ANALYTICITY ON TRANSLATES OF A JORDAN CURVE

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Abstract. Let $\Omega$ be a domain in $\mathbb{C}$ which is symmetric with respect to the real axis and whose boundary is a real analytic simple closed curve. Translate $\Omega$ vertically to get $K = \{ \Omega + it, \: -r \leq t \leq r \}$ where $r > 0$ is such that $(\Omega - ir) \cap (\Omega + ir) = \emptyset$. We prove that if $f$ is a continuous function on $K$ such that for each $t$, $-r \leq t \leq r$, the function $f(\Omega + it)$ has a continuous extension to $\Omega + it$ which is holomorphic on $\Omega + it$, then $f$ is holomorphic on $\text{Int}K$.

1. Introduction

Write $\Delta(a, r) = \{ \zeta \in \mathbb{C}: \: |\zeta - a| < r \}$ and let $\Delta = \Delta(0, 1)$. Translate $b\Delta$ vertically to get the strip $S = b\Delta + i\mathbb{R} = \{ \zeta \in \mathbb{C}: \: -1 \leq \Re \zeta \leq 1 \}$. Let $f$ be a continuous function on $S$ such that for each $t \in \mathbb{R}$ the function $f((b\Delta + it)$ has a continuous extension to $\Sigma + it$ which is holomorphic on $\Delta + it$. Must $f$ be holomorphic on $\text{Int}S$ [5]?

A positive answer was obtained for real analytic functions by M. Agranovsky and the author [2] and independently by L. Ehrenpreis [3] and for general continuous functions by A. Tumanov [9].

To answer the question above one passes in both [2] and [9] to an associated problem in $\mathbb{C}^2$. In [2] the authors use semi-quadrics

$$\Lambda_{a, \rho} = \{(z, w): \: (z - a) (w - \overline{a}) = \rho^2, \: 0 < |z - a| < \rho \}$$

which are attached to $\Sigma = \{(z, \overline{z}): \: z \in \mathbb{C} \}$ along the circles $\{(z, \overline{z}): \: z \in b\Delta(a, \rho) \}$. They use the property of $\Lambda_{a, \rho}$ that a continuous function on $b\Delta(a, \rho)$ extends holomorphically through $\Delta(a, \rho)$ if and only if the function $F$ defined on $b\Lambda_{a, \rho} = \{(z, \overline{z}): \: z \in b\Delta(a, \rho) \}$ by $F(z, \overline{z}) = f(z)$ ($z \in \Delta(a, \rho)$) has a bounded continuous extension to $\Lambda_{a, \rho} \cup b\Lambda_{a, \rho}$ which is holomorphic on $\Lambda_{a, \rho}$. Thus, when studying holomorphic extensions of a function $f$ from circles in the plane one defines $F(z, \overline{z}) = f(z)$ in a region in $\Sigma$ and then studies bounded holomorphic extensions of $F$ from $b\Lambda_{a, \rho}$ through $\Lambda_{a, \rho}$ [2, 3].

Tumanov [9] passes to a problem in $\mathbb{C}^2$ by adding an extra variable to make the translates of the disc pairwise disjoint and then, on the union of these discs, the (smooth) manifold

$$N_1 = \{(\zeta + it, \zeta): \: \zeta \in \overline{\Delta}, \: t \in \mathbb{R} \},$$

he defines a continuous function $F$ by letting, for each $t \in \mathbb{R}$, the function $\zeta \mapsto F(\zeta + it, \zeta)$ ($\zeta \in \overline{\Delta}$) be the holomorphic extension of $\zeta \mapsto f(\zeta + it)$ ($\zeta \in b\Delta$).

Received by the editors June 15, 2005 and, in revised form, December 1, 2005.

