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SELFSIMILAR EXPANDING SOLUTIONS IN A SECTOR FOR A CRYSTALLINE FLOW*
MI-HO GIGA¹, YOSHIKAZU GIGA² AND HIDEKATA HONTANI³

Abstract. For a given sector a selfsimilar expanding solution to a crystalline flow is constructed. The solution is shown to be unique. Because of selfsimilarity the problem is reduced to solve a system of algebraic equations of degree two. The solution is constructed by a method of continuity and obtained by solving associated ordinary differential equations. The selfsimilar expanding solution is useful to construct a crystalline flow from an arbitrary polygon not necessarily admissible.

key words. crystalline flow, selfsimilar expanding solutions, a priori estimate

AMS subject classification. 15A99, 34A12, 74N05, 94A08

1 Introduction.

A curvature flow is important to describe motion of phase boundaries in material sciences [12], [19] and also to modify contours in image analysis [15]. A crystalline flow is considered as a discrete version of an anisotropic curvature flow in the plane. It was introduced by J. Taylor [18] and independently by S. Angenent and M. Gurtin [1] almost a decade ago. Let us give a typical example of anisotropic curvature flow equations in $R^2$:

\begin{equation}
V = -\text{div}\xi(n) \quad \text{on } \Gamma_t;
\end{equation}

here $V$ denotes the normal velocity of an evolving curve $\{\Gamma_t\}$ in the direction of unit normal $n$ and $\xi = \nabla\gamma$ with the interfacial energy density $\gamma(p)$ which is positively one-homogeneous and convex in $R^2$; $\text{div}$ denotes the surface divergence. If $\gamma(p) = |p|$, then (1.1) is nothing but the curve shortening equation. If $\gamma$ is piecewise linear, then (1.1) is so singular that it cannot be interpreted as a conventional partial differential equation. This is a typical situation where a crystalline flow arises. To understand (1.1) one restricts $\{\Gamma_t\}$ in a special class of polygonal curves, which is often called ‘admissible’ [18], [1]. The boundary of the Wulff shape

\[ W_\gamma = \{x \in R^2; x \cdot m \leq \gamma(m) \text{ for all } m \in R^2\}. \]

is a typical example of an admissible polygon (crystal). Its weighted curvature $-\text{div}\xi(n)$ formally equals $-1$ if $n$ is taken outward. Thus if $W_\gamma$ is a regular polygon centered at the origin, then it is reasonable to say that $\Gamma_t = t^{1/2}\partial W_\gamma$ is a ‘solution’ of (1.1). We say that a polygon $\Gamma$ is an admissible crystal if the orientation of each edge (facet) is one of that in $\partial W_\gamma$ and the orientations of adjacent facets should be adjacent in $\partial W_\gamma$. We say that $\{\Gamma_t\}$ is an admissible evolving crystal if $\Gamma_t$ is an admissible crystal and the motion of all vertices of $\Gamma_t$ is $C^1$ in time $t$. Let $S_j(t)$ denote $j$-th facet of $\Gamma_t$. Then (1.1) is formally of the form:

\begin{equation}
V_j(t) = \Lambda_j(t) \quad \text{on } S_j(t)
\end{equation}

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with crystalline curvature

$$\Lambda_j(t) = \chi_j \Delta(\tilde{n}_j) / L_j(t)$$

and $V_j(t)$ denotes the normal velocity of $S_j(t)$ in the direction of $\tilde{n}_j$; here $L_j(t)$ denotes the length of $S_j(t)$ and $\chi_j$ is the transition number (see §2). The quantity $\Delta(\tilde{n}_j)$ is the length of the facet of $\partial W_\gamma$ whose orientation equals $\tilde{n}_j$. Together with a transport equation (the first displayed formula in §3) we have a finite system (3.1) of ordinary differential equations (ODEs), which is at least solvable locally-in-time. The resulting flow $\{\Gamma_t\}$ is often called a crystalline flow.

Our goal in this paper is to construct a self-similar expanding admissible evolving crystal $\{\Gamma_t\}_{t>0}$ satisfying (1.2) (shortly, self-similar expanding solution) such that it tends to the boundary of a sector as time tends to zero. We also prove its uniqueness. (Note that a self-similar expanding solution is not necessarily a dilation of the Wulff shape as numerical calculations in [13] show.) There are several reasons such a solution is important. Here is a partial list:

(a) Useful to construct a solution when initial data is a nonadmissible polygon;

(b) Useful to construct a self-similar expanding solution to (1.1) for general $\gamma$ when $\Gamma_t$ lives in a sector and touches the boundary of the sector with prescribed contact angle.

Before discussing these reasons we mention relation between crystalline flow and curvature flow with smooth strictly convex interfacial energy density. One comes up with two natural questions.

(i) Is a crystalline flow approximated by a curvature flow with smooth convex $\gamma$?

(ii) Is a flow with smooth $\gamma$ approximated by a crystalline flow with a piecewise linear $\gamma$? If so, crystalline flow provides a good numerical algorithm to calculate (1.1).

Fortunately, these problems are affirmatively settled by now; [4], [6], [8] for (i) and [4], [11], [10], [6], [8] for (ii). In [4], [6], [8] general notions of a ‘solution’ to (1.1) based on variational principle or comparison principle are given. Moreover, it is shown that the ‘solution’ in this sense exists for a general initial simple curve not necessarily admissible. Starting from a general polygon is important for a crystalline algorithm (ii). Practically, for a given curve it is easier to approximate it by a polygon rather than by an admissible crystal. However, it is not clear what is a crystalline flow starting from a general polygon although existence of a ‘solution’ is known in an abstract level [4], [5] [8]. It is also numerically calculated by [3] when $\Gamma_t$ is a graph by a variational inequality. Suppose that the initial polygon is non-admissible and that crystalline curvature of a pair of adjacent facets $S_A$ and $S_B$ equals zero. Assume that between orientations of $S_A$ and $S_B$ there are orientations of $\partial W_\gamma$. Then one expects that some new facets (with their missing orientations) are created instantaneously. If one has a self-similar expanding solution (with respect to a point where $S_A$ intersects $S_B$), then this solution provides newly created facets. (In fact, it is a unique solution in the level set sense [8]. Even if the crystalline curvature of at least one of $S_A$ and $S_B$ is not zero, a self-similar expanding solution represents a leading term of the length of newly created facets. We do not touch these two problems in this paper.) A self-similar expanding solution gives a definite way to create new facets (at least when $S_A$ and $S_B$ do not move), so it is useful to implement numerical algorithm starting with a non-admissible polygon. We gave such an application in [13] for multi-scale analysis of contour shape to extract its structure.

When the Frank diagram of $\gamma$ (1-level set of $\gamma$) is strictly convex and smooth so that $W_\gamma$ is smooth and strictly convex, we know that there is a (unique) self-similar expanding solution to
(1.1) touching the boundary of a given sector with prescribed angle [14], [2]. Our selfsimilar expanding solution to (1.2) together with approximation theory [6], [8] provides a selfsimilar expanding solution (under prescribed contact angle condition) for more general \( \gamma \) whose Frank diagram is not necessarily strictly convex. As in [14], [2] our selfsimilar solutions represents the large time behaviour of general solutions. We shall discuss this topic in a forthcoming paper. Note that our selfsimilar expanding solution is different from a selfsimilar shrinking solution studied, for example, in [16], [17].

