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<th>Title</th>
<th>Great circular surfaces in the three-sphere</th>
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Great circular surfaces in the three-sphere

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Abstract

In this paper, we consider a special class of the surfaces in the 3-sphere defined by one-parameter families of great circles. We give a generic classification of singularities of such surfaces and investigate the geometric meanings from the viewpoint of spherical geometry.

1 Introduction

In this paper we investigate a special class of surfaces in the 3-sphere which are called great circular surfaces. We say that a surface in the 3-sphere is a great circular surface if it is given by a one-parameter family of great circles (cf., §4).

On the other hand, there appeared two kinds of curvatures in the previous theory of surfaces in the 3-sphere. One is called the extrinsic Gauss curvature $K_e$ and another is the intrinsic Gauss curvature $K_I$. The intrinsic Gauss curvature is nothing but the Gauss curvature defined by the induced Riemannian metric on the surface. The relation between these curvatures is known that $K_e = K_I - 1$. We can show that an extrinsic flat surface is (at least locally) parametrized as a great circular surface (cf., Theorem 3.3). Such a surface is an extrinsic flat great circular surface (briefly, we call an E-flat great circular surface). This is one of the motivations to investigate great circular surfaces. In Euclidean space, surfaces with vanishing Gauss curvature are developable surfaces which belong to a special class of ruled surfaces [5, 6]. Therefore, the notion of great circular surfaces is one of the analogous notions with ruled surfaces in the 3-sphere. In this paper, we study geometric properties and singularities of great circular surfaces. However, there is the canonical double covering $\pi: S^3 \to \mathbb{RP}^3$ onto the projective space. A great circle corresponds to a projective line in $\mathbb{RP}^3$, so that the singularities of great circular surfaces are the same as those of ruled surfaces. There are a lot of researches on developable surfaces in $\mathbb{R}^3 \subset \mathbb{RP}^3$ from the view point of projective differential geometry [2, 4, 12, 17]. Developable surfaces with singularities in $\mathbb{R}^3$ are investigated in [13] from the view point of differential geometry. We investigate the singularities of great circular surfaces from the view point of spherical geometry (i.e, $SO(4)$-invariant geometry).
For any smooth curve $A : I \rightarrow SO(4)$ in the rotation group $SO(4)$, we can define a parametrization $F_A$ of a great circular surface $M = \text{Image} F_A$ in the 3-sphere. We can easily show that $C = A' A^{-1}$ is a smooth curve in the Lie algebra $so(4)$ of $SO(4)$. We can also obtain the curve $A$ in $SO(4)$ with initial data $A(t_0) = A_0$ from $C$ by the existence theorem of the linear ordinary differential equations. In this sense, $C(t)$ is a spherical invariant of great circular surfaces. We remark that $C(t)$ is an anti-symmetric matrix:

$$C(t) = \begin{pmatrix}
0 & c_1(t) & c_2(t) & c_3(t) \\
-c_1(t) & 0 & c_4(t) & c_5(t) \\
-c_2(t) & -c_4(t) & 0 & c_6(t) \\
-c_3(t) & -c_5(t) & -c_6(t) & 0
\end{pmatrix}.$$ 

Therefore we consider that the space of great circular surfaces is the space of smooth mappings $C^\infty(I, so(4))$ equipped with the Whitney $C^\infty$-topology, where

$$so(4) = \left\{ C = \begin{pmatrix}
0 & c_1 & c_2 & c_3 \\
-c_1 & 0 & c_4 & c_5 \\
-c_2 & -c_4 & 0 & c_6 \\
-c_3 & -c_5 & -c_6 & 0
\end{pmatrix} \mid c_i \in \mathbb{R}, (i = 1, 2, 3, 4, 5, 6) \right\} = \mathbb{R}^6.$$

A generic classification of singularities of general great circular surfaces is given as follows (cf., Theorem 4.5 and Theorem 8.1):

**Theorem 1.1.** There exists an open and dense subset $\mathcal{O} \subset C^\infty(I, so(4))$ such that $F_A(\theta, t)$ has only cross caps as singular points for any $C \in \mathcal{O}$.

Here, we say that a singular point $(\theta, t)$ of $F_A$ is the cross cap if the germ of the surface $F_A(\mathbb{R} \times I)$ at $F_A(\theta, t)$ is (locally) diffeomorphic to $CR = \{ (x_1, x_2, x_3) \in \mathbb{R}^3 \mid x_1 = u, x_2 = uv, x_3 = v^2 \}$

![Fig.1: cross cap](image)

In §5 we show that a great circular surface Image$F_A$ is extrinsic flat if and only if $c_1(t) = c_3(t) = 0$. Therefore we may regard that the space of (parametrizations of) E-flat great circular surfaces is $C^\infty(I, e\mathfrak{f}(4))$ as a subspace of $C^\infty(I, so(4))$, where

$$e\mathfrak{f}(4) = \left\{ C = \begin{pmatrix}
0 & c_1 & c_2 & c_3 \\
-c_1 & 0 & c_4 & c_5 \\
-c_2 & -c_4 & 0 & c_6 \\
-c_3 & -c_5 & -c_6 & 0
\end{pmatrix} \in so(4) \mid c_1 = c_3 = 0 \right\} = \mathbb{R}^4.$$

One of the main results in this paper is a generic classification of singularities of extrinsic flat great circular surfaces by using the spherical invariant $C(t)$. Our classification theorem is summarized as follows (cf., Theorem 5.1 and Theorem 8.1):
Theorem 1.2. There exists an open and dense subset $O \subset C^\infty(I, \mathcal{E}(4))$ such that a singular point of $F_A(\theta, t)$ is the cuspidal edge, the swallowtail or the cuspidal cross cap for any $C \in O$.

Here, we say that a singular point $(s, t)$ of $F_A$ is the cuspidal edge (respectively swallowtail and cuspidal cross cap) if the germ of the surface $F_A(\mathbb{R} \times I)$ at $F_A(s, t)$ is (locally) diffeomorphic to $CE = \{(x_1, x_2, x_3) | x_1^2 = x_2^3\}$ (respectively, $SW = \{(x_1, x_2, x_3) | x_1 = 3u^4 + u^2v, x_2 = 4u^3 + 2uv, x_3 = v\}$ and $CCR = \{(x_1, x_2, x_3) \in \mathbb{R}^3 | x_1 = u, x_2 = uv^3, x_3 = v^2\}$).

The cuspidal edge \hspace{1cm} The swallowtail \hspace{1cm} The cuspidal cross cap

Fig. 2.

We have another interesting class of E-flat great circular surfaces. In §5, we show that each generating great circle is tangent to the regular part of the singular locus of the E-flat great circular surface $F_A(\theta, t)$ if and only if $c_1(t) = c_3(t) = c_4(t) = 0$. Such the surface is called a tangential extrinsic flat great circular surface (briefly, T-E-flat great circular surface). Therefore, we consider that the space of T-E-flat great circular surfaces is given by $C^\infty(I, \mathcal{E}_\tau(4))$ as a subspace of $C^\infty(I, \mathcal{E}(4))$, where

$$\mathcal{E}_\tau(4) = \left\{ C = \begin{pmatrix} 0 & c_1 & c_2 & c_3 \\ -c_1 & 0 & c_4 & c_5 \\ -c_2 & -c_4 & 0 & c_6 \\ -c_3 & -c_5 & -c_6 & 0 \end{pmatrix} \in \mathfrak{so}(4) \left| c_1 = c_3 = c_4 = 0 \right. \right\} = \mathbb{R}^3.$$

We have the following generic classification of singularities of T-E-flat great circular surfaces (cf., Theorem 5.2 and Theorem 8.1):

Theorem 1.3. There exists an open and dense subset $O \subset C^\infty(I, \mathcal{E}_\tau(4))$ such that a singular point of $F_A(\theta, t)$ is the cuspidal edge, the swallowtail, the cuspidal cross cap or the cuspidal beaks for any $C \in O$.

Here, we say that a singular point $(s, t)$ of $F_A$ is the cuspidal beaks if the germ of the surface $F_A(\mathbb{R} \times I)$ at $F_A(s, t)$ is (locally) diffeomorphic to $CBK = \{(x_1, x_2, x_3) | x_1 = v, x_2 = -2u^3 + v^2u, x_3 = 3u^4 - v^2u^2\}$.

The cuspidal beaks

Fig. 3.

Therefore we can show that an extrinsic flat great circular surface is locally diffeomorphic to a developable surface in the Euclidean sense, so that generic singularities of extrinsic flat great circular surfaces are the same as those of developable surfaces. In §8, we present a dual...
relations among singularities of T-E-flat great circular surfaces. Comparing with the duality among surfaces in Euclidean 3-space, we can observe that the spherical duality gives beautiful dual relations [15]. In §9, we give three examples of great circular surfaces associated to a Frenet curve. Especially, the binormal great circular surface has the cross cap when \( \tau_g(s_0) = 0 \) and \( \tau_g'(s_0) \neq 0 \). In Euclidean 3-space, the binormal ruled surface is always non-singular, so that the situations are different.

All maps considered here are of class \( C^\infty \) unless otherwise stated.

2 Differential geometry of curves and surfaces in the 3-sphere

We outline in this section the differential geometry of curves and surfaces in the 3-sphere (cf., [14]).

Let \( S^3 \) be the 3-dimensional unit sphere in Euclidean space \( \mathbb{R}^4 \). Given a vector \( \mathbf{n} \in \mathbb{R}^4 \setminus \{0\} \) and a real number \( c \), the hyperplane with a normal vector \( \mathbf{n} \) is given by \( HP(\mathbf{n}, c) = \{ x \in \mathbb{R}^4 \mid \mathbf{n} \cdot x = c \} \), where \( \mathbf{v} \cdot \mathbf{v} \) is the canonical inner product. A sphere in \( S^3 \) is given by

\[
S^2(\mathbf{n}, c) = S^3 \cap H(\mathbf{n}, c) = \{ x \in S^3 \mid \mathbf{n} \cdot x = c \}.
\]

We say that \( S^2(\mathbf{n}, c) \) is a great sphere if \( c = 0 \), a small hypersphere if \( c \neq 0 \). For any \( \mathbf{a}(i) = (a_{1}(i), a_{2}(i), a_{3}(i), a_{4}(i)) \in \mathbb{R}^4 \) \((i = 1, 2, 3)\), the vector product \( \mathbf{a}(1) \times \mathbf{a}(2) \times \mathbf{a}(3) \) is defined by

\[
\mathbf{a}(1) \times \mathbf{a}(2) \times \mathbf{a}(3) = \begin{vmatrix}
\mathbf{e}(1) & \mathbf{e}(2) & \mathbf{e}(3) & \mathbf{e}(4) \\
\mathbf{a}(1) & \mathbf{a}(2) & \mathbf{a}(3) & \mathbf{a}(4) \\
\mathbf{a}(1) & \mathbf{a}(2) & \mathbf{a}(3) & \mathbf{a}(4) \\
\mathbf{a}(1) & \mathbf{a}(2) & \mathbf{a}(3) & \mathbf{a}(4)
\end{vmatrix},
\]

where \( \{ \mathbf{e}(1), \mathbf{e}(2), \mathbf{e}(3), \mathbf{e}(4) \} \) is the canonical basis of \( \mathbb{R}^4 \). We can easily show that \( \mathbf{a}(1) \times \mathbf{a}(2) \times \mathbf{a}(3) \) is orthogonal to any \( \mathbf{a}(i) \) \((i = 1, 2, 3)\).