2000 Mathematics Subject Classification. Primary 30E20.
through $\Delta$. He then observes that the symmetry

$$F(\zeta + it, \zeta) = F(\zeta + it, 1/\zeta) \quad (\zeta \in b\Delta, t \in \mathbb{R}),$$

which follows from the fact that $F(\zeta + it, \zeta) = f(\zeta + it) \quad (\zeta \in b\Delta, t \in \mathbb{R})$, makes it possible to extend $F$ continuously to a new geometric object, the (smooth) manifold

$$N_2 = \{((\zeta + it, 1/\zeta): \zeta \in \overline{\Delta} \setminus \{0\}, t \in \mathbb{R}\},$$

by using the equality (1.1) for $\zeta \in \overline{\Delta} \setminus \{0\}, t \in \mathbb{R}$ as a definition. Thus one gets a continuous CR function $F$ on $N_1 \cup N_2$, the union of two manifolds with common boundary

$$N_1 \cap N_2 = bN_1 \cup N_2 = \{((\zeta + it, \zeta): \zeta \in b\Delta, t \in \mathbb{R}\}.$$

Tumanov then uses methods of CR theory to show that $F$ does not depend on the second variable, which means that $f$ is holomorphic on Int$S$. He also discovers that this is actually a finite strip problem.

Very recently Tumanov [10] studied a similar problem for a family of circles with centers sliding along a smooth curve and with smoothly changing radii. He used semi-quadrics. He obtained the result by using a classical argument of H. Lewy about holomorphic extensions of CR functions. In particular, he found a very simple proof of the theorem on the strip.

In the present paper we generalize the result of Tumanov [9] from vertical translates of circles to vertical translates of real-analytic simple closed curves which are symmetric with respect to the real axis.

2. THE MAIN RESULTS

Our first result is about analyticity on vertical translates of curves which are symmetric with respect to the real axis.

**Theorem 2.1.** Let $\Omega$ be a domain in $\mathbb{C}$ which is symmetric with respect to the real axis and whose boundary is a real analytic simple closed curve. Let $r > 0$ and let $f$ be a continuous function on $K = \bigcup\{b\Omega + it, \ -r \leq t \leq r\}$ such that for each $t, \ -r \leq t \leq r$, the function $f(b\Omega + it)$ has a continuous extension to $\overline{\Omega + it}$ which is holomorphic on $\Omega + it$. Suppose that $(\overline{\Omega - ir}) \cap (\overline{\Omega + ir}) = \emptyset$. Then $f$ is holomorphic on Int$K$.

Note that our assumptions imply that $K = \bigcup\{b\Omega + it, \ -r \leq t \leq r\}$.

We will deduce Theorem 2.1 from a more general result below which involves vertical translates of general domains and their images under conjugation.

Let $D$ be a domain in $\mathbb{C}$ bounded by a real-analytic simple closed curve. Let $S$ be the vertical strip defined by $S = \bigcup\{bD + it, t \in \mathbb{R}\} = \{\zeta \in \mathbb{C}: \ \alpha \leq \Re \zeta \leq \beta\}$. Write $D^* = \{\overline{\zeta}: \ \zeta \in D\}$. Obviously, $\bigcup\{bD^* + is, s \in \mathbb{R}\} = S$.

**Theorem 2.2.** Let $\lambda: [\alpha, \beta] \to \mathbb{R}$ be a continuous function and let $a, b, c, d$ be real numbers such that $D + ia, D^* + ic$ are both contained in $\{t + is: \ s < \lambda(t), \ \alpha \leq t \leq \beta\}$ and such that $D + ib, D^* + id$ are both contained in $\{t + is: \ s > \lambda(t), \ \alpha \leq t \leq \beta\}$. Let

$$Q_1 = \bigcup\{bD + it: \ a \leq t \leq b\}, \ Q_2 = \bigcup\{bD^* + is: \ c \leq s \leq d\}$$
and let \( f \) be a continuous function on \( Q_1 \cup Q_2 \) such that

\[
\begin{align*}
\text{(2.1)} & \quad \text{for each } t, a \leq t \leq b, \text{ the function } f[(bD + it)] \text{ has a continuous extension to } D + it \text{ which is holomorphic on } D + it, \\
\text{(2.2)} & \quad \text{for each } s, c \leq s \leq d, \text{ the function } f[(bD^* + is)] \text{ has a continuous extension to } D^* + is.
\end{align*}
\]

Then the function \( f \) is holomorphic on \( \text{Int}Q_1 \cup \text{Int}Q_2 \).