Let us briefly mention the method of the proof. The uniqueness is proved by a geometric method (\S 2) – comparison principle [18], [9]. To construct a selfsimilar expanding solution it suffices to find a solution of ODEs with \( L_j(t) = t^{1/2}/a_j \) with \( a_j > 0 \). The problem is reduced to find a positive \( a_j \)'s solving a system of algebraic equations of degree two for \( a_j \)'s. If the number of missing orientations is small, say one or two, then one can solve it directly. However, in general it is terrible. The equation for \( a_j \)'s is of the form

\[
\begin{pmatrix}
1/a_1 \\
\vdots \\
1/a_n
\end{pmatrix} = H
\begin{pmatrix}
a_1 \\
\vdots \\
a_n
\end{pmatrix}
\]

and \( H = (H_{ij}) \) is a tridiagonal matrix; see (3.2). We solve this equation analytically by introducing extra parameter \( s \) so that for our algebraic system is decoupled for \( s = 0 \) to get \( a_j = 1/\sqrt{H_{jj}} \) and for \( s = 1 \) it agrees with (3.2). We differentiate it with respect to \( s \) to get ODEs. We solve the ODEs from \( s = 0 \) to \( s = 1 \) by establishing a priori estimates. A crucial step is to calculate the determinant of \( H \), in particular to prove its positivity. An explicit and beautiful formula of \( \det H \) is given in Lemma 4.2 up to an explicit constant. It is represented by angles of Wulff shapes. Note that our method provides not only the existence but also a way to calculate a numerical value of \( a_j \)'s by solving the ODEs numerically.

This paper is organized as follows. In section 2 we state our main results and give a proof of uniqueness. In section 3 we derive the ODEs to solve the algebraic equation (3.1). We prove the existence of a solution admitting several estimates for matrices established in section 4, which is a main technical part of this paper.

2 Main theorems.

To state our main results we formulate our problem. Let \( \partial C \) be the boundary of a given oriented cone \( C \) in \( \mathbb{R}^2 \) of the form \( \partial C = \ell_A \cup \ell_B \), where \( \ell_A \) and \( \ell_B \) are maximal half lines starting from the origin \( O \) and are indexed clockwise as Figure 2.1. In this paper, we assume that \( \tilde{n}_j = (\cos \theta_j, \sin \theta_j) \) be the outer unit normal of \( \ell_j \) for \( j = A, B \) with \( |\theta_A - \theta_B| < \pi \). Let \( n \) be a nonnegative integer. Let \( \Theta = \{ \theta_j; \ j = 1, \cdots, n \} \) with \( \theta_A > \theta_1 > \theta_2 > \cdots > \theta_n > \theta_B \) (resp. \( \theta_A < \theta_1 < \theta_2 < \cdots < \theta_n < \theta_B \)) if \( \theta_A > \theta_B \) (resp. \( \theta_A < \theta_B \)). We call \( \Theta \) as a set of admissible angles. We interpret that \( \Theta \) is an empty set if \( n = 0 \).

We call a simple oriented polygonal curve \( S \) as an admissible crystal associated with \( C \) if \( S \) is of the form \( S = \bigcup_{j=1}^{n} S_j \cup S_A \cup S_B \), where \( S_j \) is a maximal, nontrivial and closed segment with the outer unit normal \( \tilde{n}_j = (\cos \theta_j, \sin \theta_j) \) for \( j \in \{1, \cdots, n\} \cup \{A, B\} \) and \( S_j \) for \( j = A, B \) is a half line contained in \( \ell_j \). We implicitly assume that segments \( S_j \)'s are numbered clockwise. Figure 2.1 shows examples of \( C \). Figure 2.2 shows examples of admissible crystals \( S \) associated with \( C \).
We say that a family of polygon $\{S(t)\}_{t \in J}$ belongs to a set of orientation-preserving evolving curves $S$ if $S(t)$ is an admissible crystal for all $t \in J$ and each corner moves continuously differentiably in time, where $J$ is a time interval. These conditions imply that the orientation of each line (facet) is preserved for $t \in J$.

In this paper, we consider an orientation-preserving evolving curve $\{S(t)\}_{t \in J} \in S$ governed by so-called crystalline curvature or weighted curvature $\Lambda_j(t) := \frac{\chi_j(t) \Delta_j}{L_j(t)}$ for given $\Delta_j > 0$ ($j = 1, \cdots, n$), where $S(t) = \bigcup_{j=1}^{n} S_j(t) \cup S_A(t) \cup S_B(t)$ and $L_j(t)$ is the length of facet $S_j(t)$. The quantity $\chi_j(t)$ is a transition number with

$$\chi_j(t) := \begin{cases} 
1, & \text{if } S(t) \text{ is concave around } S_j(t), \\
-1, & \text{if } S(t) \text{ is convex around } S_j(t), \\
0, & \text{otherwise}
\end{cases}$$

(see Figure 2.3). We shall give notion of a selfsimilar expanding solution.

\textit{Definition.} An orientation-preserving evolving curve $\{S(t)\}_{t > 0} \in S$ is called a selfsimilar
expanding solution to (1.2) if there exists an admissible crystal $S_*$ associated with $C$ such that
\begin{align}
S(t) &= t^{1/2} S_* = \{ t^{1/2} x; x \in S_* \} \quad \text{for } t > 0; \\
V_j(t) &= \Lambda_j(t) \quad \text{for } t > 0, \ j = 1, \ldots, n,
\end{align}

where $S(t)$ is of the form $S(t) = \bigcup_{j=1}^n S_j(t) \cup S_A(t) \cup S_B(t)$ and $V_j(t)$ is the normal velocity of facet $S_j(t)$. We note that for a selfsimilar solution $\{S(t)\}_{t>0}$, the transition number is unique independent of $j$ and $t$, i.e. $\chi_j(t) = -1$ (resp. 1) if $\theta_A > \theta_B$ (resp. $\theta_A < \theta_B$) for all $j = 1, \ldots, n$ and $t > 0$.

Our main results are the existence and its uniqueness of a selfsimilar expanding solution governed by crystalline curvature. It is stated as follows.

**Theorem 2.1 (Existence).** Let $C$ be a given oriented cone in $\mathbb{R}^2$. Let $\Theta = \{ \theta_j; \ j = 1, \ldots, n \}$ (with nonnegative integer $n$) be a set of admissible angles. Let $\Delta_j$ be a positive number for $j = 1, \ldots, n$. Then there exists a selfsimilar expanding solution $\{S(t)\}_{t>0}$ such that $S(+0)$ agrees with $\partial C$.

**Theorem 2.2 (Uniqueness).** Under the same hypotheses of Theorem 2.1 there is at most one selfsimilar expanding solution $\{S(t)\}_{t>0}$ such that $S(+0) = \partial C$.

We shall prove Theorem 2.1 in §3 based on key a priori estimates shown in §4. In the rest of this section we shall prove Theorem 2.2 by geometric argument.

**Proof of Theorem 2.2.** Let $\{S(t)\}_{t>0}$ and $\{R(t)\}_{t>0}$ be selfsimilar expanding solutions such that $S(+0)$ and $R(+0)$ agree with the boundary of $\partial C$. We may assume that $\theta_A > \theta_B$, i.e. the cone $C$ is convex. We may also assume that $n \geq 1$. Then transition numbers of all facets of $S(t)$ and $R(t)$ are -1. Let $S(t)$ (resp. $R(t)$) be of the form $S(t) = \bigcup_{j=1}^n S_j(t) \cup S_A(t) \cup S_B(t)$ (resp. $R(t) = \bigcup_{k=1}^n R_k(t) \cup R_A(t) \cup R_B(t)$). For convenience we introduce an unbounded region
\( D_S(t) \subset \mathbb{R}^2 \) enclosed by \( S(t) \) for \( t > 0 \); let \( D_S(t) \) denote the closure of the interior region bounded by curve \( S(t) \) (see Figure 2.4). Let \( \tilde{R}(t) \) be of the form \( \tilde{R}(t) = \bigcup_{k=1}^{n} R_k(t) \).