We now construct the extrinsic differential geometry on curves in \( S^3 \). Let \( \gamma : I \rightarrow S^3 \) be a regular curve. Since \( S^3 \) is a Riemannian manifold, we can reparametrize \( \gamma \) by the arc-length. Hence, we may assume that \( \gamma(s) \) is a unit speed curve. So we have the tangent vector \( \mathbf{t}(s) = \gamma'(s) \) with \( \| \mathbf{t}(s) \| = 1 \). In the case when \( \mathbf{t}'(s) \cdot \mathbf{t}'(s) \neq 1 \), we have a unit vector \( \mathbf{n}(s) = (\mathbf{t}'(s) + \gamma(s))/\|\mathbf{t}'(s) + \gamma(s)\| \). Moreover, define \( \mathbf{e}(s) = \gamma(s) \times \mathbf{t}(s) \times \mathbf{n}(s) \), then we have an orthonormal frame \( \{ \gamma(s), \mathbf{t}(s), \mathbf{n}(s), \mathbf{e}(s) \} \) of \( \mathbb{R}^4 \) along \( \gamma \). By standard arguments, under the assumption that \( \mathbf{t}'(s) \cdot \mathbf{t}'(s) \neq 1 \), we have the following Frenet-Serre type formulae:

\[
\begin{align*}
\gamma'(s) &= \mathbf{t}(s) \\
\mathbf{t}'(s) &= \kappa_g(s) \mathbf{n}(s) - \gamma(s) \\
\mathbf{n}'(s) &= -\kappa_g(s) \mathbf{t}(s) + \tau_g(s) \mathbf{e}(s) \\
\mathbf{e}'(s) &= -\tau_g(s) \mathbf{n}(s)
\end{align*}
\]

(2.1)

where \( \kappa_g(s) = \| \mathbf{t}'(s) + \gamma(s) \| \) and \( \tau_g(s) = -\frac{\det(\gamma(s), \gamma'(s), \gamma''(s), \gamma'''(s))}{(\kappa_g(s))^2} \).

We can easily show that the condition \( \mathbf{t}'(s) \cdot \mathbf{t}'(s) \neq 1 \) is equivalent to the condition \( \kappa_g(s) \neq 0 \). We can show that the curve \( \gamma(s) \) satisfies the condition \( \kappa_g(s) \equiv 0 \) if and only if \( \gamma(s) \) is a great
circle (i.e., the geodesic). We can study many properties of curves in the 3-sphere by using this fundamental equation.

On the other hand, we give a brief review on the extrinsic differential geometry of surfaces in $S^3$. Let $\mathbf{X}: U \to S^3$ be a regular surface (i.e., an embedding), where $U \subset \mathbb{R}^2$ is an open subset. We denote that $M = \mathbf{X}(U)$ and identify $M$ with $U$ through the embedding $\mathbf{X}$. Define a vector

$$e(u) = \frac{\mathbf{X}(u) \times \mathbf{X}_{u_1}(u) \times \mathbf{X}_{u_2}(u)}{\| \mathbf{X}(u) \times \mathbf{X}_{u_1}(u) \times \mathbf{X}_{u_2}(u) \|},$$

then we have $e \cdot \mathbf{X}_{u_i} \equiv e \cdot \mathbf{X} \equiv 0$, $e \cdot e = 1$, where $\mathbf{X}_{u_i} = \partial \mathbf{X}/\partial u_i$. Therefore we have a mapping

$$\mathbb{G} : U \to S^3$$

by $\mathbb{G}(u) = e(u)$ which is called the Gauss map of $M = \mathbf{X}(U)$. It is easy to show that the surface $M = \mathbf{X}(U)$ is a part of a great sphere if and only if the Gauss map $\mathbb{G}$ is constant. It is well known that $D_v \mathbb{G} \in T_p M$ for any $p = \mathbf{X}(u_0) \in M$ and $v \in T_p M$, where $D_v$ denotes the covariant derivative with respect to the tangent vector $v$. This means that $d \mathbb{G}(u_0)$ can be considered as a linear transformation of $T_p M$. We call the linear transformation $S_p = -d \mathbb{G}^\perp(u_0) : T_p M \to T_p M$ the shape operator of $M = \mathbf{X}(U)$ at $p = \mathbf{X}(u_0)$. We denote the eigenvalues of $S_p$ by $\kappa_i(p)$ ($i = 1, 2$). We call $\kappa_i(p)$ principal curvatures of $M = \mathbf{X}(U)$ at $p = \mathbf{X}(u_0)$. We now describe the geometric meaning of the principal curvatures. Let $\gamma(s) = \mathbf{X}(u_1(s), u_2(s))$ be a unit speed curve on $M = \mathbf{X}(U)$ with $p = \gamma(s_0)$. We consider the spherical curvature vector $k(s) = t'(s) + \gamma(s)$ and the normal curvature

$$\kappa_n(s_0) = k(s_0) \cdot \mathbb{G}(u_1(s_0), u_2(s_0)) = t'(s_0) \cdot \mathbb{G}(u_1(s_0), u_2(s_0))$$

of $\gamma(s)$ at $p = \gamma(s_0)$. We can show that the spherical normal curvature depends only on the point $p$ and the unit tangent vector of $M$ at $p$ analogous to the Euclidean case. Therefore we have the maximum and the minimum of the spherical normal curvature at $p \in M$. We can also show that the principal curvatures $\kappa_i(p)$ are equal to the maximum or the minimum of the spherical normal curvature at $p$. Then we have the following spherical Rodoriges type formula: If $\gamma(s) = \mathbf{X}(u_1(s), u_2(s))$ is a line of curvature, then $\kappa_n(s)$ is one of the principal curvatures at $\gamma(s)$, so that we have

$$-\frac{d \mathbb{G}}{ds}(u_1(s), u_2(s)) = \kappa_n(s) \frac{d \mathbf{X}}{ds}(u_1(s), u_2(s)).$$

The spherical Gauss-Kronecker curvature of $M = \mathbf{X}(U)$ at $p = \mathbf{X}(u_0)$ is defined to be

$$K_c(u_0) = \det S_p = \kappa_1(p) \kappa_2(p).$$

The spherical mean curvature of $M = \mathbf{X}(U)$ at $p = \mathbf{X}(u_0)$ is defined to be

$$H_c(u_0) = \frac{1}{2} \text{Trace} S_p = \frac{\kappa_1(p) + \kappa_2(p)}{2}. $$

We also call $K_c(u_0)$ the extrinsic spherical Gauss curvature.

We say that a point $u \in U$ or $p = \mathbf{X}(u)$ is an umbilical point if $\kappa_1(p) = \kappa_2(p)$. We say that $M = \mathbf{X}(U)$ is totally umbilical if all points on $M$ are umbilical. The following proposition is a well-known result:
Proposition 2.1. Suppose that \( M = X(U) \) is totally umbilic. Then \( \kappa(p) \) is constant \( \kappa \). Under this condition, we have the following classification:

(1) If \( \kappa = 0 \), then \( M \) is a part of a great hypersphere.

(2) If \( \kappa \neq 0 \), then \( M \) is a part of a small hypersphere.

We establish next the spherical version of the Weingarten formula. We have the Riemannian metric (spherical first fundamental form) given by \( ds^2 = \sum_{i=1}^{2} g_{ij} du_i du_j \) on \( M = X(U) \), where \( g_{ij}(u) = X_{u_i}(u) \cdot X_{u_j}(u) \) and the spherical second fundamental invariant defined by \( h_{ij}(u) = -G_{u_i}(u) \cdot X_{u_j}(u) \) for any \( u \in U \). It is easy to show the following (cf., [14]):

Proposition 2.2. Under the above notations, we have the following formula:

\[ G_{u_i} = - \sum_{j=1}^{2} h_{ij} X_{u_j}, \]  
(The spherical Weingarten formula),

where \( (h_{ij}) = (g^{kj}) \) and \( (g^{kj}) = (g_{kj})^{-1} \).

As a corollary of the above proposition, we have an explicit expression of the spherical extrinsic Gauss curvature in terms of the Riemannian metric and the spherical second fundamental invariant.

Corollary 2.3. Under the same notations as those in the above proposition, we have the following formula:

\[ K_e = \frac{\det(h_{ij})}{\det(g_{i\alpha})}. \]

We now consider the Riemannian curvature tensor

\[ R_{\ell ijk} = \frac{\partial}{\partial u_k} \left\{ \ell \right\}_{i j} - \frac{\partial}{\partial u_j} \left\{ \ell \right\}_{i k} + \sum_m \left\{ m \right\}_{i j} \left\{ m \right\}_{k \ell} - \sum_m \left\{ m \right\}_{i k} \left\{ m \right\}_{j \ell}. \]

We also consider the tensor \( R_{ij\ell k} = \sum_m g_m R_{j k \ell}^m \). Standard calculations, analogous to those used in the study of the classical differential geometry on surfaces in Euclidean space, lead to the following:

Proposition 2.4. Under the above notations, we have

\[ K_e = - \frac{R_{1212}}{g} - 1, \]

where \( g = \det(g_{i\alpha}) \).

We remark that \(-R_{1212}/g\) is the intrinsic Gaussian curvature of the surface \( M = X(U) \). It is denoted by \( K_I \), so that we have \( K_e = K_I - 1 \).

We now consider the spherical duality from the viewpoint of contact geometry. We briefly review some properties of contact manifolds and Legendrian submanifolds [1, Part III]. Let \( W \) be a \((2n+1)\)-dimensional smooth manifold and \( K \) be a tangent hyperplane field on \( W \). Locally such a field is defined as the field of zeros of a 1-form \( \alpha \). If tangent hyperplane field \( K \) is non-degenerate, we say that \((W,K)\) is a contact manifold. Here \( K \) is said to be non-degenerate if \( \alpha \wedge (da)^n \neq 0 \) at any point of \( W \). In this case \( K \) is called a contact structure.
and $\alpha$ is a contact form. A submanifold $i : L \subset W$ of a contact manifold $(W, K)$ is a Legendrian submanifold if $\dim L = n$ and $d_{ip}(T_p L) \subset K_{i(p)}$ at any point $p \in L$. We consider a smooth fiber bundle $\pi : N \to A$. The fiber bundle $\pi : N \to A$ is called a Legendrian fibration if its total space $W$ is furnished with a contact structure and its fibers are Legendrian submanifolds. Let $\pi : N \to A$ be a Legendrian fibration. For a Legendrian submanifold $i : L \subset N$, a map $\pi \circ i : L \to A$ is called a Legendrian map. The image of the Legendrian map $\pi \circ i$ is called a wavefront set of $i$ which is denoted by $W(i)$.