Our assumptions about \( a, b, c, d \) mean that \( D + it, D^* + ic \) both lie below the curve \( \ell = \{t + i\lambda(t): \alpha \leq t \leq \beta \} \) and \( D + ib, D^* + id \) both lie above the curve \( \ell \). Note that this implies that \( Q_1 = \bigcup (D^* + it: a \leq t \leq b) \) and \( Q_2 = \bigcup (D + is: c \leq s \leq d) \).

Theorem 2.1 follows from Theorem 2.2 by putting \( \Omega = D = D^*; a = c = -r; b = d = r \) and \( \lambda \equiv 0 \), that is, \( \ell = [a, \beta] \).

3. FROM CIRCLES TO GENERAL CURVES

In this section we describe the idea for passing from circles to general curves. Let \( \Omega \) be a domain bounded by a real-analytic simple closed curve which is symmetric with respect to the real axis. With no loss of generality assume that \( \Omega \) contains the origin. Let \( f \) be a continuous function on \( \bigcup \{b\Omega + it: t \in \mathbb{R} \} \) such that for each \( t \in \mathbb{R} \), the function \( \zeta \mapsto f(\zeta + it) (\zeta \in b\Omega) \) has a continuous extension to \( \overline{\Omega} \) which is holomorphic on \( \Omega \).

Semi-quadrics are related to circles, so they cannot be used to study the analyticity of functions on a family of translates of a given curve that is not a circle. We look again at the way in which Tumanov \cite{10} adds the extra variable in the case of the circles. An important point in his setting is that on \( b\Delta \) the conjugation \( z \mapsto \overline{z} \) extends to the map \( z \mapsto 1/z \) which carries \( \Delta \setminus \{0\} \) biholomorphically onto \( \mathbb{C} \setminus \overline{\Delta} \). This is not the case for general curves, so for domains \( \Omega \) more general than a disc it seems difficult to work with the manifold \( \{ (\zeta + it, \zeta): \zeta \in \overline{\Omega}, t \in \mathbb{R} \} \) used in \cite{10} when \( \Omega \) is a disc. However, since the reflection (1.1) takes place only in the second variable the idea is to replace the manifold \( \{ (\zeta + it, \zeta): \zeta \in \overline{\Omega}, t \in \mathbb{R} \} \) with a manifold that is attached to the cylinder \( \{ (z, w): |w| = 1 \} \). To do this we take the conformal map \( \Phi: \Omega \rightarrow \Delta \) that satisfies \( \Phi(\overline{\zeta}) = \overline{\Phi(\zeta)} (\zeta \in \Omega), \Phi(0) = 0 \), notice that \( \Phi \) extends to a diffeomorphism \( \Phi \) from \( \overline{\Omega} \) to \( \overline{\Delta} \) and define the smooth manifold \( N_1 \) by

\[ N_1 = \{ (\zeta + it, \Phi(\zeta)): \zeta \in \overline{\Omega}, t \in \mathbb{R} \}. \]

We define a continuous function \( F \) on \( N_1 \) by letting, for each \( t \in \mathbb{R} \), the function \( \zeta \mapsto F(\zeta + it, \Phi(\zeta)) (\zeta \in \overline{\Omega}) \) be the holomorphic extension of \( \zeta \mapsto f(\zeta + it) (\zeta \in b\Omega) \) through \( \Omega \).

If \( \zeta \in b\Omega \), then \( \overline{\zeta} \in b\overline{\Omega} \), and if \( t \in \mathbb{R} \), then \( \zeta + it = \zeta + is \), where \( s = t + (\zeta - \zeta)/i \in \mathbb{R} \), so

\[
F(\zeta + it, \Phi(\zeta)) = f(\zeta + it) = f(\overline{\zeta} + is) = F(\overline{\zeta} + is, \Phi(\overline{\zeta})) = F(\overline{\zeta} + is, 1/\Phi(\zeta)) = F(\zeta + it, 1/\Phi(\zeta)),
\]

which makes it possible to extend \( F \) continuously to a new geometric object, the smooth manifold