![Figure 2.4: Region \( D_S(t) \) enclosed by \( S(t) \)](image)

Suppose that \( S \neq R \). We may assume that \( \tilde{R}(1) \cap \text{int} \, D_S(1) \neq \emptyset \). By this assumption, \( t_0 \in (0,1) \) holds for \( t_0 := \sup\{t|\tilde{R}(t) \cap \text{int} \, D_S(1) = \emptyset \} \). Since \( \tilde{R}(0) \) is a singleton and \( S(1-t_0) \neq \partial C \), there exists \( \delta > 0 \) such that \( \tilde{R}(\delta) \cap \text{int} \, D_S(t_1) = \emptyset \) with \( t_1 := 1-t_0 \). We fix such \( \delta \). Setting \( t_2 := \sup\{\tau > 0; \tilde{R}(\sigma+\delta) \cap \text{int} \, D_S(\sigma+t_1) = \emptyset \text{ for } \sigma \in (0,\tau)\} \), we have \( 0 < t_2 < t_0 \). Since \( \tilde{R}(\sigma+\delta) \) touches \( D_S(\sigma+t_1) \) first time at \( \sigma = t_2 \), there exists a facet \( R_j(t_2+\delta) \) of \( \tilde{R}(t_2+\delta) \) and a facet \( S_j(t_2+t_1) \) of \( S(t_2+t_1) \) such that the normal of \( R_j(t_2+\delta) \) coincides with that of \( S_j(t_2+t_1) \), we conclude that \( R_j(t_2+\delta) \cap S_j(t_2+t_1) \neq \emptyset \) and that the length of \( R_j(t_2+\delta) \) does not equal the length of \( S_j(t_2+t_1) \). By geometry the length of \( R_j(t_2+\delta) \) is greater than the length of \( S_j(t_2+t_1) \), so that the weighted curvature of \( R_j(t_2+\delta) \) is negative and is greater than that of \( S_j(t_2+t_1) \) (cf. [18], [9]). So the normal velocity of \( R_j(t_2+\delta) \) is negative and is greater than that of \( S_j(t_2+t_1) \), which contradicts \( 0 < t_2 \).

**Remark.** (i) The evolution equation (2.2) can be viewed as a crystalline curvature flow equation (1.1) (or (1.2)) with a suitable polygonal Wulff shape. Indeed, if \( \theta_A > \theta_B \) for example, then there exists a convex polygon \( W \) such that the set \( \mathcal{N} \) of the orientations of all facets in \( W \) includes all \( \tilde{n}_j \)’s with \( j \in \{1, \cdots, n\} \) and the length of facet with \( \tilde{n}_j \) equals \( \Delta_j \) and that \( \mathcal{N} \) does not include any \( \tilde{m} = (\cos \theta, \sin \theta) \) for \( \theta \neq \theta_j, \theta \in (\theta_B, \theta_A) \). We may assume that \( W \) contains the origin as an interior point. The corresponding interfacial energy density \( \gamma \) is given as a support function: \( \gamma(x) = \sup\{x \cdot p; p \in W\} \) for \( x \in \mathbb{R}^2 \). The case \( \theta_A < \theta_B \) can be treated in a similar way.

![Figure 2.5: Wulff shape \( W \)](image)
(ii) If we dilate the Wulff shape so that the length of \( j \)-th facet equals \( \lambda \Delta_j \), then \( \sqrt{\lambda} S(t) \) is the corresponding selfsimilar expanding solution to (1.2) with \( \Delta_j \) replaced by \( \lambda \Delta_j \), where \( S(t) \) is defined by (2.1) with (2.2).

(iii) Here is a numerical example of a profile \( S_{\epsilon} \) of the selfsimilar expanding solutions for given two different sectors with a fixed Wulff shape having many facets so that it looks a smooth curve. See Figures 2.5, 2.6 and 2.7. We use a Newton type iteration which is closely related to our ODEs (3.4) to find numerical values of \( a_j \)'s.

![Figure 2.6: Selfsimilar expanding solution \( S(t) \)](image)

![Figure 2.7: Selfsimilar expanding solution \( S(t) \)](image)

3 Existence of selfsimilar solution of ODE system.

We shall show the existence theorem (Theorem 2.1). When \( n = 0 \), \( \{ S(t) \}_{t \geq 0} \) with \( S(t) = t^{1/2}(\partial C) \) is the desired selfsimilar expanding solution. In the following we suppose \( n \geq 1 \). Let a family of polygon \( \{ S(t) \}_{t \geq 0} \) belongs to \( S \). Then we have a transport equation of \( \{ S(t) \}_{t \geq 0} : \)

\[
\frac{dL_j(t)}{dt} = (\cot \varphi_j + \cot \varphi_{j+1})V_j(t) - \frac{1}{\sin \varphi_j}V_{j-1}(t) - \frac{1}{\sin \varphi_{j+1}}V_{j+1}(t), \quad t > 0
\]

for \( j = 1, \cdots, n \), where \( \varphi_j := \theta_j - \theta_{j-1} \) for \( j = 1, \cdots, n + 1 \). Here we set \( \theta_0 := \theta_A, \theta_{n+1} := \theta_B, V_0 := 0 \) and \( V_{n+1} := 0 \) for convenience. Plugging the governing law \( V_j(t) = \Lambda_j(t) \) for \( j = 1, \cdots, n \), we have an ODE system:

\[
(3.1) \quad \frac{dL_j(t)}{dt} = \frac{1}{2} \left\{ \frac{p_j}{L_j(t)} + \frac{q_{j-1}}{L_{j-1}(t)} + \frac{r_{j+1}}{L_{j+1}(t)} \right\}, \quad t > 0
\]
for \( j = 1, \ldots, n \), where
\[
p_j = 2\chi_j \Delta_j \frac{\sin(\varphi_j + \varphi_{j+1})}{\sin \varphi_j \sin \varphi_{j+1}} \quad \text{for} \quad j = 1, \ldots, n,
\]
\[
q_j = -2\chi_j \Delta_j \frac{1}{\sin \varphi_{j+1}} \quad \text{for} \quad j = 1, \ldots, n-1,
\]
\[
r_j = -2\chi_j \Delta_j \frac{1}{\sin \varphi_j} \quad \text{for} \quad j = 2, \ldots, n,
\]
and \( q_0 = 0 \) and \( r_{n+1} = 0 \). Here we used \( \cot \varphi_j + \cot \varphi_{j+1} = \frac{\sin(\varphi_j + \varphi_{j+1})}{\sin \varphi_j \sin \varphi_{j+1}} \).

By the assumption on \( \theta_A \) and \( \theta_B \) in §2, we note that \( \left| \sum_{j=1}^{n+1} \varphi_j \right| = |\theta_A - \theta_B| < \pi \). When \( C \) is convex (resp. concave), i.e. \( \theta_A > \theta_B \) (resp. \( \theta_A < \theta_B \)), then \( \varphi_j < 0 \) (resp. \( \varphi_j > 0 \)) for \( j = 1, \ldots, n+1 \) and \( \chi_j < 0 \) (resp. \( \chi_j > 0 \)) for \( j = 1, \ldots, n \). So, we have \( p_j > 0 \) for \( j = 1, \ldots, n \), \( q_j < 0 \) for \( j = 1, \ldots, n-1 \) and \( r_j < 0 \) for \( j = 2, \ldots, n \).

Definition. A family of function \( \{L_j(t)\}_{j=1}^{n} \) is called a selfsimilar solution of the ODE system (3.1) if \( L_j(t) \) is of the form \( L_j(t) = \alpha_j t^{1/2} \) with positive number \( \alpha_j \) satisfying (3.1) for \( j = 1, \ldots, n \).

Theorem 2.1 is obtained by showing

**Theorem 3.1.** Let \( n \) be a positive integer. There exists a selfsimilar solution \( \{L_j(t)\}_{j=1}^{n} \) of the ODE system (3.1).

When \( n = 1 \), equation (3.1) yields an ODE:
\[
\frac{dL_1(t)}{dt} = \frac{p_1}{2L_1(t)}, \quad t > 0.
\]
Since \( (d/dt)\{L_1(t)^2\} = p_1 \), \( t > 0 \), we obtain \( L_1(t) = t^{1/2} p_1^{1/2} \) for \( t > 0 \), so that Theorem 2.1 holds for \( n = 1 \).