We now consider the following double fibrations over $S^3$:

$$\Delta = \{(v, w) \in S^3 \times S^3 | v \cdot w = 0\},$$
$$\pi_1 : \Delta \ni (v, w) \mapsto v \in S^3, \quad \pi_2 : \Delta \ni (v, w) \mapsto w \in S^3,$$
$$\theta_1 = dv \cdot w|\Delta, \quad \theta_2 = v \cdot dw|\Delta.$$

Here, $dv \cdot w = \sum_{i=1}^4 w_i dv_i$ and $v \cdot dw = \sum_{i=1}^4 v_i dw_i$. Since $d(v \cdot w) = dv \cdot w + v \cdot dw$ and $v \cdot w = 0$ on $\Delta$, $\theta_1^{-1}(0)$ and $\theta_2^{-1}(0)$ define the same tangent hyperplane field over $\Delta$ which is denoted by $K$. The following proposition is well-known.

**Proposition 2.5.** Under the above notations, $(\Delta, K)$ is a contact manifold and both of $\pi_i$ are Legendrian fibrations.

We now interpret the Gauss map of a surface in $S^3$ as a wave front set in the above contact manifold. For any regular surface $X : U \to S^3$, we have $X(u) \cdot e(u) = 0$. Therefore we can define an embedding $L_X : U \to \Delta$ by $L_X(u) = (X(u), e(u)) = (X(u), \mathbb{G}(u))$.

**Proposition 2.6.** The mapping $L_X$ is a Legendrian embedding to the contact manifold $(\Delta, K)$.

**Proof.** Since $X : U \to S^3$ is an embedding, $L_X$ is also an embedding and $\dim(L_X(U)) = 2$. Since $L_X^* \theta_1 = dX \cdot e = 0$, $L_X$ is a Legendrian embedding. This completes the proof. \qed

By definition, we have $\pi_2 \circ L_X(U) = \mathbb{G}(U)$. Then we have the following corollary:

**Corollary 2.7.** For any surface $X : U \to S^3$, $\mathbb{G}(U)$ is a wave front set of $L_X(U)$ with respect to the Legendrian fibration $\pi_2$.

We say that a $C^\infty$-mapping $L : U \to \Delta$ is an isotropic mapping if $L^* \theta_i = 0$ ($i = 1$ or 2). We remark that the isotropic mapping is Legendrian immersion if it is an immersion. If we have an isotropic mapping $L : U \to \Delta$, then we say that $\pi_1 \circ L(U)$ and $\pi_2 \circ L(U)$ are $\Delta$-dual to each other. By Corollary 2.7, $X$ and $\mathbb{G}$ are $\Delta$-dual to each other.

In [16] differential geometric properties of $X$ were investigated when the Gauss map $\mathbb{G}$ has the $A_k$-singularities.

### 3 Extrinsic flat surfaces

In this section we consider surfaces with vanishing extrinsic Gauss curvature. We say that a surface $M = X(U)$ is an extrinsic flat surface (briefly, E-flat surface) if $K_e(p) = 0$ at any point $p \in M$. By Proposition 2.4, $K_e(p) = 0$ if and only if $K_I(p) = 1$.

One of the typical E-flat surfaces is the great sphere which is the totally umbilical surface with the vanishing curvature. If we suppose that a surface is umbilically free, then we have the
following expression: Let $X : U \to S^3$ be an E-flat surface without umbilical points, where $U \subset \mathbb{R}^2$ is a neighborhood around the origin. In this case, we have two lines of curvature at each point and one of which corresponds to the vanishing principal curvature. We may assume that both the $u$-curve and the $v$-curve are the lines of curvature for the coordinate system $(u, v) \in U$. Moreover, we assume that the $u$-curve corresponds to the vanishing principal curvature. By the spherical Weingarten formula (Proposition 2.2), we have

$$G_u(u, v) = 0 \quad \text{and} \quad G_v(u, v) = -\kappa(u, v)X_v(u, v),$$

where $\kappa(u, v) \neq 0$. It follows that $G(0, v) = G(u, v)$. We define a function $F : S^3 \times (-\varepsilon, \varepsilon) \to \mathbb{R}$ by

$$F(x, v) = G(0, v) \cdot x,$$

for sufficiently small $\varepsilon > 0$. For any fixed $v \in (-\varepsilon, \varepsilon)$, we have a great sphere $S^2(\mathbb{G}(0, v), 0)$, so that $F = 0$ defines a one-parameter family of great spheres. We have the following proposition.

**Proposition 3.1.** Under the above notations, the surface $M = X(U)$ is a part of the envelope of the family of great spheres defined by $F = 0$.

**Proof.** The envelope defined by $F = 0$ is the surface (might be singular) satisfying the condition $F = F_v = 0$. Here we have

$$F_v(x, v) = G_v(0, v) \cdot x = -\kappa(0, v)(X_v(0, v) \cdot x).$$

We now consider the function $H(u, v) = F(X(u, v), v)$, then

$$H(0, v) = F(X(0, v), v) = G(0, v) \cdot X(0, v) = 0.$$

We also have $H_u(u, v) = G(0, v) \cdot X_u(u, v)$. Since $G(0, v) = G(u, v)$, we have $H_u(u, v) = G(u, v) \cdot X_u(u, v) = 0$. It follows that $H(u, v) = H(0, v) = 0$.

On the other hand, we consider a function $F_v(X(u, v), v)$. By the same reason as the above arguments, we have $G_v(u, v) = G_v(0, v)$, so that

$$F_v(X(u, v), v) = G_v(0, v) \cdot X(u, v) = G_v(u, v) \cdot X(u, v) = -\kappa(u, v)(X_v(u, v) \cdot X(u, v)).$$

Since $X(u, v) \cdot X(u, v) = 1$, we have $X_v(u, v) \cdot X(u, v) = 0$, so that $F_v(X(u, v), v) = 0$. Therefore $X(u, v)$ satisfies both the condition

$$F(X(u, v), v) = F_v(X(u, v), v) = 0.$$ 

This means that $M = X(U)$ is a part of the envelope of the family of great spheres defined by $F = 0$. \hfill \Box

On the other hand, we consider a surface $\overline{X} : J \times I \to S^3$ defined by

$$\overline{X}(\theta, v) = \cos \theta X(0, v) + \sin \theta \frac{X_v(0, v)}{\|X_v(0, v)\|},$$

where $I \subset \mathbb{R}$ and $J \subset [0, 2\pi]$ are open intervals. We have the following proposition.

**Proposition 3.2.** The surface $\overline{M} = \overline{X}(J \times I)$ is a part of the envelope of the family of great spheres defined by $F = 0$.
Proof. We remind that $G(u, v) = e(u, v)$ and $e(u, v)$ is the unit normal of $M = X(U)$ at $X(u, v)$ with $e(u, v) \cdot X(u, v) = 0$. It follows that

$$G(0, v) \cdot \left(\cos \theta X(0, v) + \sin \theta \frac{X_u(0, v)}{\|X_u(0, v)\|}\right) = 0,$$

so that $F(\theta, v), v = 0$. We remark that $X(u, v) \cdot X_v(u, v) = 0$. Since $G_v(0, v) = -\kappa(0, v) X_v(0, v)$, we have

$$G_v(0, v) \cdot \left(\cos \theta X(0, v) + \sin \theta \frac{X_u(0, v)}{\|X_u(0, v)\|}\right) = -\sin \theta \kappa(0, v) \frac{X_v(0, v) \cdot X_u(0, v)}{\|X_u(0, v)\|}.$$ 

Since both the $u$-curve and the $v$-curve are the lines of curvature, $X_v(0, v) \cdot X_u(0, v) = 0$. This means that $F_v(\theta, s, v) = 0$. This completes the proof.

By Propositions 3.1 and 3.2, an E-flat surface can be reparametrized (at least locally) by

$$X(\theta, v) = \cos \theta X(0, v) + \sin \theta \frac{X_u(0, v)}{\|X_u(0, v)\|}.$$ 

We now consider the meaning of the above parametrization. If we fix $v = v_0$, we denote that

$$a_0 = e(0, v_0), \ a_1 = X(0, v_0), \ a_2 = \frac{X_v(0, v_0)}{\|X_v(0, v_0)\|}, \ a_3 = \frac{X_u(0, v)}{\|X_u(0, v)\|}.$$ 

Then we have $\det(a_0, a_1, a_2, a_3) = 1$. We define a curve by

$$\gamma(\theta) = \cos \theta a_1 + \sin \theta a_3.$$ 

Since $\gamma'(\theta) = -\sin \theta a_1 + \cos \theta a_3$, we have $\gamma'(s) \cdot \gamma'(s) = 1$. Therefore $\gamma(s)$ has the unit speed. Moreover, $\gamma(\theta)$ is known to be the geodesic (the great circle) through $a_1$ whose direction is given by $a_3$. Therefore the E-flat surface is given by the one-parameter family of great circles. By the definition of $e(u, v)$, we have $\det(a_0, a_1, a_2, a_3) = 1$, so that $A = (a_0, a_1, a_2, a_3) \in SO(4)$. We say that a surface is a great circular surface if it is locally parametrized by one-parameter families of great circles around any point. Eventually we have the following theorem.

**Theorem 3.3.** If $M \subset S^3$ is an umbilically free E-flat surface, then it is a great circular surface. Moreover, each great circle is the line of curvature with the vanishing principal curvature.