\[ N_2 = \{ (\zeta + it, 1/\Phi(\zeta)): \zeta \in \overline{\Omega} \setminus \{0\}, t \in \mathbb{R} \}, \]
by using the equality (3.1) for \( \zeta \in \overline{\Omega} \setminus \{0\} \) as a definition. Thus we get a continuous CR function \( F \) on \( N_1 \cup N_2 \), the union of two manifolds with the common boundary

\[
N_1 \cap N_2 = bN_1 = bN_2 = \{(\zeta + it, \Phi(\zeta)): \ z \in \Omega, \ t \in \mathbb{R}\}.
\]

We then show that the classical argument of H. Lewy, which Tumanov used with semiquadrics, works also in the present situation. This helps us to prove that \( F \) depends only on the first variable, which implies that \( f \) is holomorphic.

In fact, our main result, Theorem 2.2, is somewhat more general than the one just described. Its proof, although technically a bit complicated, uses essentially the idea above.

4. THE MANIFOLD \( N \)

We now begin with the proof of Theorem 2.2. With no loss of generality we assume that \( 0 \in D \) and that the imaginary axis intersects \( bD \) transversely.

Let \( \Phi: D \to \Delta \) be a conformal map such that \( \Phi(0) = 0 \). Since \( bD \) is real-analytic the map \( \Phi \) extends to a biholomorphic map from a neighbourhood of \( \overline{D} \) to a neighbourhood of \( \overline{\Delta} \). Define \( \Psi: D^* \to \Delta \) by

\[
\Psi(\zeta) = \Phi(\overline{\zeta}) \quad (\zeta \in D^*).
\]

The map \( \Psi \) maps \( D^* \) conformally onto \( \Delta \) and extends to a biholomorphic map from a neighbourhood of \( \overline{D^*} \) to a neighbourhood of \( \overline{\Delta} \).

Define

\[
N_1 = \{(\xi + it, \Phi(\xi)): \ x \in \overline{\Omega}, \ t \in \mathbb{R}\},
\]

\[
N_2 = \{(\xi + is, 1/\Psi(\xi)): \ x \in \overline{\Delta} \setminus \{0\}, \ s \in \mathbb{R}\}
\]

and set \( N = N_1 \cup N_2 \). Write

\[
\Phi^{-1}(w) = p(w) + iq(w) \quad (w \in \overline{\Delta}),
\]

where \( p \) and \( q \) are real functions. Then \( N_1 = \{(p(w) + iq(w) + it, w): \ w \in \overline{\Delta}, \ t \in \mathbb{R}\} = \{(p(w) + it, w): \ w \in \overline{\Delta}, \ t \in \mathbb{R}\} = \{(p(w), w): \ w \in \overline{\Delta} \setminus \mathbb{R}(i, 0)\}. \) If \( w = 1/\Psi(\zeta) \), then \( \Phi(\overline{\zeta}) = \Psi(\zeta) = 1/w \), so \( \zeta = \Phi^{-1}(1/\overline{w}) = p(1/\overline{w}) - iq(1/\overline{w}) \), which implies that \( N_2 = \{(p(1/\overline{w}) - iq(1/\overline{w}) + is, w): \ w \in \overline{\Delta} \setminus \Delta, \ s \in \mathbb{R}\} = \{(p(1/\overline{w}) + is, w): \ w \in \mathbb{C} \setminus \Delta, \ s \in \mathbb{R}\} = \{(p(1/\overline{w}), w): \ w \in \mathbb{C} \setminus \Delta \setminus \mathbb{R}(i, 0)\}. \) Define

\[
\theta(w) = \begin{cases} 
   \frac{1}{p(w)} & (w \in \overline{\Delta}), \\
   \frac{1}{p(1/\overline{w})} & (w \in \mathbb{C} \setminus \Delta).
\end{cases}
\]

