit ($1001010^2$) is not qod, but it forces all qod orbits with height greater than $1/3$. Thurston Types: finite order (fo), reducible (red), and pseudo-Anosov (pA).

| Period | Name   | Height | Entropy | Type      |
|--------|--------|--------|---------|-----------|
| 1      | 1      | 1/2    | 0       | fo        |
| 2      | 10     | 1/3    | 0       | fo        |
| 3      | 101    | 1/3    | 0       | fo        |
| 3      | 100    | 1/3    | 0       | fo        |
| 4      | 1011   | 1/2    | 0       | red       |
| 5      | 10111  | 2/5    | 0       | fo        |
| 5      | 10110  | 2/5    | 0       | fo        |
| 6      | 101110 | 1/2    | 0       | red       |
| 6      | 101111 | 1/2    | 0       | red       |
| 6      | 100101 | 1/3    | 0       | red       |
| 7      | 1011111| 3/7    | 0       | fo        |
| 7      | 1011110| 3/7    | 0       | fo        |
| 7      | 1011010| 2/5    | 0.442138| pA, qod   |
| 7      | 1011011| 2/5    | 0.442138| pA, qod   |
| 7      | 1001011| 1/3    | 0.476818| pA        |
| 7      | 1001010| 1/3    | 0.476818| pA        |
| 8      | 10111010| 1/2  | 0     | red       |
| 8      | 10111110| 1/2  | 0     | red       |
| 8      | 10111111| 1/2  | 0     | red       |
| 8      | 10110111| 3/8  | 0     | fo        |
| 8      | 10110110| 3/8  | 0     | fo        |
| 8      | 10010110| 1/3  | 0.346034| pA        |
| 8      | 10010111| 1/3  | 0.346034| pA        |
| 8      | 10010101| 1/3  | 0.498093| pA        |
| 8      | 10010100| 1/3  | 0.498093| pA        |
| 9      | 10111010| 3/7  | 0.397081| pA, qod   |
| 9      | 10111101| 3/7  | 0.397081| pA, qod   |
| 10     | 101101010| 3/8 | 0.473404| pA, qod   |
| 10     | 10110111| 3/8  | 0.473404| pA, qod   |
| 11     | 1011111010| 4/9 | 0.373716| pA, qod   |
| 13     | 101101101010| 4/11| 0.479450| pA, qod   |
| 13     | 101101101110| 4/11| 0.479450| pA, qod   |
| 15     | 10111111111011| 6/13| 0.354176| pA, qod   |
| 15     | 101101111011010| 5/13| 0.467734| pA, qod   |
| 16     | 1011011011010| 5/14| 0.480804| pA, qod   |
TABLE IV. Periodic orbits extracted from the Belousov-Zhabotinskii Reaction time-series up to period 15. All orbits with a best (normalized) recurrence of less than 0.1 are shown. The period 16 orbits are from Ref. [15].

| Period | Name           | Recurrence | Type                        |
|--------|----------------|------------|-----------------------------|
| 1      | 1              | 0.016782   | fo                          |
| 2      | 10             | 0.002615   | fo                          |
| 3      | 101            | 0.000128   | fo                          |
| 4      | 1011           | 0.002648   | fo                          |
| 5      | 10111          | 0.002962   | fo                          |
| 6      | 101110         | 0.006449   | fo                          |
| 7      | 1011101        | 0.000128   | fo                          |
| 8      | 10111011       | 0.002648   | fo                          |
| 9      | 101110111      | 0.002962   | fo                          |
| 10     | 1011101111     | 0.006449   | fo                          |
| 11     | 10111011111    | 0.006449   | fo                          |
| 12     | 101110111111   | 0.006449   | fo                          |
| 13     | 1011101111111  | 0.006449   | fo                          |
| 14     | 10111011111111 | 0.006449   | fo                          |
| 15     | 101110111111111| 0.006449   | fo                          |

Note: The recurrence values are normalized and represent the best recurrence for each orbit. The table lists orbits up to period 15, with period 16 orbits from Ref. [15].
### TABLE V. Number of periodic orbits extracted and predicted for time series data from the Belousov-Zhabotinskii reaction (≈ 500 points in the return map). As illustrated with the Rossler data, we expect that the time series is far too short to be able to extract all the predicted orbits of any except the lowest periods.

| Period | # predicted | # found | # missing | # marginal |
|--------|-------------|---------|-----------|------------|
| 1      | 1           | 1       | 1         | 1          |
| 2      | 1           | 1       | 1         | 1          |
| 3      | 1           | 1       | 1         | 1          |
| 4      | 1           | 2       | 2         | 2          |
| 5      | 2           | 2       | 2         | 2          |
| 6      | 2           | 2       | 2         | 2          |
| 7      | 4           | 3       | 1         | 1          |
| 8      | 5           | 2       | 2         | 1          |
| 9      | 8           | 4       | 2         | 2          |
| 10     | 11          | 5       | 6         | 6          |