Proof. The first part of the theorem is a direct consequence of the above arguments. For the second part, we assume that $M = X(U)$ and both the $u$-curve and the $v$-curve are the lines of curvature which satisfy $G_u(u, v) = 0$ and $G_v(u, v) = -\kappa(u, v) X_v(u, v)$. We now consider the parametrization

$$X(\theta, v) = \cos \theta X(0, v) + \sin \theta \frac{X_u(0, v)}{\|X_u(0, v)\|}$$

of $M = X(U)$. By a straightforward calculation, we have

$$X_{\theta}(\theta, v) = -\sin \theta X(0, v) + \cos \theta \frac{X_u(0, v)}{\|X_u(0, v)\|},$$

$$X_v(s, v) = \cos \theta X_v(0, v) + \sin \theta \left(\frac{X_u(0, v)}{\|X_u(0, v)\|} - \frac{2X_u(0, v) \cdot X_{uu}(0, v)}{\|X_u(0, v)\|^2} X_u(0, v)\right).$$
Since $G(0,v) \cdot X_u(0,v) = 0$, we have $G_v(0,v) \cdot X_u(0,v) + G(0,v) \cdot X_{uv}(0,v) = 0$. By the assumption that $v$-curve is the line of curvature with $G_v(0,v) = -\kappa(0,v)X_v(0,v)$, we have $G_v(0,v) \cdot X_u(0,v) = -\kappa(0,v)(X_v(0,v) \cdot X_u(0,v)) = 0$. Therefore we have $G(0,v) \cdot X_{uv}(0,v) = 0$. Since $G(0,v)$ is the normal vector of $M = X(U)$ at $X(0,v)$, we have $G(0,v) \cdot \hat{X}(\theta,v) = \mathbb{G}(0,v) \cdot \hat{X}(\theta,v) = 0$. This means that $G(0,v)$ is the normal of $M = X(U)$ at $\hat{X}(s,v)$. Therefore we have the unit normal $\bar{G}$ which is constant along the $\theta$-curve. Since the $\theta$-curve is a great circle, it is the line of curvature with vanishing principal curvature.

Under the above notations, we remark that $e(0,v)$ is a unit normal vector field of $\hat{X}(\theta,v)$.

4 Great circular surfaces

In this section we study general properties of great circular surfaces. Let $a_i : I \to S^3$ ($i = 0, 1, 2, 3$) be a smooth maps from an open interval $I$ with $a_i(t) \cdot a_j(t) = \delta_{ij}$, so that we have an orthonormal frame $\{a_0, a_1, a_2, a_3\}$ of $\mathbb{R}^4$. We now define a mapping

$$F_A : [0, 2\pi] \times I \to S^3$$

by

$$F_A(\theta, t) = \cos \theta a_1(t) + \sin \theta a_3(t),$$

where we assume that $A(t) = (a_0(t), a_1(t), a_2(t), a_3(t)) \in SO(4)$. We have a great circle $F_A(\theta, t_0)$ for any fixed $t = t_0$. We call $F_A$ (or the image of it) a great circular surface. We also call $a_1(t)$ a base curve and $a_3(t)$ a directrix. Each great circle $F_A(\theta, t_0)$ is called a generating great circle. By using the above orthonormal frame, we define the following fundamental invariants:

$$c_1(t) = a_0'(t) \cdot a_1(t) = -a_0(t) \cdot a_1'(t), \quad c_4(t) = a_0'(t) \cdot a_2(t) = -a_1(t) \cdot a_2'(t),$$

$$c_2(t) = a_0'(t) \cdot a_2(t) = -a_0(t) \cdot a_2'(t), \quad c_5(t) = a_1'(t) \cdot a_3(t) = -a_1(t) \cdot a_3'(t),$$

$$c_3(t) = a_0'(t) \cdot a_3(t) = -a_0(t) \cdot a_3'(t), \quad c_6(t) = a_2'(t) \cdot a_3(t) = -a_2(t) \cdot a_3'(t).$$

We can show that the following fundamental differential equations for the horocyclic surface:

$$\begin{cases}
    a_0'(t) = c_1(t)a_1(t) + c_2(t)a_2(t) + c_3(t)a_3(t) \\
    a_1'(t) = -c_1(t)a_0(t) + c_4(t)a_2(t) + c_5(t)a_3(t) \\
    a_2'(t) = -c_2(t)a_0(t) - c_4(t)a_1(t) + c_6(t)a_3(t) \\
    a_3'(t) = -c_3(t)a_0(t) - c_5(t)a_1(t) - c_6(t)a_2(t).
\end{cases}$$

It can be written in the following form:

$$\begin{pmatrix}
    a_0'(t) \\
    a_1'(t) \\
    a_2'(t) \\
    a_3'(t)
\end{pmatrix} = 
\begin{pmatrix}
    0 & c_1(t) & c_2(t) & c_3(t) \\
    -c_1(t) & 0 & c_4(t) & c_5(t) \\
    -c_2(t) & -c_4(t) & 0 & c_6(t) \\
    -c_3(t) & -c_5(t) & -c_6(t) & 0
\end{pmatrix} 
\begin{pmatrix}
    a_0(t) \\
    a_1(t) \\
    a_2(t) \\
    a_3(t)
\end{pmatrix}.$$

We remark that

$$C(t) = 
\begin{pmatrix}
    0 & c_1(t) & c_2(t) & c_3(t) \\
    -c_1(t) & 0 & c_4(t) & c_5(t) \\
    -c_2(t) & -c_4(t) & 0 & c_6(t) \\
    -c_3(t) & -c_5(t) & -c_6(t) & 0
\end{pmatrix} \in \mathfrak{so}(4).$$
where $\mathfrak{so}(4)$ is the Lie algebra of the rotation group $SO(4)$. If $\{a_0(t), a_1(t), a_2(t), a_3(t)\}$ is an orthonormal frame field as above, the $4 \times 4$-matrix determined by the frame defines a smooth curve $A : I \rightarrow SO(4)$. Therefore we have the relation that $A'(t) = C(t)A(t)$. For the converse, let $A : I \rightarrow SO(4)$ be a smooth curve, then we can show that $A'(t)A(t)^{-1} \in \mathfrak{so}(4)$. Moreover, for any smooth curve $C : I \rightarrow \mathfrak{so}(4)$, we apply the existence theorem on the linear systems of ordinary differential equations, so that there exists a unique curve $A : I \rightarrow SO(4)$ such that $C(t) = A'(t)A(t)^{-1}$ with an initial data $A(t_0) \in SO(4)$. Therefore, a smooth curve $C : I \rightarrow \mathfrak{so}(4)$ might be identified with a great circular surface in $S^3$. Let $C : I \rightarrow \mathfrak{so}(4)$ be a smooth curve with $C(t) = A'(t)A(t)^{-1}$ and $B \in SO(4)$, then we have $C(t) = (A(t)B)'(A(t)B)^{-1}$. This means that the curve $C : I \rightarrow \mathfrak{so}(4)$ is a rotational invariant (spherical invariant) of the orthonormal frame $\{a_0(t), a_1(t), a_2(t), a_3(t)\}$, so that it is a spherical invariant of the corresponding great circular surface.

Let $C^\infty(I, \mathfrak{so}(4))$ be the space of smooth curves into $\mathfrak{so}(4)$ equipped with Whitney $C^\infty$-topology. By the above arguments, we may regard $C^\infty(I, \mathfrak{so}(4))$ as the space of great circular surfaces, where $I$ is an open interval or the unit circle.

On the other hand, we consider the singularities of great circular surfaces. Let $F_A : \mathbb{R} \times I \rightarrow S^3$ be a great circular surface defined by

$$F_A(\theta, t) = \cos \theta a_1(t) + \sin \theta a_3(t).$$

(4.2)

Then we have

$$\frac{\partial F_A}{\partial \theta}(\theta, t) = -\sin \theta a_1(t) + \cos \theta a_3(t)$$

$$\frac{\partial F_A}{\partial t}(\theta, t) = (-\cos \theta c_1(t) - \sin \theta c_3(t))a_0(t) - \sin \theta c_5(t)a_1(t) + (\cos \theta c_4(t) - \sin \theta c_6(t))a_2(t) + \cos \theta c_5(t)a_3(t).$$

Since $(\theta_0, t_0)$ is a singular point of $F_A$ if and only if $(\partial F_A / \partial \theta)(\theta_0, t_0)$ and $(\partial F_A / \partial t)(\theta_0, t_0)$ are parallel, we have conditions

$$\begin{cases}
\cos \theta_0 c_1(t_0) + \sin \theta_0 c_3(t_0) = 0 \\
-\lambda \sin \theta_0 + \sin \theta_0 c_5(t_0) = 0 \\
\cos \theta_0 c_4(t_0) - \sin \theta_0 c_6(t_0) = 0 \\
\lambda \cos \theta_0 - \cos \theta_0 c_5(t_0) = 0
\end{cases}$$

(4.3)

for some $\lambda \in \mathbb{R}$. It is equivalent to the conditions that

$$\begin{cases}
\cos \theta_0 c_1(t_0) + \sin \theta_0 c_3(t_0) = 0 \\
\cos \theta_0 c_4(t_0) - \sin \theta_0 c_6(t_0) = 0.
\end{cases}$$

(4.4)

The above relation means that $(\cos \theta_0, \sin \theta_0)$ is a non-trivial solution of the following simultaneous linear equation:

$$\begin{cases}
c_1(t_0)x + c_3(t_0)y = 0 \\
c_4(t_0)x - c_6(t_0)y = 0.
\end{cases}$$

(4.5)

It follows that we have $c_1(t_0)c_6(t_0) + c_3(t_0)c_4(t_0) = 0$. If $t_0$ satisfies this condition, there are non-trivial solutions $(x, y)$, so that there exists $\theta_0$ such that $(\cos \theta_0, \sin \theta_0)$ is a non-trivial solution of (4.5). Therefore we have the following proposition.
Corollary 4.4. A point \((\theta_0, t_0)\) is a singular point of \(F_A(\theta, t)\) if and only if \(c_1(t_0)c_6(t_0) + c_3(t_0)c_4(t_0) = 0\) and \((\cos \theta_0, \sin \theta_0)\) is a nontrivial solution of (4.5).

We now investigate geometric properties of the function \(c_1(t)c_6(t) + c_3(t)c_4(t)\). We consider the vector defined by

\[
n(\theta, t) = (\cos \theta c_4(t) - \sin \theta c_6(t))a_0(t) + (\cos \theta c_1(t) + \sin \theta c_3(t))a_3(t).
\]

We can easily show that

\[
\frac{\partial F_A}{\partial \theta}(\theta, t) \cdot n(\theta, t) = \frac{\partial F_A}{\partial t}(\theta, t) \cdot n(\theta, t) = 0.
\]

Thus, \(n(\theta_0, t_0)\) is a normal vector of \(F_A(\theta, t)\) at \(\theta_0, t_0\). Therefore, we have the unit normal vector field

\[
e(\theta, t) = \lambda(\theta, t)n(\theta, t), \text{ where } \lambda(\theta, t) = \frac{1}{\sqrt{(\cos \theta c_4(t) - \sin \theta c_6(t))^2 + (\cos \theta c_1(t) + \sin \theta c_3(t))^2}}
\]

under the assumption that \((\theta, t)\) is not a singular point of \(F_A\). Moreover, we have

\[
e_\theta(\theta, t) = \lambda_\theta(\theta, t)n(\theta, t) + \lambda(\theta, t)\{(-\sin \theta c_4(t) - \cos \theta c_6(t))a_0(t) + (-\sin \theta c_1(t) + \cos \theta c_3(t))a_2(t)\}.
\]

It follows that

\[
\frac{\partial F_A}{\partial \theta}(\theta, t) \cdot e_\theta(\theta, t) = 0, \text{ and } \frac{\partial F_A}{\partial t}(\theta, t) \cdot e_\theta(\theta, t) = \lambda(\theta, t)(c_1(t)c_6(t) + c_3(t)c_4(t))
\]

so that the second fundamental matrix is given by

\[
h_{ij}(\theta, t) = \begin{pmatrix}
0 & \lambda(\theta, t)(c_1(t)c_6(t) + c_3(t)c_4(t)) \\
\lambda(\theta, t)(c_1(t)c_6(t) + c_3(t)c_4(t)) & *
\end{pmatrix}.
\]

We also have

\[
g(\theta, t) = \det(g_{ij}(\theta, t)) = \frac{1}{\lambda^2(\theta, t)}.
\]

Thus, we have the following proposition:

**Proposition 4.2.** Let \((\theta, t)\) be a regular point of \(F_A\). Then the extrinsic Gauss curvature is

\[
K_e(\theta, t) = \frac{-(c_1(t)c_6(t) + c_3(t)c_4(t))^2}{((\cos \theta c_4(t) - \sin \theta c_6(t))^2 + (\cos \theta c_1(t) + \sin \theta c_3(t))^2)^2}.
\]

**Corollary 4.3.** If \((\theta_0, t_0)\) is a singular point, then \(K_e(\theta, t_0) = 0\) for any regular point \((\theta, t_0)\). Moreover, if \(K_e(\theta_0, t_0) = 0\), then there exists \(\theta_1\) such that \((\theta_1, t_0)\) is a singular point of \(F_A\).