The function \( \theta \) is well defined and continuous on \( \mathbb{C} \) since \( w = 1/\overline{w} \) (\( w \in b\Delta \)). The function \( \theta \) is invariant with respect to \( w \to 1/\overline{w} \), the reflection across \( b\Delta \). Note that \( \theta(\overline{\Delta}) \) is smooth as it extends to a harmonic function in a neighbourhood of \( \overline{\Delta} \). Similarly, \( \theta(\mathbb{C} \setminus \Delta) \) is smooth. We have

\[
N = \{(\theta(w) + it, w): \ w \in \mathbb{C}, t \in \mathbb{R}\},
\]

which shows that we obtain \( N \) by taking the graph \( \{(\theta(w), w): \ w \in \mathbb{C}\} \) of \( \theta \) in \( \mathbb{R} \times \mathbb{C} = \mathbb{R} \times \{0\} \times \mathbb{C} \) and then forming the union of all translates of this graph in the extra perpendicular direction \( (i, 0) \), that is,

\[
N = \{(\theta(w), w): \ w \in \mathbb{C} \setminus \mathbb{R}(i, 0)\}.
\]
Since
\[ N_1 = \{ (\theta(w), w) : w \in \overline{\Delta} + \mathbb{R}(i, 0) \}, \]
\[ N_2 = \{ (\theta(w), w) : w \in \mathbb{C} \setminus \Delta + \mathbb{R}(i, 0) \}, \]
we see that \( N \) is the union of manifolds \( N_1 \) and \( N_2 \) with boundary which meet along the common boundary
\[ N_1 \cap N_2 = bN_1 = bN_2 = \{ (\theta(w), w) : w \in b\Delta \} + \mathbb{R}(i, 0). \]

The complement of the graph of \( \theta \) in \( \mathbb{R} \times \mathbb{C} \) has two components: \( \{ (t, w) : t > \theta(w), w \in \mathbb{C} \} \) and \( \{ (t, w) : t < \theta(w), w \in \mathbb{C} \} \), which, by (4.1), implies that \( \mathbb{C}^2 \setminus N \) has two components:
\[ P_1 = \{ (t + is, w) : t > \theta(w), s \in \mathbb{R}, w \in \mathbb{C} \}, \]
\[ P_2 = \{ (t + is, w) : t < \theta(w), s \in \mathbb{R}, w \in \mathbb{C} \}. \]

5. Intersecting \( N \) with complex lines

We will apply the reasoning of H. Lewy concerning holomorphic extensions of CR functions. To this end, we look first at the intersections of \( N \) with complex lines \( L(z) = \{ (z, w) : w \in \mathbb{C} \} \). We shall use the fact that since \( bD \) is real-analytic and compact there are at most finitely many points \( \zeta \in bD \) such that the tangent line to \( bD \) at \( \zeta \) is parallel to the imaginary axis.

For \( z \in S \) write
\[ \tilde{E}(z) = N \cap L(z), \quad \tilde{E}_j(z) = N_j \cap L(z), \quad j = 1, 2 \]
and
\[ \Lambda(z) = \{ w \in \mathbb{C} : (z, w) \in N \}, \quad \Lambda_j(z) = \{ w \in \mathbb{C} : (z, w) \in N_j \}, \quad j = 1, 2, \]
so that
\[ \tilde{E}(z) = \{ z \} \times \Lambda(z), \quad \tilde{E}_j(z) = \{ z \} \times \Lambda_j(z), \quad j = 1, 2. \]

For each \( t \in \mathbb{R} \) we have \( N + t(i, 0) = N, \quad N_j + t(i, 0) = N_j, \quad j = 1, 2 \), so it follows that
\[ \Lambda(z) = \Lambda(\mathbb{R}z), \quad \Lambda_j(z) = \Lambda_j(\mathbb{R}z) \quad (j = 1, 2, \quad z \in S). \]

Thus, it is enough to study \( \Lambda(\tau), \quad \Lambda_j(\tau), \quad j = 1, 2, \) where \( \alpha \leq \tau \leq \beta \).