In the following we assume that \( n \geq 2 \). Our strategy to prove Theorem 3.1 is as follows. Substituting \( L_j(t) = \alpha_j t^{1/2} \) to (3.1), we have
\[
\begin{pmatrix}
1/a_1 \\
1/a_2 \\
\vdots \\
1/a_n
\end{pmatrix} = H
\begin{pmatrix}
a_1 \\
2 \\
\vdots \\
a_n
\end{pmatrix}
\]
with unknowns \( a_j = 1/\alpha_j \), where
\[
H = \begin{pmatrix}
p_1 & r_2 & q_1 & p_2 & r_3 & 0 \\
& \ddots & \ddots & \ddots & \ddots & \ddots \\
& & q_{n-2} & p_{n-1} & r_n & 0 \\
& & & q_{n-1} & p_n
\end{pmatrix}.
\]
In particular
\[
H = \begin{pmatrix}
p_1 & r_2 \\
q_1 & p_2
\end{pmatrix}
\]
when \( n = 2 \). To show the existence of nonlinear algebraic equations (3.2), we consider the following continuation method sometimes called Davidenko’s method. Introducing extra parameter \( s \geq 0 \) and matrix \( K(s) \):

\[
K(s) = \begin{pmatrix}
p_1 & s r_2 & 0 \\
s q_1 & p_2 & s r_3 \\
\vdots & \vdots & \ddots \\
0 & s q_{n-2} & p_{n-1} & s r_n \\
s q_{n-1} & 0 & \ldots & p_n
\end{pmatrix},
\]

we consider a system of nonlinear algebraic equations:

\[
\begin{pmatrix}
1/b_1(s) \\
1/b_2(s) \\
\vdots \\
1/b_n(s)
\end{pmatrix} = K(s) \begin{pmatrix}
b_1(s) \\
b_2(s) \\
\vdots \\
b_n(s)
\end{pmatrix}
\]

(3.3)

with parameter \( s \geq 0 \) and \( b(s) > 0 \). Evidently \( b_j(0) = 1/\sqrt{p_j} \), since \( K(0) \) is a diagonal matrix. If the solution can be extended up to \( s = 1 \), then \( b_j(1) \) is a solution of (3.2) since \( K(1) = H \).

Differentiating (3.3) formally with respect to parameter \( s \), we have

\[
-\begin{pmatrix}
b'_j(s)/b_j(s)^2 \\
\vdots \\
\end{pmatrix} = K(s) \begin{pmatrix}
b'_j(s) \\
\vdots \\
\end{pmatrix} - J \begin{pmatrix}
b'_j(s) \\
\vdots \\
\end{pmatrix},
\]

which yields

\[
Q(s, \vec{b}(s)) \begin{pmatrix}
b'_j(s) \\
\vdots \\
\end{pmatrix} = J \begin{pmatrix}
b_j(s) \\
\vdots \\
\end{pmatrix},
\]

(3.4)

i.e.

\[
Q(s, \vec{b}(s)) \vec{y}(s) = J \vec{b}(s) \quad \text{with} \quad \vec{b}(s) = \begin{pmatrix} b_1(s) & \cdots & b_n(s) \end{pmatrix},
\]

where

\[
J = -\begin{pmatrix}
0 & r_2 & & 0 \\
q_1 & 0 & r_3 & & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & \cdots & & 0 & r_n \\
0 & q_{n-2} & 0 & r_n & 0
\end{pmatrix}
\]

and

\[
Q(s, \vec{h}) = K(s) + \text{diag}(1/h_1^2, \cdots, 1/h_n^2) \quad \text{with} \quad \vec{h} = \begin{pmatrix} h_1 & \cdots & h_n \end{pmatrix}.
\]

Here \( \prime \) denotes \( d/ds \), differentiation with respect to \( s \). If the inverse matrix of \( Q \) exists, (3.4) formally yields

\[
\vec{y}(s) = G(s, \vec{b}(s)) \vec{b}(s).
\]

(3.5)
Here we set \( G(s, \bar{h}) = Q^{-1}(s, \bar{h}) \). We consider a system of ODEs (3.5) for \( s > 0 \) with initial condition

\[
(3.6) \quad \bar{b}(0) = \bar{h}^* , \quad \bar{h}^* := t(1/\sqrt{p_1}, \ldots, 1/\sqrt{p_n}).
\]

Local-in-time unique existence of a positive solution \( \bar{b}(s) \) of (3.5) and (3.6) is guaranteed, since \( Q \) is smooth and \( \det Q \neq 0 \) near \((0, \bar{h}^*)\), so that \( Q^{-1} \) is smooth near \((0, \bar{h}^*)\).

As we shall prove in Lemma 3.2, the local solution \( \bar{b}(s) \) can be extended uniquely up to \( s = 1 + \tau \) with some \( \tau > 0 \) (obtained in Theorem 4.1). Then \( a_j := b_j(1) \) \((j = 1, \ldots, n)\) is a solution of (3.2), so that \( \{L_j(t)\}_{j=1}^n \) with \( L_j(t) = t^{1/2}/b_j(1) \) for \( t > 0 \), \( j = 1, \ldots, n \) is a self-similar solution of (3.1), which implies Theorem 3.1.

**Lemma 3.2 (Unique solvability up to \( s = 1 \)).** There exists the unique positive solution \( \bar{b}(s) \) (i.e. \( \bar{b}(s) > \bar{0} \)) of the system of ODEs (3.5) and (3.6) for \( s \in [0, 1 + \tau] \), where \( \tau \) is a positive number obtained in Theorem 4.1.

Here we use notation \( \bar{x} < \bar{y} \) (resp. \( \bar{x} \leq \bar{y} \)) for \( \bar{x} = (x_1, \ldots, x_n), \bar{y} = (y_1, \ldots, y_n) \in \mathbb{R}^n \) if \( x_j < y_j \) (resp. \( x_j \leq y_j \)) for \( j = 1, \ldots, n \).

Proof admitting a priori estimate (Lemma 3.3). Let \( S_0 \) be the maximal existence time of (3.5) and (3.6), and set \( S_1 := \min(S_0, 1 + \tau) \). We note that \( G(s, \bar{b}(s)) \) is well-defined for \( s \in [0, S_1] \) by Lemma 3.3. Integrating (3.5), we have

\[
\bar{b}(s) - \bar{b}(0) = \int_0^s G(u, \bar{b}(u))\bar{b}(u)du \quad \text{for} \quad s \in [0, S_1),
\]

which implies

\[
|\bar{b}(s)| \leq |\bar{b}(0)| + \int_0^s |G(u, \bar{b}(u))|_{op} |\bar{b}(u)|du \quad \text{for} \quad s \in [0, S_1).
\]

Here \( |\cdot| \) denotes the Euclidean norm and \( |\cdot|_{op} \) denotes the operator norm from \( \mathbb{R}^n \) to \( \mathbb{R}^n \). Lemma 3.3 implies that there exist a constant \( C_1 \) independent of \( s \) such that

\[
0 < |G(s, \bar{b}(s))|_{op} \leq C_1 \quad \text{for} \quad s \in [0, S_1),
\]

since each component of \( J \) is nonnegative. So we have

\[
|\bar{b}(s)| \leq |\bar{b}(0)| + C_1 \int_0^s |\bar{b}(u)|du \quad \text{for} \quad s \in [0, S_1).
\]

Gronwall’s Lemma implies

\[
|\bar{b}(s)| \leq |\bar{b}(0)|\exp(C_1 s) \leq |\bar{h}^*|\exp(C_1 S_1) =: C_2 \quad \text{for} \quad s \in [0, S_1).
\]

Suppose that \( S_0 \leq 1 + \tau \). Then Lemma 3.3 (II) yields

\[
1/\sqrt{p_j} \leq b_j(s) \leq C_2 \quad \text{for} \quad s \in [0, S_0), \quad j = 1, \ldots, n,
\]

which contradicts the definition of the maximal existence time. Thus we have \( S_0 > 1 + \tau \). \( \square \)
Lemma 3.3 (A priori estimate). Let $S_0 > 0$ denote the maximal existence time of a positive solution of the system of ODEs (3.5) and (3.6). Set $S_1 := \min(S_0, 1 + \tau)$, where $\tau$ is a positive number obtained in Theorem 4.1. Let $\tilde{b}(s)$ be the solution of (3.5) and (3.6).