If \((c_1(t_0), c_3(t_0), c_4(t_0), c_6(t_0)) = (0, 0, 0, 0)\), then all points on the great circle \(F_A(\theta, t_0)\) are the singularities. We say that \(F_A\) is non-cyclic if \((c_1(t), c_3(t), c_4(t), c_6(t)) \neq (0, 0, 0, 0)\).

By the above results, the function \(c_1(t)c_6(t) + c_3(t)c_4(t)\) has a special meaning. We denote that \(c_n(t) = c_1(t)c_6(t) + c_3(t)c_4(t)\).

**Corollary 4.4.** Let \((\theta_0, t_0)\) be a regular point of \(F_A(\theta, t)\). Then \(F_A(\theta, t)\) is extrinsic flat at \((\theta_0, t_0)\) if and only if \(c_n(t_0) = 0\).
If \( c_\kappa(t_0) = 0 \), then there exists \( \theta_1 \) such that \((\theta_1, t_0)\) is a singular point of \( F_A(\theta, t) \). For classifications of singularities of general great circular surfaces, we have the following:

**Theorem 4.5.** Let \( F_A \) be a non-cyclic great circular surface. A point \((\theta_0, t_0)\) is \( A \)-equivalent to the cross cap if and only if \( c_\kappa(t_0) = 0 \) and \( \theta_0 \) satisfies (4.4), and \( c'_\kappa(t_0) \neq 0 \).

Two map germs \( f_i: (\mathbb{R}^2, 0) \to (\mathbb{R}^3, 0) \) \((i = 1, 2)\) are \( A \)-equivalent (or locally diffeomorphic) if there exist germs of \( C^\infty \) diffeomorphisms \( d_i: (\mathbb{R}^2, 0) \to (\mathbb{R}^2, 0) \) and \( d_1: (\mathbb{R}^3, 0) \to (\mathbb{R}^3, 0) \) such that \( d_1 \circ f_1 = f_2 \circ d_1 \) holds.

**Proof.** A point \((t_0, \theta_0)\) is a singular point of \( F_A \) if and only if \( c_\kappa(t_0) = 0 \) and \( \theta_0 \) satisfies the conditions (4.4). It has been known in [18, p.161 (b)] that \( F_A \) at \((t_0, \theta_0)\) is \( A \)-equivalent to the cross cap if and only if \((t_0, \theta_0)\) is a singular point and satisfies the condition that

\[
\det \left( F_A, \frac{\partial F_A}{\partial \theta}, \frac{\partial^2 F_A}{\partial \theta \partial t}, \frac{\partial^2 F_A}{\partial t^2} \right)(t_0, \theta_0) \neq 0.
\]

Under the assumption that \((c_1 c_6 + c_3 c_4)(t_0) = 0\) and the relation (4.4), we can calculate that

\[
\det \left( F_A, \frac{\partial F_A}{\partial \theta}, \frac{\partial^2 F_A}{\partial \theta \partial t}, \frac{\partial^2 F_A}{\partial t^2} \right)(t_0, \theta_0)
\]

\[
= \sin \theta_0 c_1(t_0) c'_4(t_0) - \sin \theta_1 c_1(t_0) c'_6(t_0) - \cos^2 \theta_0 c_3(t_0) c'_4(t_0)
+ \cos \theta_0 \sin \theta_0 c_3(t_0) c'_6(t_0) - \sin \theta_0 \cos \theta_0 c_4(t_0) c'_3(t_0) - \sin^2 \theta_0 c_4(t_0) c'_3(t_0)
- \cos^2 \theta_0 c_2(t_0) c'_3(t_0) - \cos \theta_0 \sin \theta_0 c_2(t_0) c'_3(t_0)
= -(c_2(t_0) c'_3(t_0) + c_1(t_0) c'_6(t_0) + c_6(t_0) c'_1(t_0) - c_4(t_0) c'_3(t_0)) = -(c_1 c_6 + c_3 c_4)'(t_0).
\]

This completes the proof. \( \square \)

This theorem shows that generic singularities of great circular surfaces are cross cap (cf., §8, Proposition 8.1). Remark that this theorem implies if \((\theta_0, t_0)\) is the cross cap, then \((\theta_0 + \pi, t_0)\) is also the cross cap. Since a great circular surface is a double covering of a ruled surface in \( \mathbb{RP}^3 \), generic classifications of singularities are the same as those of ruled surfaces (see, [5, 6]). However, we emphasize that we give an exact condition for the cross cap by using the invariant \( c_\kappa(t) \). Moreover, the above theorem shows that great circular surfaces have a different property with the circular surfaces in \( \mathbb{R}^3 \) (see [7]).

On the other hand, we consider a parameter transformation \( \Theta = \theta - \theta(t) \), \( T = t \) for any smooth function \( \theta(t) \). We define \( \overline{A} = (\overline{a}_0(T), \overline{a}_1(T), \overline{a}_2(T), \overline{a}_3(T)) \) by

\[
\overline{a}_0(T) = a_0(t), \quad \overline{a}_1(T) = \cos \theta(t) a_1(t) + \sin \theta(t) a_3(t)
\overline{a}_2(T) = a_2(t) \quad \text{and} \quad \overline{a}_3(T) = -\sin \theta(t) a_1(t) + \cos \theta(t) a_3(t).
\]

Then \( \overline{A}(T) \in SO(4) \) and \( F_{\overline{A}}(\theta(t)) = F_{\overline{A}}(\Theta, T) \). By straightforward calculations, we have

\[
\begin{align*}
\overline{c}_1(T) &= c_1(t) \cos \theta(t) + c_3(t) \sin \theta(t) \\
\overline{c}_2(T) &= c_2(t) \\
\overline{c}_3(T) &= -c_1(t) \sin \theta(t) + c_3(t) \cos \theta(t) \\
\overline{c}_4(T) &= c_4(t) \cos \theta(t) - c_6(t) \sin \theta(t) \\
\overline{c}_5(T) &= -\theta'(t) - c_5(t) \\
\overline{c}_6(T) &= c_4(t) \sin \theta(t) + c_6(t) \cos \theta(t).
\end{align*}
\]

We call the above parameter transformation an adapted parameter transformation of \( F_A \).
5 Extrinsic flat great circular surfaces

In this section we consider extrinsic flat great circular surfaces. By Proposition 4.2, \( F_A(\theta, t) \) is extrinsic flat if and only if \( c_6(t) = 0 \) for any \( t \). Suppose that \( F_A(\theta, t) \) is non-cyclic and extrinsic flat. Since \( e(\theta, t) \) is independent of \( \theta \), we have the following new orthonormal frame:

\[
\begin{aligned}
\vec{a}_0(t) &= e(\theta, t) = \lambda(\theta, t)((\cos \theta c_4(t) - \sin \theta c_6(t))a_0(t) + (\cos \theta c_1(t) + \sin \theta c_3(t))a_2(t)), \\
\vec{a}_1(t) &= a_1(t), \\
\vec{a}_2(t) &= \lambda(\theta, t)((\cos \theta c_4(t) - \sin \theta c_6(t))a_2(t) - (\cos \theta c_1(t) + \sin \theta c_3(t))a_0(t)), \\
\vec{a}_3(t) &= a_3(t).
\end{aligned}
\]

(5.1)

It follows that we have

\[
\begin{aligned}
\vec{c}_1(t) &= -\vec{a}_0(t) \cdot \vec{a}_1'(t) = -\lambda(\theta, t) \sin \theta (c_1(t)c_6(t) + c_3(t)c_4(t)) = 0, \\
\vec{c}_3(t) &= -\vec{a}_0(t) \cdot \vec{a}_3'(t) = -\lambda(\theta, t) \cos \theta (c_1(t)c_6(t) + c_3(t)c_4(t)) = 0, \\
\vec{c}_4(t) &= \vec{a}_1'(t) \cdot \vec{a}_2(t) = \lambda(\theta, t)\{\cos \theta (c_1^2(\theta) + c_3^2(\theta)) + \sin \theta (c_1(\theta)c_3(\theta) - c_3(\theta)c_1(\theta))\}.
\end{aligned}
\]

Moreover, we have \( F_A(\theta, t) = \tilde{F}_A(\theta, t) \) and \( \vec{a}_0(t) \) is the unit normal vector of \( F_A(\theta, t) \) at regular point \((\theta, t)\), where \( \tilde{A}(t) = (\vec{a}_0(t), \vec{a}_1(t), \vec{a}_2(t), \vec{a}_3(t)) \in \text{SO}(4) \).

On the other hand, we can easily calculate that

\[
\begin{aligned}
\frac{\partial F_A}{\partial \theta}(\theta, t) \cdot \vec{a}_0(t) &= 0 \quad \text{and} \quad \frac{\partial F_A}{\partial t}(\theta, t) \cdot \vec{a}_0(t) = -\cos \theta c_1(t) - \sin \theta c_3(t).
\end{aligned}
\]

Therefore \( \vec{a}_0(t) \) is a unit normal of \( F_A \) at any \((\theta, t)\) if and only if \( c_1(t) \equiv c_3(t) \equiv 0 \). By the same arguments, \( \vec{a}_2(t) \) is a unit normal at any point \((\theta, t)\) if and only if \( c_4(t) \equiv c_6(t) \equiv 0 \).