The set \( \tilde{E}(\tau) = \{ \tau \} \times \Lambda(\tau) \), contained in \( \mathbb{R}^3 = \mathbb{R} \times \{ 0 \} \times \mathbb{C} \), is the intersection of \( \{ (\theta(w), w) : w \in \mathbb{C} \} \), the graph of \( \theta \), with the two-plane (in fact, the complex line), \( \{ \tau \} \times \mathbb{C} \). Since \( \theta \) is invariant with respect to the reflection across \( b\Delta \) it follows that we get \( \Lambda_2(\tau) \) by reflecting \( \Lambda_1(\tau) \subset \overline{\mathbb{C}} \) across \( b\Delta \). So it is enough to study \( \Lambda_1(\tau) \).

Clearly
\[ \Lambda_1(\tau) = \Phi(K(\tau)) \quad \text{where} \quad K(\tau) = (\tau + i\mathbb{R}) \cap \overline{\mathbb{T}}. \]
If \( \tau \in [\alpha, \beta] \) is such that \( \tau + i\mathbb{R} \) meets \( bD \) transversely, as happens for all but finitely many \( \tau \), then \( \Lambda_1(\tau) \) consists of finitely many pairwise disjoint closed arcs with endpoints on \( b\Delta \) but otherwise contained in \( \Delta \) which meet \( b\Delta \) transversely. By transversality and by the fact that \( \Phi \) extends across \( bD \) as a conformal map, these arcs change smoothly with \( \tau \) as long as \( \tau + i\mathbb{R} \) meets \( bD \) transversely. If \( \tau \in (\alpha, \beta) \) is such that \( \tau + i\mathbb{R} \) does not meet \( bD \) transversely, then \( \Lambda(\tau) \) consists of a finite number of arcs with endpoints on \( b\Delta \) and pairwise disjoint interiors plus a possibly finite set on \( b\Delta \). There may be points on \( b\Delta \) which are common endpoints of two (but not more than two) of these arcs. Since we get \( \Lambda_2(\tau) \) by reflecting \( \Lambda_1(\tau) \) across \( b\Delta \) it follows that if \( \tau \neq 0 \) and if \( \tau + i\mathbb{R} \) is transverse to \( bD \), then \( \Lambda(\tau) \) consists of
finitely many pairwise disjoint simple closed curves, symmetric with respect to \( b\Delta \). If \( \tau \neq 0 \) and \( \tau + i\mathbb{R} \) does not meet \( b\Delta \) transversely, then \( \Lambda(\tau) \) consists of finitely many pairwise disjoint simple closed curves, symmetric with respect to \( b\Delta \) plus a possibly finite subset of \( b\Delta \). There may be points on \( b\Delta \) that are common points of two, but not more than two of these curves. Except for these points, the curves are pairwise disjoint. Clearly \( \Lambda(0) \) consists of finitely many pairwise disjoint simple closed curves, symmetric with respect to \( b\Delta \). Since \( \Lambda \) meets \( b\Delta \) transversely, \( \Lambda(0) \) consists of finitely many pairwise disjoint closed arcs with endpoints on \( b\Delta \) but otherwise contained in \( \Delta \) which meet \( b\Delta \) transversely. One of these arcs passes through the origin so its image under the reflection across \( b\Delta \) passes through infinity. Thus, \( \Lambda(0) \cup \{\infty\} \) consists of finitely many pairwise disjoint simple closed curves on the Riemann sphere, one of which contains infinity.

For each \( z \), \( \alpha < \Re z < 0 \) the set \( Y(z) = P_1 \cap L(z) \) is a bounded open subset of \( L(z) \) whose boundary \( E(z) = bY(z) \) is the part of \( E(z) = \{z\} \times \Lambda(z) \) consisting of curves (recall that in addition to these curves, \( E(z) \) may contain an additional finite set contained in \( \{z\} \times b\Delta \)). The complex line \( L(z) \) has a natural orientation. We orient \( E(z) \) as the boundary of \( Y(z) \) in \( L(z) \). Similarly, for \( 0 < \Re z < \beta \) we orient \( E(z) \) as the boundary of \( Y(z) = P_2 \cap L(z) \) in \( L(z) \). This determines the orientation of \( \Lambda(z) \), \( \alpha < \Re z < \beta \), \( \Re z \neq 0 \), or more precisely, the part of \( \Lambda(z) \) consisting of curves, and the orientation of \( K(\tau) \), \( \alpha < \tau < \beta \), \( \tau \neq 0 \), upwards if \( \alpha < \tau < 0 \) and downwards if \( 0 < \tau < \beta \).