(I) The derivative of each component of $\tilde{b}(s)$ is positive, i.e., $\tilde{b}'(s) > 0$ for $s \in [0, S_1]$.

(II) In particular, $\tilde{b}(s) > \tilde{b}^*(> 0)$ for $s \in (0, S_1]$.

(III) There exists a constant $C_3 > 0$ independent of $s$ such that

$$0 \leq \{\text{each component of } Q^{-1}(s, \tilde{b}(s))\} \leq C_3 \quad \text{for } s \in [0, S_1].$$

Proof. The main steps of this lemma are proved in the next section, as summarized in Theorem 4.1. Since each component of matrix $J$ is nonnegative and $\tilde{b}(s) > 0$ for $s \in [0, S_1)$, we have $J\tilde{b}(s) > 0$. We now observe that (II) and (III) of Theorem 4.1 implies $\tilde{b}'(s) = G(s, \tilde{b}(s))\tilde{b}(s) > 0$ for $s \in [0, S_1)$. Initial condition (3.6) and (I) yield (II). Theorem 4.1 and (II) implies (III). \hfill \Box

4 A priori estimates for matrices.

Theorem 4.1 (A priori estimates). (I) There exist positive constants $C_4$ and $\tau$ (independent of $s$ and $\tilde{h}$) such that

$$\det Q(s, \tilde{h}) > C_4 \prod_{j=1}^{n} p_j(> 0) \quad \text{for all } s \in [0, 1 + \tau] \text{ and all } \tilde{h} \in (\mathbb{R}_+)^n.$$

(II) The matrix $Q(s, \tilde{h})$ has its inverse for $s \in [0, 1 + \tau] \text{ and } \tilde{h} \in (\mathbb{R}_+)^n$. Each component of $Q^{-1}(s, \tilde{h})$ is smooth on $[0, 1 + \tau] \times (\mathbb{R}_+)^n$.

(III) Let $\tilde{h}^t \in (\mathbb{R}_+)^n$ with $\tilde{h}^t > 0$. There exists constant $C_5 > 0$ (independent of $s$ and $\tilde{h}$) such that $0 \leq \{\text{each component of } Q^{-1}(s, \tilde{h})\} \leq C_5$ for all $s \in [0, 1 + \tau]$ and all $\tilde{h} \in (\mathbb{R}_+)^n$ with $\tilde{h} \geq \tilde{h}^t$.

Here we use notation $\mathbb{R}_+ := (0, \infty)$, so that $(\mathbb{R}_+)^n = (0, \infty) \times \cdots \times (0, \infty)$. To prove the theorem we shall show the following lemma and propositions. To show positiveness of the determinant of matrix $Q$ we consider matrix $M^{k\ell}(s)$:

$$M^{k\ell}(s) := \begin{pmatrix}
1 & s\eta_{k+1}/p_{k+1} & 0 \\
\eta_{k}/p_k & 1 & s\eta_{k+2}/p_{k+2} \\
\eta_{k+1}/p_{k+1} & \eta_{k+2}/p_{k+2} & 1 & \ddots & \ddots & \ddots \\
\ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
0 & \eta_{\ell-1}/p_{\ell-1} & \eta_{\ell}/p_{\ell} & \ddots & \ddots & \ddots \\
\eta_{\ell-2}/p_{\ell-2} & \ddots & \ddots & \ddots & \ddots & 1 \\
\eta_{\ell-1}/p_{\ell-1} & \eta_{\ell}/p_{\ell} & \ddots & \ddots & 1 & 1
\end{pmatrix}$$

for $s \geq 0$ and $k, \ell = 1, \cdots, n$ with $k \leq \ell$. In particular,

$$M^{kk}(s) = \begin{pmatrix} 1 \end{pmatrix} \quad \text{for } s \geq 0, \ k = 1, \cdots, n,$$

$$M^{kk+1}(s) = \begin{pmatrix} 1 & s\eta_{k+1}/p_{k+1} \\
\eta_{k}/p_k & 1 \end{pmatrix} \quad \text{for } s \geq 0, \ k = 1, \cdots, n - 1.$$
We note that $M^{ln}(s)$ is obtained by dividing each $j$-th column of $K(s)$ by $p_j$'s. We set $\tilde{M}^{kl} = M^{kl}(1)$. Fortunately, $\det \tilde{M}^{kl}$ is computable. Note that $\det H = \prod_{j=1}^{n} p_j \cdot \det M^{1n}$.

**Lemma 4.2.** For $k, \ell = 1, \ldots, n$ with $k \leq \ell$,

$$
\det \tilde{M}^{kl} = \frac{\sin \left( \sum_{j=k}^{l+1} \varphi_j \right)}{\left( \prod_{j=k}^{l} \nu_j \right) \left( \prod_{j=k}^{l+1} \sin \varphi_j \right)}, \tag{4.1}
$$

where

$$
\nu_j := \cot \varphi_{j+1} + \cot \varphi_j = \frac{\sin(\varphi_j + \varphi_{j+1})}{\sin \varphi_j \sin \varphi_{j+1}}. \tag{4.2}
$$

**Proof.** Quantities $q_j/p_j$ and $r_j/p_j$ appearing in matrix $M^{kl}(s)$ can be calculated as follows:

$$
\frac{q_j}{p_j} = -\frac{1}{\nu_j \sin \varphi_{j+1}}, \quad \frac{r_j}{p_j} = -\frac{1}{\nu_j \sin \varphi_j}.
$$

We may assume that $k = 1$ without loss of generality. We shall prove (4.1) by induction. Let $m^l$ denote the right hand side of (4.1) with $k = 1$.

(i) Using equality (4.2), we have

$$
m^1 = \frac{\sin(\varphi_1 + \varphi_2)}{(\cot \varphi_2 + \cot \varphi_1) \sin \varphi_2} = 1 = \det \tilde{M}^{11},
$$

which implies (4.1) with $k = 1 = \ell$.

(ii) Next we shall show (4.1) with $k = 1, \ell = 2$. We have

$$
\det \tilde{M}^{12} = 1 - \frac{-1}{\nu_1 \sin \varphi_2} \cdot \frac{-1}{\nu_2 \sin \varphi_2} = \frac{d_2}{\nu_1 \nu_2 \sin \varphi_1 \sin^2 \varphi_2 \sin \varphi_3} \tag{4.3}
$$

with $d_2 = (\nu_1 \nu_2 \sin^2 \varphi_2 - 1) \sin \varphi_1 \sin \varphi_3$. Equality (4.2) yields $d_2 = \sin(\varphi_1 + \varphi_2) \sin(\varphi_2 + \varphi_3) - \sin \varphi_1 \sin \varphi_3$. Using the identity

$$
\sin \alpha \sin \beta = -\{\cos(\alpha + \beta) - \cos(\alpha - \beta)\}/2, \tag{4.4}
$$

we have

$$
d_2 = -\{\cos(\varphi_1 + 2\varphi_2 + \varphi_3) - \cos(\varphi_1 + \varphi_3)\}/2.
$$

By the identity

$$
\cos \alpha - \cos \beta = -2 \sin \frac{\alpha + \beta}{2} \sin \frac{\alpha - \beta}{2}, \tag{4.5}
$$

we have $d_2 = \sin(\varphi_1 + \varphi_2 + \varphi_3) \sin \varphi_2$. Substituting this to (4.3), we obtain

$$
\det \tilde{M}^{12} = \frac{\sin(\varphi_1 + \varphi_2 + \varphi_3)}{\nu_1 \nu_2 \sin \varphi_1 \sin \varphi_2 \sin \varphi_3} = m^2,
$$

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which is (4.1) for $k = 1, \ell = 2$.