Suppose that \( \vec{a}_2(t) \) is a unit normal of \( F_A \) at any point \((\theta, t)\). If we have another orthonormal frame \( \tilde{A}(t) = (\vec{a}_0(t), \vec{a}_1(t), \vec{a}_2(t), \vec{a}_3(t)) \) defined by \( \vec{a}_0(t) = -\vec{a}_2(t), \vec{a}_1(t) = -\vec{a}_1(t), \vec{a}_2(t) = \vec{a}_0(t), \vec{a}_3(t) = -\vec{a}_3(t) \), then we have \( F_A(\theta, t) = \tilde{F}_A(\theta, t) \) and

\[
\begin{aligned}
\vec{c}_1(t) &= c_4(t), \quad \vec{c}_2(t) = c_2(t), \quad \vec{c}_3(t) = -c_6(t), \quad \vec{c}_4(t) = -c_1(t), \quad \vec{c}_5(t) = c_5(t), \quad \vec{c}_6(t) = c_3(t).
\end{aligned}
\]

It follows that \( c_4(t) \equiv c_6(t) \equiv 0 \) if and only if \( \vec{c}_1(t) \equiv \vec{c}_3(t) \equiv 0 \).

Throughout the remainder in this paper, we say that a great circular surface \( F_A(\theta, t) \) is extrinsic flat (briefly, \( E \)-flat) if \( c_1(t) = c_6(t) = 0 \).

Suppose that \( F_A \) is an \( E \)-flat great circular surface with \( (c_4, c_6)(t) \neq (0, 0) \). Let \( \theta(t) \) be a smooth function with

\[
\begin{aligned}
c_4(t) \cos \theta(t) - c_6(t) \sin \theta(t) = 0.
\end{aligned}
\]

(5.2)

By the adopted parameter transformation \( \Theta = \theta - \theta(t), \ T = t \), we have \( \tilde{\tau}_1(T) \equiv \tilde{\tau}_3(T) \equiv \tilde{\tau}_4(T) \equiv 0 \). Therefore, we assume that \( c_1(t) \equiv c_3(t) \equiv c_4(t) \equiv 0 \) for an \( E \)-flat great circular surface.

Let \( \vec{\sigma}(t) = \cos \theta(t) \vec{a}_1(t) + \sin \theta(t) \vec{a}_3(t) \) be a curve on the great circular surface \( F_A \) defined by the condition (5.2). If \( (c_4(t), c_6(t)) \neq (0, 0) \), the function \( \theta(t) \) is well-defined. The condition \( c_1(t) \equiv c_4(t) \equiv 0 \) is equivalent to the condition that all generating great circles are always tangent to the curve \( \vec{\sigma}(t) \) at regular points of the curve.

**Theorem 5.1.** Suppose that \( c_1 \equiv c_3 \equiv 0 \) and \( (c_4, c_6)(t_0) \neq (0, 0) \). Then \( p_0 = (\theta_0, t_0) \in S(F_A) \) if and only if \( \theta_0 = \theta(t_0) \), where \( \theta(t) \) is the function defined by (5.2). The following assertions hold:
(a) $F_A$ at $p_0$ is $\mathcal{A}$-equivalent to the cuspidal edge if and only if $c_2(t_0)(c_5(t_0) + \theta'(t_0)) \neq 0$.

(b) $F_A$ at $p_0$ is $\mathcal{A}$-equivalent to the swallowtail if and only if $c_5(t_0) + \theta'(t_0) = 0$ and $c_2(t_0)(c_5(t_0) + \theta''(t_0)) \neq 0$.

(c) $F_A$ at $p_0$ is $\mathcal{A}$-equivalent to the cuspidal cross cap if and only if $c_2(t_0) = 0$ and $c_2(t_0)(c_5(t_0) + \theta'(t_0)) \neq 0$.

By the previous arguments, if $c_1(t) = c_3(t) = 0$ and $(c_4(t), c_6(t)) \neq (0, 0)$, then we have $c_1(t) = c_3(t) = 0$ and $c_6(t) \neq 0$ by choosing the different orthonormal frame $A(t)$ with $F_A(\theta, t) = F_A(\theta, t)$. Therefore, we consider the case when $c_1 \equiv c_3 \equiv c_4 \equiv 0$ without the assumption $c_6(t) \neq 0$.

**Theorem 5.2.** Suppose that $c_1 \equiv c_3 \equiv c_4 \equiv 0$ and $p_0 = (\theta_0, t_0) \in S(F_A)$.

1. If $c_6(t_0) \neq 0$. Then $\theta_0 = 0$ or $\pi$ and the following assertions hold.

   (d) $F_A$ at $p_0$ is $\mathcal{A}$-equivalent to the cuspidal edge if and only if $c_2(t_0)c_5(t_0) \neq 0$.

   (e) $F_A$ at $p_0$ is $\mathcal{A}$-equivalent to the swallowtail if and only if $c_2(t_0) = 0$ and $c_2(t_0)c_5'(t_0) \neq 0$.

   (f) $F_A$ at $p_0$ is $\mathcal{A}$-equivalent to the cuspidal cross cap if and only if $c_2(t_0) = 0$ and $c_2(t_0)c_5'(t_0) \neq 0$.

2. If $c_6(t_0) = 0$, then $\theta_0 = \theta(t_0)$ and the following assertions hold.

   (g) $F_A$ at $p_0$ is $\mathcal{A}$-equivalent to the cuspidal edge if and only if $\theta_0 \neq 0, \pi$ and $c_2(t_0)c_5(t_0)c_5'(t_0) \neq 0$.

   (h) $F_A$ at $p_0$ is $\mathcal{A}$-equivalent to the cuspidal beaks if and only if $\theta_0 = 0$ or $\theta_0 = \pi$ and $c_2(t_0)c_5(t_0)c_5'(t_0) \neq 0$.

   (i) $F_A$ at $p_0$ is never $\mathcal{A}$-equivalent to the swallowtail, cuspidal lips, and cuspidal cross cap.

We say that $F_A$ is a tangent extrinsic flat great circular surface (briefly, a T-E-flat great circular surface) if $c_1(t) = c_3(t) = c_4(t) = 0$.

### 6 Proofs of Theorems 5.1 and 5.2

In this section, we prove Theorems 5.1 and 5.2 by using criteria for singularities of fronts. For the detailed descriptions of fronts, see [1]. Let $(M, g)$ be a 3-dimensional Riemannian manifold. The unit cotangent bundle $T^*_1 M$ is canonically identified with the unit tangent bundle $T_1 M$ and has the canonical contact structure. Let $U$ be an open domain of $\mathbb{R}^2$. A map $f : U \rightarrow M$ is a *frontal* if there exists a unit vector field $\nu : U \rightarrow T_1 M$ along $f$ such that $g(df(X), \nu)(p) = 0$.
for any $X \in T_pU$. This condition is equivalent to that $L_f = (f, \nu) : U \to T_1M$ is isotropic with respect to the canonical contact structure of $T_1M$. A frontal is a front if $L_f$ is an immersion, namely the image of $f$ is a wavefront set of $L_f$. Let $(u, v)$ be a local coordinate system of $U$ and $f$ a frontal. The signed area density $\lambda$ of $f$ is defined by

$$\lambda(u, v) = \Omega(f_u, f_v, \nu),$$

where $\Omega$ is a non-zero 3-form of $M$. Then we have $\lambda^{-1}(0) = S(f)$. A singular point $p$ is non-degenerate if $d\lambda(p) \neq 0$. Let $p$ be a non-degenerate singular point then there exists a regular curve $\gamma : (-\varepsilon, \varepsilon) \to U$ such that $\gamma(0) = p$ and $\text{image}(\gamma) = S(f)$ near $p$. If $\text{rank}(df_p) = 1$, we have a non-zero vector field $\eta$ near $p$ satisfying $\langle \eta_q, \nu \rangle = \text{ker} df_q$ at $q \in S(f)$. We call $\eta$ the null vector field. If $p$ is non-degenerate, $\eta$ can be regarded as a vector field along $\gamma$. In this case, we write $\eta|_{\gamma(t)} = \eta(t)$. Under these settings, the following theorem holds:

**Theorem 6.1.** Let $f : U \to M$ be a frontal and $p \in U$ a singular point of $f$.

(A) Let $p$ be a non-degenerate singular point, and $p = \gamma(0)$. If $f$ is a front at $p$, then $f$ at $p$ is $\mathcal{A}$-equivalent to the cuspidal edge if and only if $\mu_{sw}(0) \neq 0$ holds. Here,

$$\mu_{sw}(t) = \det(\gamma', \eta)(t).$$

(B) Let $p$ be a non-degenerate singular point, and $p = \gamma(0)$. If $f$ is a front at $p$, then $f$ at $p$ is $\mathcal{A}$-equivalent to the swallowtail if and only if $\mu_{sw}(0) = 0$ and $\mu'_{sw}(0) \neq 0$ hold.

(C) If $f$ is a front at $p$. Then $f$ at $p$ is $\mathcal{A}$-equivalent to the cuspidal lips (respectively, the cuspidal lips) if and only if $d\lambda(p) = 0$, $\det \text{Hess} \lambda(p) < 0$ and $\eta \eta \lambda(p) \neq 0$ hold. (respectively, $d\lambda(p) = 0$ and $\det \text{Hess} \lambda(p) > 0$ hold.)

(D) If $p$ is non-degenerate and $p = \gamma(0)$, then $f$ at $p$ is $\mathcal{A}$-equivalent to the cuspidal cross cap if and only if $\mu_{sw}(0) \neq 0$, $\mu_{ccr}(0) = 0$ and $\mu'_{ccr}(0) \neq 0$. Here,

$$\mu_{ccr}(t) = \Omega((f \circ \gamma)'(t), \nu \circ \gamma(t), d\nu(\eta(t))).$$

For the detailed descriptions and proofs of (A) and (B), see [11]. For the proof of (C), see [10]. For the proof of (D), see [3].

**Proof of Theorem 5.1.** We apply Theorem 6.1 considering $(M, g) = (S^3, \cdot)$ and $\Omega = \det(p, \nu_1, \nu_2, \nu_3)$ for $(\nu_1, \nu_2, \nu_3) \in (T_pS^3)^3$. By the assumption $c_1 \equiv c_3 \equiv 0$, we can take $\nu = a_0$ as the normal vector field of $F_A$. Since we have

$$(F_A)_\theta = -\sin \theta a_1 + \cos \theta a_2, \quad (F_A)_t = -\sin \theta c_5 a_1 + (\cos \theta c_4 - \sin \theta c_6) a_2 + \cos \theta c_5 a_3, \quad (6.1)$$

and $(c_4, c_6) \neq (0, 0)$, we see that $S(F_A) = \{(\theta(t), t)\}$, where $\theta(t)$ is a function satisfying $\cos \theta(t) c_4(t) - \sin \theta(t) c_6(t) = 0$. Let we set $s(t) = (\theta(t), t)$. Then $s(t)$ is a parameterization of $S(F_A)$. We have $\lambda(\theta, t) = \det(F_A, (F_A)_\theta, (F_A)_t, a_0) = \cos \theta c_4 - \sin \theta c_6$. Then we see that $\lambda = \sin \theta c_4 - \cos \theta c_6 \neq 0$ on $s(t)$. So $p_0 \in S(F_A)$ is non-degenerate.