If \( 0 < \tau < \beta \) and a point \((\tau, w)\) is above the graph of \( \theta \), that is, contained in \( P_1 \), then \([\tau, \beta] \times \{w\}\) is contained in \( P_1 \). A consequence of this is

**Proposition 5.1.** Suppose that \( 0 < \tau < \beta \) and let \( q_0 \in L(\tau + i\lambda(\tau)) \cap P_1 \). Then there is a path \( t \mapsto q(t) (\tau \leq t \leq \beta) \) such that \( q(\tau) = q_0 \) and \( q(t) \in L(t + i\lambda(t)) \cap P_1 (\tau \leq t \leq \beta) \).

**Proof.** We have \( q_0 = (\tau + i\lambda(\tau), w) \) where \( \tau > \theta(w) \). Define \( q(t) = (t + i\lambda(t), w) (\tau \leq t \leq \beta) \). It is easy to see that \( q \) has all the required properties. \( \square \)

A similar proposition holds for \( \alpha < \tau < 0 \) and for \( P_2 \) in the place of \( P_1 \).

6. **CONTINUITY OF AN INTEGRAL**

We shall need

**Proposition 6.1.** Let \( z_0 \in S \) and suppose that \( G \) is a continuous function on a neighbourhood of \( \bar{E}(z_0) \) in \( N \). Then the function

\[
\Theta(z) = \int_{\Lambda(z)} G(z, w) \, dw,
\]

defined in a neighbourhood of \( z_0 \) in \( S \), is continuous at \( z_0 \).

**Proof.** We prove the continuity of

\[
\Theta_1(z) = \int_{\Lambda_1(z)} G(z, w) \, dw = \int_{K(\Re z)} G(z, \Phi(\zeta)) \Phi'(\zeta) \, d\zeta.
\]

The proof for \( \Theta_2(z) = \int_{\Lambda_2(z)} G(z, w) \, dw \) will be analogous; note that \( \Theta = \Theta_1 + \Theta_2 \) since \( \Lambda_1(z) \) and \( \Lambda_2(z) \) meet in a finite set. Recall that \( \Phi \) and \( \Phi' \) extend holomorphically into a neighbourhood of \( \bar{D} \), so the continuity of \( \Theta_1 \) depends on how \( K(t) = \bar{D} \cap (t + i\mathbb{R}) \) changes with \( t \nearrow t_0 = \Re z_0 \). Assume for a moment that
\( \alpha < t_0 < \beta \). There are at most finitely many \( t, \alpha \leq t \leq \beta \) such that \( t + i\mathbb{R} \) does not intersect \( bD \) transversely. Thus there is an \( \eta > 0 \) such that \( t + i\mathbb{R} \) intersects \( bD \) transversely for every \( t, 0 < |t - t_0| < \eta \). In particular, for each \( t, t_0 - \eta < t < \eta \), \( K(t) \) is a finite collection of pairwise disjoint closed segments with endpoints varying continuously with \( t \). Since \( bD \cap (t_0 + i\mathbb{R}) \) is a finite set and since \( bD \) is compact it follows that each of these endpoints has a limit as \( t \searrow t_0 \).

As \( t \nearrow t_0 \) some segments may degenerate into points in the limit \( K(t_0 - 0) \) and some pairs of segments may get a common endpoint. Clearly \( K(t_0 - 0) \subset K(t_0) \) and \( K(t_0) \setminus K(t_0 - 0) \subset bD \cap (t_0 + i\mathbb{R}) \). Since the set \( bD \cap (t_0 + i\mathbb{R}) \) is finite it follows that \( K(t_0 - 0) \subset K(t_0) \) is a finite set. Thus, \( \lim_{z \to z_0, \mathbb{R}z \leq \mathbb{R}z_0} \Theta(z) = \Theta(z_0) \). Similarly we show that \( \lim_{z \to z_0, \mathbb{R}z \geq \mathbb{R}z_0} \Theta(z) = \Theta(z_0) \) which proves that \( \Theta \) is continuous at \( z_0 \).