(iii) We assume that $\ell \geq 3$ and (4.1) holds for $\tilde{M}^{11}, \tilde{M}^{12}, \ldots, \tilde{M}^{1,\ell-1}$. We have

$$\det \tilde{M}^{1\ell} = \det \tilde{M}^{1,\ell-1} - \frac{r_{\ell} q_{\ell-1}}{p_{\ell} p_{\ell-1}} \det \tilde{M}^{1,\ell-2},$$

since

$$\tilde{M}^{1\ell} = \begin{pmatrix} \tilde{M}^{1,\ell-1} & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & r_{\ell}/p_{\ell} \\ 0 & \cdots & 0 & 1 \end{pmatrix}$$

for $i = 2, \ldots, \ell$.

The assumption of the induction yields

$$\det \tilde{M}^{1\ell} = \frac{\sin \left( \sum_{j=1}^{\ell} \varphi_j \right)}{\left( \prod_{j=1}^{\ell-1} \sin \varphi_j \right)} - \frac{1}{\nu_{\ell} \sin \varphi_{\ell}} \cdot \frac{1}{\nu_{\ell-1} \sin \varphi_{\ell}} \cdot \frac{\sin \left( \sum_{j=1}^{\ell-1} \varphi_j \right)}{\left( \prod_{j=1}^{\ell-1} \sin \varphi_j \right)}.$$

Elementary calculation yields

(4.6) $$\det \tilde{M}^{1\ell} = \frac{d_{\ell}}{\left( \prod_{j=1}^{\ell} \nu_j \right) \left( \prod_{j=1}^{\ell+1} \sin \varphi_j \right) \sin \varphi_{\ell}}$$

with

$$d_{\ell} = \sin \left( \sum_{j=1}^{\ell} \varphi_j \right) \sin(\varphi_{\ell} + \varphi_{\ell+1}) - \sin \left( \sum_{j=1}^{\ell-1} \varphi_j \right) \sin \varphi_{\ell+1}.$$

The identity (4.4) yields

$$d_{\ell} = \frac{-1}{2} \left\{ \cos \left( \sum_{j=1}^{\ell+1} \varphi_j + \varphi_{\ell} \right) - \cos \left( \sum_{j=1}^{\ell-1} \varphi_j + \varphi_{\ell+1} \right) \right\},$$

and the identity (4.5) yields

$$d_{\ell} = \sin \left( \sum_{j=1}^{\ell+1} \varphi_j \right) \sin \varphi_{\ell}.$$

Substituting this to (4.6), we obtain (4.1) for $\det \tilde{M}^{1\ell}$. By induction the proof is now complete. □
Proposition 4.3. The identities

\[
\frac{d}{ds} \{ \det M^{k \ell}(s) \} = -s \left\{ \sum_{j=k+1}^{\ell-2} \frac{q_j r_{j+1}}{p_j p_{j+1}} \det M^k j-1(s) \cdot \det M^{j+2} \ell(s) \right. \\
+ \left. \sum_{j=k+2}^{\ell-1} \frac{q_{j-1} r_j}{p_{j-1} p_j} \det M^k j-2(s) \cdot \det M^{j+1} \ell(s) \right. \\
+ \left. 2 \frac{q_k r_{k+1}}{p_k p_{k+1}} \det M^{k+2} \ell(s) + 2 \frac{q_{\ell-1} r_{\ell}}{p_{\ell-1} p_{\ell}} \det M^k \ell-2(s) \right\}
\]

for \( s \geq 0 \) and \( k, \ell = 1, \ldots, n \) with \( k + 2 < \ell \) hold. Moreover

\[
\frac{d}{ds} \{ \det M^{k k}(s) \} = 0 \quad \text{for } s \geq 0 \text{ and } k = 1, \ldots, n;
\]

\[
\frac{d}{ds} \{ \det M^{k k+1}(s) \} = -2s \frac{q_k r_{k+1}}{p_k p_{k+1}} \quad \text{for } s \geq 0 \text{ and } k = 1, \ldots, n-1;
\]

\[
\frac{d}{ds} \{ \det M^{k k+2}(s) \} = -2s \left( \frac{q_k r_{k+1}}{p_k p_{k+1}} + \frac{q_{k+1} r_{k+2}}{p_{k+1} p_{k+2}} \right) \quad \text{for } s \geq 0 \text{ and } k = 1, \ldots, n-2.
\]

Proof. We observe that for \( s \geq 0 \) and \( k, \ell = 1, \ldots, n \) with \( k + 2 < \ell \)

\[
\frac{d}{ds} \{ \det M^{k \ell}(s) \}
\]

\[
= \sum_{j=k+1}^{\ell-1} \det \begin{pmatrix}
M^k j-1(s) & 0 & \cdots & 0 \\
0 & \ddots & \ddots & \ddots \\
0 & \cdots & 0 & \cdots & 0 \\
q_j/p_j & 0 & \cdots & 0 \\
0 & q_j/p_j & \cdots & 0 \\
0 & \cdots & \ddots & \ddots & \ddots \\
0 & \cdots & \cdots & 0 & M^{j+1} \ell(s)
\end{pmatrix}
\]

\[
+ \det \begin{pmatrix}
0 & \cdots & 0 & \cdots & 0 \\
q_k/p_k & 0 & \cdots & 0 & \cdots \\
0 & q_k/p_k & \cdots & 0 & \cdots \\
0 & \cdots & \ddots & \ddots & \ddots \\
0 & \cdots & \cdots & 0 & M^{k+1} \ell(s)
\end{pmatrix}
\]

\[
+ \det \begin{pmatrix}
M^k j-1(s) & 0 & \cdots & 0 \\
0 & \ddots & \ddots & \ddots \\
0 & \cdots & 0 & \cdots & 0 \\
0 & \cdots & 0 & \cdots & 0 \\
0 & \cdots & 0 & \ddots & \ddots \\
0 & \cdots & 0 & \cdots & \ddots \\
0 & \cdots & 0 & \cdots & \cdots & 0 \\
0 & \cdots & 0 & \cdots & M^{j+2} \ell(s)
\end{pmatrix}
\]

\[
= -\sum_{j=k+1}^{\ell-2} \frac{q_j}{p_j} \det \begin{pmatrix}
M^k j-1(s) & 0 & \cdots & 0 \\
0 & \ddots & \ddots & \ddots \\
0 & \cdots & 0 & \cdots & 0 \\
0 & \cdots & 0 & \cdots & 0 \\
0 & \cdots & 0 & \cdots & 0 \\
0 & \cdots & 0 & \ddots & \ddots \\
0 & \cdots & 0 & \cdots & \ddots \\
0 & \cdots & 0 & \cdots & \cdots & 0 \\
0 & \cdots & 0 & \cdots & M^{j+2} \ell(s)
\end{pmatrix}
\]

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\[ -\frac{q_{\ell-1}}{p_{\ell-1}} \det \begin{pmatrix} M^k \ell-2(s) & 0 \\ \vdots & \vdots \\ 0 & 0 \end{pmatrix} \]
\[ - \sum_{j=k+2}^{\ell-1} \frac{r_j}{p_j} \det \begin{pmatrix} M^j \ell-2(s) & 0 \\ \vdots & \vdots \\ 0 & 0 \end{pmatrix} \]
\[ -\frac{r_{k+1}}{p_{k+1}} \det \begin{pmatrix} \frac{sq_k}{p_k} & \frac{sr_{k+2}}{p_{k+2}} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & M^{k+2} \ell(s) \end{pmatrix} \]
\[ -\frac{q_k}{p_k} \frac{r_{k+1}}{p_{k+1}} \det M^{k+2} \ell(s) - \frac{r_{\ell}}{p_{\ell}} \frac{q_{\ell-1}}{p_{\ell-1}} \det M^k \ell-2(s), \]

which yields (4.6). A direct calculation yields the desired formulas for \( k + 2 \geq \ell. \)

**Proposition 4.4.**

(I) For \( k, \ell = 1, \ldots, n \) with \( k \leq \ell \), \( \det M^{\ell}(1) = \det \tilde{M}^{\ell} > 0. \)

(II) There exists \( \tau > 0 \) such that

\[ \frac{d}{ds} \{ \det M^{\ell}(s) \} \leq 0 \quad \text{and} \quad \det M^{\ell}(s) \geq \det M^{\ell}(1 + \tau) > 0 \]

for \( s \in [0, 1 + \tau] \) and \( k, \ell = 1, \ldots, n \) with \( k \leq \ell \).