By (6.1) again, we may take $\eta(t) = -c_5(t)(\partial / \partial \theta) + (\partial / \partial t)$ as the null vector field on $s(t)$. Since $\eta \nu = c_2 a_2$, $F_A$ to be a front near $s(t_0)$ if and only if $c_2(t_0) \neq 0$. Since $\eta(t) = -c_5(t)(\partial / \partial \theta) + (\partial / \partial t)$ and $s'(t) = \theta'(\partial / \partial \theta) + (\partial / \partial t)$, we have $\mu_{sw}(t) = \theta' + c_5$. Thus we have assertions (a) and (b) using (A) and (B) of Theorem 6.1.
On the other hand, assume that a point $p_0$ satisfies $\mu_{sw} = \theta' + c_5 \neq 0$. Then since $\mu_{ccr}(t) = \det(F_A(s(t)), (d/dt)F_A(s(t)), a_0, c_2a_2) = c_2(\theta' + c_5)$, we see that $\mu_{ccr}(t_0) = 0$ and $\mu'_{ccr}(t_0) \neq 0$ if and only if $c_2(t_0) = 0$ and $c'_2(t_0) \neq 0$. By (D) of Theorem 6.1, we have the assertion (c). \hfill $\square$

**Proof of Theorem 5.2.** Putting $c_4 = 0$ in Theorem 5.1, one can easily show (d), (e) and (f) of Theorem 5.2. We shall prove (g), (h) and (i). Assume that $c_1 \equiv c_3 \equiv c_4 \equiv 0, c_6(t_0) = 0$ hold and take $p_0 = (\theta_0, t_0)$. Put $\delta(\theta) = (\theta, t_0)$. Then $\delta(\theta)$ is a parameterization of $S(F_A)$ near $p_0$. Like as the proof of Theorem 5.1, the null vector field $\eta$ is given by $\eta(\theta) = -c_5(t)(\partial/\partial \theta) + (\partial/\partial t)$ on $\delta(\theta)$. Since we see $\mu_{ccr}(\theta) = c_2(t_0)$, if $c_2(t_0) \neq 0$, then $F_A$ at $p_0$ to be a front, but if $c_2(t_0) = 0$, then $(d/dt)\mu_{ccr}(\theta) = 0$ hold. Thus $p_0$ never $A$-equivalent to the cuspidal cross cap. Now we assume $c_1 \equiv c_3 \equiv c_4 \equiv 0, c_6(t_0) = 0$ and $c_2(t_0) \neq 0$. Then we have $\lambda = \sin \theta c_6$, the singular point $p_0$ is non-degenerate if and only if $(d/dt)\lambda(p_0) = \sin \theta c'_6(t_0) \neq 0$. On the other hand, $\mu_{sw}(\theta) = c_5(t_0)$ holds. Summarizing the above arguments, we have (g), and that $F_A$ is never $A$-equivalent to the swallowtail. Assume $\sin \theta c'_6(t_0) = 0$ in addition. Then

$$\det \text{Hess } \lambda(p_0) = \det \begin{pmatrix} -\sin \theta c_6 & \cos \theta c'_6 \\ \cos \theta c'_6 & \sin \theta c_6 \end{pmatrix}(p_0) = -\cos^2 \theta(c'_6(t_0))^2 \leq 0$$

holds. Thus $F_A$ at $p_0$ is never $A$-equivalent to the cuspidal lip and we have (i). We assume that $c'_6(t_0) \neq 0$. Then $\sin \theta_0 = 0$ by the assumption $\sin \theta c'_6(t_0) = 0$. In this case, $\eta \lambda(p_0) = -2c_5(t_0)c'_6(t_0) \cos \theta_0$ holds. By (C) of Theorem 6.1, we have the assertion (h). \hfill $\square$

7 Duality of singularities

In this section, we consider the $\Delta$-dual surface to the locus of singular values of $F_A$ under the assumption that $c_1 \equiv c_4 \equiv 0$ and $c_6 \neq 0$. By the equation (4.4), the singular point of $F_A$ is $(t, 0)$ and $(t, \pi)$ so that the singular value is $a_1(t)$. We consider a great circular surface defined by

$$F_A^\sharp(\theta, t) = \cos \theta a_0(t) + \sin \theta a_2(t).$$

Then $F_A^\sharp(\theta, t) \cdot a_1(t) = 0$, so that we have a mapping $\mathcal{L} : J \times I \rightarrow \Delta$ defined by $\mathcal{L}(\theta, t) = (F_A^\sharp(\theta, t), a_1(t))$. It follows that $\mathcal{L}^* \theta_2 = F_A^\sharp(\theta, t) \cdot a'_1(t) = -\cos \theta c_1(t) + \sin \theta c_2(t) = 0$. Therefore $\mathcal{L}$ is an isotropic mapping. Thus, $F_A^\sharp(\theta, t)$ and $a_1(t)$ are $\Delta$-dual to each other. Let $\psi(t)$ be a function satisfying the condition that $\cos \psi(t)c_3(t) + \sin \psi(t)c_4(t) = 0$. Then we have that $S(F_A^\sharp) = \{(\psi(t), t)\}$. If we consider the orthonormal frame $\hat{A}(t) = (a_1(t), a_0(t), a_3(t), a_2(t)) \in SO(4)$, $F_A^\sharp$ is equal to $F_A$ and we have

$$\bar{c}_1 = -c_1, \quad \bar{c}_2 = c_3, \quad \bar{c}_3 = c_4, \quad \bar{c}_4 = c_3, \quad \bar{c}_5 = c_2, \quad \bar{c}_6 = -c_6,$$

where $\bar{C}$ is the fundamental invariants of $\hat{A}$. Thus $F_A^\sharp$ is an E-flat great circular surface if and only if $c_1 \equiv c_4 \equiv 0$ and $F_A^\sharp$ is a T-E-flat great circular surface if and only if $c_1 \equiv c_3 \equiv c_4 \equiv 0$. In this case $F_A$ is also a T-E-flat great circular surface. If we assume $c_1 \equiv c_3 \equiv c_4 \equiv 0$, then $F_A^\sharp(S(F_A^\sharp)) = \{a_0(t) \mid t \in J\}$ and we have the following diagram:

\[
\begin{array}{ccccc}
F_A & \xrightarrow{\text{taking singular value}} & a_1 \\
\Delta\text{-dual} & & \Delta\text{-dual} \\
a_0 & \xleftarrow{\text{taking singular value}} & F_A^\sharp
\end{array}
\]
Under the assumption $c_1 \equiv c_3 \equiv c_4 \equiv 0$, by Theorem 5.2 and (7.1), we have the following corollary.

**Corollary 7.1.** Suppose that $c_1 \equiv c_3 \equiv c_4 \equiv 0$ and $p_0 = (\theta_0, t_0) \in S(F_A^4)$. 

1. If $c_6(t_0) \neq 0$, then $\theta_0 = 0$ or $\pi$ and the following assertions hold:
   - $F_A^4$ at $p_0$ is $A$-equivalent to the cuspidal edge if and only if $c_2(t_0)c_5(t_0) \neq 0$.
   - $F_A^4$ at $p_0$ is $A$-equivalent to the swallowtail if and only if $c_2(t_0) = 0$ and $c_5(t_0)c'_2(t_0) \neq 0$.
   - $F_A^4$ at $p_0$ is $A$-equivalent to the cuspidal cross cap if and only if $c_5(t_0) = 0$ and $c_2(t_0)c'_5(t_0) \neq 0$.

2. If $c_6(t_0) = 0$, then the following assertions hold:
   - $F_A^4$ at $p_0$ is $A$-equivalent to the cuspidal edge if and only if $\theta_0 \neq 0, \pi$ and $c_2(t_0)c_5(t_0)c'_4(t_0) \neq 0$.
   - $F_A^4$ at $p_0$ is $A$-equivalent to the cuspidal beaks if and only if $\theta_0 = 0$ or $\theta_0 = \pi$ and $c_2(t_0)c_5(t_0)c'_5(t_0) \neq 0$.
   - $F_A^4$ at $p_0$ is not $A$-equivalent to the swallowtail, cuspidal lips or the cuspidal cross cap.

Comparing with Theorem 5.2, we can observe a duality of singularities between the swallowtail and the cuspidal cross cap as we pointed out in [9] (cf., [17, 3]). We can also observe a self duality of cuspidal beaks. We summarize this situation on the Table 1. In the table, we explain the conditions for the singularities at the point $(\theta_0, t_0) \in J \times I$. We observe the complete correspondence between the singularities for $F_A$ and $F_A^4$ by exchanging the invariants $c_2$ and $c_5$.

<table>
<thead>
<tr>
<th></th>
<th>CE $c_6 \neq 0$</th>
<th>SW $c_6 \neq 0$</th>
<th>CCR $c_6 \neq 0$</th>
<th>CE $c_6 = 0$</th>
<th>CBK $c_6 = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_A(\theta_0, t_0)$</td>
<td>$c_2c_5 \neq 0$, $\theta_0 = 0, \pi$</td>
<td>$c_5 = 0$, $\theta_0 = 0, \pi$</td>
<td>$c_2 = 0$, $c_2c_5 \neq 0$, $\theta_0 = 0, \pi$</td>
<td>$c_2c_5c_6' \neq 0$, $\theta_0 \neq 0, \pi$</td>
<td>$c_2c_5c_6' \neq 0$, $\theta_0 = 0, \pi$</td>
</tr>
<tr>
<td>$F_A^4(\theta_0, t_0)$</td>
<td>$c_2c_5 \neq 0$, $\theta_0 = 0, \pi$</td>
<td>$c_2 = 0$, $c_2c_5 \neq 0$, $\theta_0 = 0, \pi$</td>
<td>$c_5 = 0$, $c_2c_5 \neq 0$, $\theta_0 = 0, \pi$</td>
<td>$c_2c_5c_6' \neq 0$, $\theta_0 \neq 0, \pi$</td>
<td>$c_2c_5c_6' \neq 0$, $\theta_0 = 0, \pi$</td>
</tr>
</tbody>
</table>

Table 1: Dualities of condition for singularity.
8 Generic properties

In this section we stick to the study of the generic singularities of great circular surfaces. In §1 and §4, we have shown that the space of great circular surfaces are regarded as $C^\infty(I, \mathfrak{so}(4))$ and E-flat surfaces are regarded as $C^\infty(I, \mathfrak{e}(4))$. In §5, we have defined the notion of T-E-flat great circular surfaces and regarded $C^\infty(I, \mathfrak{e}_\infty(4))$ as the space of T-E-flat great circular surfaces. The topology of these spaces are given by the Whitney $C^\infty$-topology. In this section, we prove the following theorem.

**Theorem 8.1.** (1) There exists a residual subset $O_1 \subset C^\infty(I, \mathfrak{so}(4))$ such that for any $C \in O_1$, $F_A$ is non-cyclic at any point and singularities of $F_A$ are only cross cap.

(2) There exists a residual subset $O_2 \subset C^\infty(I, \mathfrak{e}(4))$ such that for any $C \in O_2$, singularities of $F_A$ are only cuspidal edge, swallowtail or cuspidal cross cap.

(3) There exists a residual subset $O_3 \subset C^\infty(I, \mathfrak{e}_\infty(4))$ such that for any $C \in O_3$, singularities of $F_A$ are only cuspidal edge, swallowtail, cuspidal beaks or cuspidal cross cap.

Here, $A$ is an orthonormal frame obtained from the data $C$ by the equation (4.1).

**Proof.** (1) We consider the 1-jet space

$$J^1(I, \mathfrak{so}(4)) \cong I \times \mathbb{R}^6 \times \mathbb{R}^6 = \{(t, c, d) \mid t \in I, c, d \in \mathbb{R}^6\},$$

where $c = (c_1, \ldots, c_6), d = (d_1, \ldots, d_6)$. Define

$$S_1 = \{c_1 = c_3 = 0\}, \quad S_2 = \{c_4 = c_6 = 0\}, \quad S_3 = \{(c_3c_4 + c_1c_6)(t) = 0\}, \quad S_4 = \{c_3d_4 + d_3c_4 + c_1d_6 + d_1c_6 = 0\}.$$

Then we see that $S_1$, $S_2$ are codimension two submanifolds and $S_3$ and $S_4$ are algebraic subsets of codimension one. Moreover, $S_3 \cap S_4$ is an algebraic subset of codimension two. Therefore, we have stratifications of $S_3$ and $S_3 \cap S_4$. We say that $j^1C$ is transverse to $S_3$ (or, $S_3 \cap S_4$) if $j^1C$ is transverse to all strata of these stratifications. By the Thom jet transversality theorem, $O_1 = \{C \in C^\infty(I, \mathfrak{so}(4)) \mid j^1C$ is transverse to $S_1, \ S_2, \ S_3$ and $S_3 \cap S_4\}$ is an open and dense in $C^\infty(I, \mathfrak{so}(4))$. On the other hand, one can easily see that Theorem 4.5 implies that $O_1$ satisfies the required condition.

(2) Suppose that $(c_4(t), c_6(t)) \neq (0, 0)$. Then we have a function $\theta(t)$ defined by $c_4(t) \cos \theta(t) = c_6(t) \sin \theta(t) = 0$. It follows that

$$\theta'(t) = \frac{c'_4(t) \cos \theta(t) - c'_6(t) \sin \theta(t)}{c_4(t) \sin \theta(t) + c_6(t) \cos \theta(t)}.$$

Therefore, $c_5(t) \theta'(t) = 0$ if and only if

$$c'_4(t)c_6(t) + c_5(t)c'_6(t) - c'_6(t)c_4(t) - c_5(t)c'_4(t) = 0.$$

Moreover, we can show that $c_5'(t) \theta''(t) = 0$ if and only if

$$-2(c'_4(t)c_4(t) + c'_6(t)c_6(t))c_4(t)c_5(t) - c'_6(t)c_4(t) = 0.$$

We now consider the 2-jet space

$$J^2(I, \mathfrak{e}(4)) \cong I \times \mathbb{R}^4 \times \mathbb{R}^4 \times \mathbb{R}^4 = \{(t, c, d) \mid t \in I, c, d \in \mathbb{R}^4\},$$

19
where $c = (c_2, c_4, c_5, c_6)$, $d = (d_2, d_4, d_5, d_6)$, $e = (e_2, e_4, e_5, e_6)$. Define

$S_1 = \{c_4 = c_6 = 0\}$, $S_2 = \{c_2 = 0\}$, $S_3 = \{d_4 c_6 + c_5 c_6^2 - d_6 c_4 - c_5 c_4^2 = 0\}$, $S_4 = \{d_2 = 0\}$, $S_5 = \{d_5 (c_4^2 + c_6^2) + (e_4 c_6 - e_6 c_4) (e_4^2 + c_6^2) - 2(d_4 c_4 + d_6 c_6) (d_4 c_6 - d_6 c_4) = 0\}$.

By the similar reason to the case (1), we have an open dense subset

$\mathcal{O}_2 = \{C \in C^\infty(I, \mathbf{c}_f(4)) \mid j^1 C \text{ is transverse to } S_1, S_2, S_3, S_2 \cap (S_3 \cup S_4) \text{ and } S_3 \cap (S_4 \cup S_5)\}$.

By Theorem 5.1, $\mathcal{O}_2$ satisfies the required condition.

(3) In this case, we consider the 1-jet space

$$J^1(I, \mathbf{c}_f(4)) \cong I \times \mathbb{R}^3 \times \mathbb{R}^3 = \{(t, c, d) \mid t \in I, c, d \in \mathbb{R}^3\},$$

where $c = (c_2, c_5, c_6)$, $d = (d_2, d_5, d_6)$.

We also define $S_0 = \{c_6 = 0\}$, $S_1 = \{c_2 = 0\}$, $S_2 = \{c_5 = 0\}$, $S_3 = \{d_2 = 0\}$, $S_4 = \{d_5 = 0\}$ and $S_5 = \{d_6 = 0\}$.

We have the following open dense subset of $C^\infty(I, \mathbf{c}_f(4))$:

$$\mathcal{O}_3 = \{C \in C^\infty(I, \mathbf{c}_f(4)) \mid j^1 C \text{ is transverse to } S_0, S_0 \cap S_2, S_0 \cap S_3, S_2 \cap (S_1 \cup S_4), S_1 \cap (S_2 \cup S_3) \text{ and } S_0 \cap (S_1 \cup S_2 \cup S_5)\}.$$

By Theorem 5.2, $\mathcal{O}_3$ satisfies the required condition.

\[\square\]

9 Great circular surfaces associated to the Frenet frame

In §2 we defined the Frenet frame for a unit speed curve in $S^3$. We have three kinds of great circular surfaces associated to the Frenet frame.

Let $\gamma : I \rightarrow S^3$ be a unit speed curve with $\kappa_g(s) \neq 0$. We consider the Frenet frame $\{\gamma(s), t(s), n(s), e(s)\}$ which is defined in §2. We define canonical great circular surfaces associated to the Frenet frame as follows:

(1) $F_T(\theta, s) = \cos \theta \gamma(s) + \sin \theta t(s)$: the tangent great circular surface,

(2) $F_N(\theta, s) = \cos \theta \gamma(s) + \sin \theta n(s)$: the principal normal great circular surface,

(3) $F_E(\theta, s) = \cos \theta \gamma(s) + \sin \theta e(s)$: the binormal great circular surface.

(1) Tangent great circular surfaces. In this case, we consider the orthonormal frame $T = \{e(s), \gamma(s), n(s), t(s)\} \in SO(4)$. By the Frenet-Serret type formulae, we have

$$T'(s) = \begin{pmatrix}
0 & 0 & -\tau_g(s) & 0 \\
0 & 0 & 0 & 1 \\
\tau_g(s) & 0 & 0 & -\kappa_g(s) \\
0 & -1 & \kappa_g(s) & 0 \\
\end{pmatrix} T(s).$$

Therefore, we have $c_1 = 0, c_2 = -\tau_g, c_3 = 0, c_4 = 0, c_5 = 1, c_6 = -\kappa_g$. By Theorem 5.2, we have the following proposition:
Proposition 9.1. The singular point of the tangent great circular surface $F_T(\theta, s)$ is $\theta = 0, \pi$. Both of the germs of tangent great circular surface $F_T$ at $(0, s_0), (\pi, s_0)$ are $\mathcal{A}$-equivalent to the following germs:

- The cuspidal edge if $\tau_g(s_0) \neq 0$
- The cuspidal cross cap if $\tau_g(s_0) = 0, \tau'_g(s_0) \neq 0$.
- The swallowtail does not appear.

We remark that this proposition corresponds to the result of Cleave[2].

(2) Principal normal great circular surfaces. In this case, we consider the orthonormal frame $N = (t(s), \gamma(s), e(s), n(s)) \in SO(4)$. By the Frenet-Serret type formulae, we have

$$N'(s) = \begin{pmatrix}
0 & -1 & 0 & \kappa_g(s) \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & -\tau_g(s) \\
-k_g(s) & 0 & \tau_g(s) & 0
\end{pmatrix} N(s)$$

Therefore, we have $c_1 = -1, c_2 = 0, c_3 = \kappa_g, c_4 = 0, c_5 = 0, c_6 = -\tau_g$. By Theorem 4.5, we have the following proposition:

Proposition 9.2. The singular point $(\theta_0, s_0)$ of the principal normal great circular surface $F_N(\theta, s)$ is given by $\tan \theta_0 = -1/\kappa_g(s_0)$ and $\tau_g(s_0) = 0$. The germ of principal normal great circular surface $F_N$ at $(\theta_0, s_0)$ is $\mathcal{A}$-equivalent to the cross cap if $\tau_g(s_0) = 0, \tau'_g(s_0) \neq 0$.

We remark that this proposition corresponds to the result [6, Theorem 5.3].

(3) Binormal great circular surfaces. In this case, we consider the orthonormal frame $E = (n(s), \gamma(s), t(s), e(s)) \in SO(4)$. By the Frenet-Serret type formulae, we have

$$E'(s) = \begin{pmatrix}
0 & 0 & -\kappa_g(s) & \tau_g(s) \\
0 & 0 & -1 & 0 \\
\kappa_g(s) & -1 & 0 & 0 \\
-\tau_g(s) & 0 & 0 & 0
\end{pmatrix} E(s)$$

Therefore, we have $c_1 = 0, c_2 = -\kappa_g, c_3 = \tau_g, c_4 = 1, c_5 = 0, c_6 = 0$. By Theorem 4.5, we have the following proposition:

Proposition 9.3. The singular point $(\theta_0, s_0)$ of the binormal great circular surface $F_E(\theta, s)$ is given by $\theta_0 = \pi/2, 3\pi/2$ and $\tau_g(s_0) = 0$. The germ of binormal great circular surface $F_E$ at $(\theta_0, s_0)$ is $\mathcal{A}$-equivalent to the cross cap if $\theta_0 = \pi/2, 3\pi/2$ and $\tau_g(s_0) = 0, \tau'_g(s_0) \neq 0$.

We remark that binormal ruled surfaces in $\mathbb{R}^3$ are always non-singular, so that we have a completely different situation for binormal great circular surfaces in $S^3$.

References


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