**Proof.** (I) For all \( j = 1, \ldots, n+1 \) we see that \( \varphi_j < 0 \) (resp. \( \varphi_j > 0 \)) if the cone \( C \) is convex (resp. concave). Since the original assumption in \( \S 2 \) yields \( \sum_{j=1}^{n+1} \varphi_j = |\theta_A - \theta_B| < \pi \), identity (4.1) in Lemma 4.2 implies (I).

(II) We shall prove by induction.

(i) For \( k = 1, \ldots, n, \) \( \det M^k(s) = 1 \), so that \( (d/ds)\{ \det M^k(s) \} = 0 \) for \( s \in \mathbb{R} \).

(ii) For \( k = 1, \ldots, n-1, \) \( (d/ds)\{ \det M^{k+1}(s) \} \leq 0 \) for \( s \geq 0 \) by Proposition 4.3. By (I) with \( \ell = k + 1, \) there exists \( \tau^{k+1} > 0 \) such that \( \det M^{k+1}(s) > 0 \) for \( s \in [0, 1 + \tau^{k+1}] \).

(iii) Next we consider when \( n \geq 3 \). Let \( m \) be \( 2, 3, \ldots, n-1 \). For a moment we fix \( m \). Assume that for \( k = 1, 2, \ldots, n - (m-1), \) \( i = 0, 1, \ldots, m-1, \) there exists \( \tau^{k+i} > 0 \) such that \( \det M^{k+i}(s) > 0 \) for \( s \in [0, 1 + \tau^{k+i}] \). For \( k = 1, 2, \ldots, n-m, \) identity (4.6) in Proposition 4.3 with \( \ell = k + m \) yields \( (d/ds)\{ \det M^{k+m}(s) \} \leq 0 \) for \( s \in [0, 1 + \tau^{k+m}] \) with \( \tau^{k+m} = \min\{ \min\{ \tau^{k+j}; j = k+1, k+2, \ldots, k+m \}; \min\{ \tau^{k+j}; j = k+2, k+3, \ldots, k+m \} \} \), since \( p_j > 0 \) \( (j = 1, \ldots, n), q_j < 0 \) \( (j = 1, \ldots, n-1) \) and \( r_j < 0 \) \( (j = 2, \ldots, n) \). By (I) with \( \ell = k + m, \) there exists \( \tau^{k+m} > 0 \) such that \( \det M^{k+m}(s) > 0 \) for \( s \in [0, 1 + \tau^{k+m}] \). □

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Proof of Theorem 4.1. (I) Setting

\[ W^{k\ell} (s, \bar{h}^{k\ell}) := M^{k\ell} (s) + \text{diag} \left( \frac{1}{p_k h_k^2}, \frac{1}{p_{k+1} h_{k+1}^2}, \ldots, \frac{1}{p_k h_k^2} \right) \]

for \( s \geq 0, \bar{h}^{k\ell} = (h_k, h_{k+1}, \ldots, h_{\ell}) \in (\mathbb{R}_+)^{\ell-k+1} \) and \( k, \ell = 1, \ldots, n \) with \( k \leq \ell \), we have

\[ \det Q^{k\ell} (s, \bar{h}^{k\ell}) = \det W^{k\ell} (s, \bar{h}^{k\ell}) \cdot \prod_{j=k}^\ell p_j. \]

Here

\[ Q^{k\ell} (s, \bar{h}^{k\ell}) := K^{k\ell} (s) + \text{diag} \left( 1/h_k^2, 1/h_{k+1}^2, \ldots, 1/h_{\ell}^2 \right) \]

and

\[ K^{k\ell} (s) := \left( K_{ij} (s) \right)_{i,j=k,k+1,\ldots,\ell}, \]

where \( \left( K_{ij} (s) \right)_{i,j=1,\ldots,n} \) is the matrix \( K (s) \) defined in §3. Proposition 4.4 (II) yields that there exists \( \tau > 0 \) such that \( \det M^{pq} (s) \geq C_{pq} \) for \( s \in [0, 1+\tau] \) and \( p, q = 1, \ldots, n \) with \( p \leq q \), where \( C_{pq} := \det M^{pq} (1+\tau) > 0 \). As we shall show later in Proposition 4.5, we have

\[ \det W^{k\ell} (s, \bar{h}^{k\ell}) > \det M^{k\ell} (s) \text{ for } s \in [0, 1+\tau] \text{ and } \bar{h}^{k\ell} \in (\mathbb{R}_+)^{\ell-k+1}. \]

Since \( p > 0 \) (\( j = 1, \ldots, n \)),

\[ (4.7) \quad \det Q^{k\ell} (s, \bar{h}^{k\ell}) > C_{k\ell} \prod_{j=k}^\ell p_j \quad (> 0) \]

for \( s \in [0, 1+\tau] \) and \( \bar{h}^{k\ell} \in (\mathbb{R}_+)^{\ell-k+1} \).

(II) Part (II) follows from (I) with \( k = 1 \) and \( \ell = n \) and the definition of \( Q \).

(III) When \( n = 1 \), \( Q (s, \bar{h}) \) is a scalar and equals \( (p_1 + 1/h_1^2) \), so that \( 0 < Q^{-1} (s, \bar{h}) = (p_1 + 1/h_1^2)^{-1} < 1/p_1 \). We may assume that \( n \geq 2 \). Since \( Q (s, \bar{h}) \) is invertible for \( s \in [0, 1+\tau] \) and \( \bar{h} \in (\mathbb{R}_+)^n \) by (I), the \((p, q)\) component of the inverse of \( Q (s, \bar{h}) \) equals \( \Delta_{pq} (s, \bar{h}) / \det Q (s, \bar{h}) \) for \( p, q = 1, \ldots, n \), where \( \Delta_{pq} (s, \bar{h}) \) denotes the \((p, q)\) cofactor of \( Q (s, \bar{h}) \). As we shall observe later in Proposition 4.6, we have

\[ \Delta_{pq} (s, \bar{h}) = (-1)^{p+q} \left( \prod_{j=p}^{p-1} q_j \right) s^{q-p} \det Q^{1-p-1} (s, \bar{h}) \det Q^{p+1} (s, \bar{h}) \quad \text{for } p < q; \]

\[ \Delta_{pq} (s, \bar{h}) = (-1)^{p+q} \left( \prod_{j=q+1}^{p} r_j \right) s^{p-q} \det Q^{1-q-1} (s, \bar{h}) \det Q^{p+1} (s, \bar{h}) \quad \text{for } p > q; \]

\[ \Delta_{pp} (s, \bar{h}) = \det Q^{p-1} (s, \bar{h}) \det Q^{p+1} (s, \bar{h}) \]

for \( s \geq 0 \) and \( \bar{h} \in (\mathbb{R}_+)^n \). Here we use convention \( \det Q^{0} (s, \bar{h}) = 1 = \det Q^{n+1} (s, \bar{h}) \). Since \( q_j < 0 \) (\( j = 1, \ldots, n-1 \)) and \( r_j < 0 \) (\( j = 2, \ldots, n \)), inequality (4.7) yields \( \Delta_{pq} (s, \bar{h}) \geq 0 \) for \( s \in [0, 1+\tau], \bar{h} \in (\mathbb{R}_+)^n \) and \( p, q = 1, \ldots, n \), which implies \( \{(p, q) \text{ component of } Q^{-1} (s, \bar{h})\} = \Delta_{pq} (s, \bar{h}) / \det Q (s, \bar{h}) \geq 0 \) by (I). On the other hand \( \Delta_{pq} (s, \bar{h}) \) is bounded from the above for
\[ s \in [0, 1 + \tau] \text{ and } \tilde{h} = (h_1, \ldots, h_n) \in (\mathbb{R}_+)^n \text{ with } \tilde{h} \geq \tilde{h}', \text{ since } \Delta_{pq}(s, \tilde{h}) \text{ is a polynomial of } 1/h_1^2, \ldots, 1/h_n^2 \text{ and } s. \text{ Thus (I) yields that there exists } C_5 > 0 \text{ such that } \Delta_{pq}(s, \tilde{h})/\det Q(s, \tilde{h}) \leq C_5 \text{ for } s \in [0, 1 + \tau], \tilde{h} \in (\mathbb{R}_+)^n \text{ with } \tilde{h} \geq \tilde{h}' \text{ and } p, q = 1, \ldots, n. \tag*{\Box}

Next we shall show an inequality, which is used in the proof of Theorem 4.1. For \( \mu_j > 0 \ (j = 1, \ldots, n) \), \( \xi_j \in \mathbb{R} \ (j = 1, \ldots, n - 1) \) and \( \eta_j \in \mathbb{R} \ (j = 2, \ldots, n) \), we set

\[
A^{k\ell} := B^{k\ell} + \text{diag}(\mu_k, \mu_{k+1}, \ldots, \mu_\ell),
\]

\[
B^{k\ell} := \begin{pmatrix}
1 & \eta_{k+1} & & & \\
\xi_k & 1 & \eta_{k+2} & & \\
\xi_{k+1} & 1 & \eta_{k+3} & & \\
& \ddots & \ddots & \ddots & \ddots \\
& & \xi_{\ell-3} & 1 & \eta_{\ell-1} \\
& & & \xi_{\ell-2} & 1 & \eta_\ell \\
& & & & \xi_{\ell-1} & 1
\end{pmatrix}
\]

for \( k, \ell = 1, \ldots, n \) with \( k \leq \ell \). In particular,

\[
B^{kk} := \begin{pmatrix} 1 \end{pmatrix} \quad \text{for } k = 1, \ldots, n;
\]

\[
B^{k k+1} := \begin{pmatrix} 1 & \eta_{k+1} \\
\xi_k & 1 \end{pmatrix} \quad \text{for } k = 1, \ldots, n - 1 \text{ when } n \geq 2.
\]

**Proposition 4.5.** Let \( k \) and \( \ell \) be \( 1, \ldots, n \) with \( k \leq \ell \). If \( \det B^{pq} > 0 \) for \( p, q = k, k+1, \ldots, \ell \) with \( p \leq q \) then \( \det A^{k\ell} > \det B^{k\ell} \).

**Proof.** For \( k, \ell = 1, \ldots, n \) with \( k \leq \ell \) we set

\[
C^{k\ell}(r) := B^{k\ell} + r \text{ diag}(\mu_k, \ldots, \mu_\ell) \quad \text{for } r > 0,
\]

which yields \( C^{k\ell}(0) = B^{k\ell} \) and \( C^{k\ell}(1) = A^{k\ell} \). We shall prove by induction on \( \ell - k = 0, 1, 2, \ldots, n - 1 \). If \( 0 \leq \ell - k \leq 1 \), direct calculation yields \( (d/dr)\{\det C^{k\ell}(r)\} > 0 \) for \( r > 0 \), which implies \( \det C^{k\ell}(r) > \det B^{k\ell} > 0 \) for \( r > 0 \). We assume that \( k, \ell = 1, \ldots, n \) with \( k + 2 \leq \ell \). Suppose that \( (d/dr)\{\det C^{pq}(r)\} > 0 \) for \( r > 0 \) and for \( p, q = k, k+1, \ldots, \ell \) with \( p \leq q \leq p + \ell - k - 1 \). An elementary calculation yields

\[
\frac{d}{dr} \det C^{k\ell}(r) = \mu_k \cdot \det C^{k+1 \ell}(r) + \det C^{k \ell-1}(r) \cdot \mu_\ell
\]

\[
+ \sum_{j=k+1}^{\ell-1} \det C^{k j-1}(r) \cdot \mu_j \cdot \det C^{j+1 \ell}(r)
\]

\[
> 0 \quad \text{for } r > 0,
\]

since \( \det C^{pq}(r) > \det C^{pq}(0) = \det B^{pq} > 0 \) for \( r > 0 \) and for \( p, q = k, k+1, \ldots, \ell \) with \( p \leq q \leq p + \ell - k - 1 \) by the assumption of the induction. Thus we obtain

\[
\det A^{k\ell} = \det C^{k\ell}(1) > \det C^{k\ell}(0) = \det B^{k\ell}
\]

for \( k \leq \ell \). \( \Box \)
Finally, we shall show identities on a cofactor of tridiagonal matrix, which are used in the proof of Theorem 4.1. For $\lambda_j \in \mathbb{R}$ ($j = 1, \cdots, n$), $\xi_j \in \mathbb{R}$ ($j = 2, \cdots, n$) and $\eta_j \in \mathbb{R}$ ($j = 1, \cdots, n - 1$), we set matrices

$$E^{k\ell} := \begin{pmatrix} \lambda_k & \xi_{k+1} & \xi_{k+2} & \xi_{k+3} & \cdots & \xi_{\ell-3} & \xi_{\ell-2} & \xi_{\ell-1} & \xi_{\ell} \\ \eta_k & \lambda_{k+1} & \xi_{k+2} & \xi_{k+3} & \cdots & \xi_{\ell-3} & \xi_{\ell-2} & \xi_{\ell-1} & \xi_{\ell} \\ \eta_{k+1} & \lambda_{k+2} & \xi_{k+3} & \cdots & \xi_{\ell-3} & \xi_{\ell-2} & \xi_{\ell-1} & \xi_{\ell} \\ \vdots & \vdots & \vdots & \ddots & \ddots & \cdots & \cdots & \cdots & \cdots \\ 0 & \vdots & \vdots & \vdots & \cdots & \xi_{\ell-3} & \xi_{\ell-2} & \xi_{\ell-1} & \xi_{\ell} \\ 0 & \cdots & \cdots & \cdots & \cdots & \xi_{\ell-3} & \xi_{\ell-2} & \xi_{\ell-1} & \xi_{\ell} \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \xi_{\ell-3} & \xi_{\ell-2} & \xi_{\ell-1} \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \xi_{\ell-3} & \xi_{\ell-2} \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \xi_{\ell-3} \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \xi_{\ell-3} \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \xi_{\ell-3} \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \xi_{\ell-3} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \xi_{\ell-3} \end{pmatrix}$$

for $k, \ell = 1, \cdots, n$ with $k \leq \ell$. In particular,

$$E^{kk} := \begin{pmatrix} \lambda_k \end{pmatrix}$$

for $k = 1, \cdots, n$;

$$E^{k+1 \ell} := \begin{pmatrix} \lambda_k & \eta_{k+1} \\ \eta_k & \lambda_{k+1} \end{pmatrix}$$

for $k = 1, \cdots, n - 1$ when $n \geq 2$.

Let $D_{pq}$ be the $(p, q)$ cofactor of matrix $E^{1n}$ for $p, q = 1, \cdots, n$. The next proposition is obtained by an elementary calculation.

**Proposition 4.6** For $p, q = 1, \cdots, n$ the following identities hold.

(I) When $p < q$,

$$D_{pq} = (-1)^{p+q} \prod_{j=p}^{q-1} \eta_j \det E_{1}^{p+1} \det E_{1}^{q+1}. n.$$

(II) When $p > q$,

$$D_{pq} = (-1)^{p+q} \prod_{j=q+1}^{p} \xi_j \det E_{1}^{p+1} \det E_{1}^{q+1}. n.$$

(III) $D_{pp} = \det E_{1}^{p+1} \det E_{1}^{p+1}. n$.

Here we use convention $\det E_{1}^{10} = 1 = \det E_{1}^{n+1}. n$.

**References**