The same (one-sided) reasoning applies if \( z_0 \in bS \). The proof is complete. \( \square \)

7. The manifold \( M \) and the function \( F \)

We now define a submanifold of \( N \) that is more closely related to our problem. Write

\[ M_1 = \{ (\xi + it, \Phi(\xi)) : \xi \in \mathcal{D}, \; a \leq t \leq b \}, \]
\[ M_2 = \{ (\zeta + is, 1/\Psi(\zeta)) : \zeta \in \mathcal{D}^* \setminus \{0\}, \; c \leq s \leq d \} \]

and let \( M = M_1 \cup M_2 \). Note that \( M_1 \) is a smooth manifold with boundary \( bM_1 = \{(\xi + it, \Phi(\xi)) : \xi \in bD, \; a \leq t \leq b\} \cup \{(\xi + ia, \Phi(\xi)) : \xi \in \mathcal{D}\} \cup \{(\xi + ib, \Phi(\xi)) : \xi \in \mathcal{D}\} \).

It is a submanifold of \( N_1 \). Similarly, \( M_2 \) is a smooth manifold with boundary \( bM_2 = \{(\zeta + is, 1/\Psi(\zeta)) : \zeta \in bD^*, \; c \leq s \leq d\} \cup \{(\zeta + ic, 1/\Psi(\zeta)) : \zeta \in \mathcal{D}^* \setminus \{0\}\} \cup \{(\zeta + id, 1/\Psi(\zeta)) : \zeta \in \mathcal{D}^* \setminus \{0\}\} \).

Suppose that \( f \) is a continuous function on \( Q_1 \cup Q_2 \) which satisfies (2.1) and (2.2). For each \( t, a \leq t \leq b, \) let \( g_t \) be a continuous extension of \( \xi \mapsto f(\xi + it) \) \( (\xi \in bD) \) to \( \mathcal{D} \) which is holomorphic on \( D \) and for each \( s, c \leq s \leq d, \) let \( h_s \) be the continuous extension of \( \zeta \mapsto f(\zeta + is) \) \( (\zeta \in bD^*) \) to \( \mathcal{D}^* \) which is holomorphic on \( D^* \). Define the function \( G \) on \( M_1 \) by

\[ G(\xi + it, \Phi(\xi)) = g_t(\xi) \quad (\xi \in \mathcal{D}, \; a \leq t \leq b) \]

and the function \( H \) on \( M_2 \) by

\[ H(\zeta + is, 1/\Psi(\zeta)) = h_s(\zeta) \quad (\zeta \in \mathcal{D}^* \setminus \{0\}, \; c \leq s \leq d). \]

In particular, on the part of \( bM_1 \) contained in \( bN_1 \) we have

\[ G(\xi + it, \Phi(\xi)) = f(\xi + it) \quad (\xi \in bD, \; a \leq t \leq b), \]

and on the part of \( bM_2 \) contained in \( bN_2 \) we have

\[ H(\zeta + is, 1/\Psi(\zeta)) = f(\zeta + is) \quad (\zeta \in bD^*, \; c \leq s \leq d). \]

Suppose that \((z, w) \in M_1 \cap M_2 \). Then there are \( \xi \in bD, \; \zeta \in bD^* \) and \( t, s, \; a \leq t \leq b, \; c \leq s \leq d, \) such that \( (\xi + it, \Phi(\xi)) = (z, w) = (\zeta + is, 1/\Psi(\zeta)) = (\zeta + is, \Phi(\overline{\zeta})) \), which implies that \( \zeta = \overline{\xi} \) and \( \xi + it = \overline{\xi} + is \). Thus, \( G(z, w) = G(\xi + it, \Phi(\xi)) = f(\xi + it) = f(\overline{\xi} + is) = H(\overline{\xi} + is, 1/\Psi(\overline{\xi})) = H(\zeta + is, 1/\Psi(\zeta)) = H(z, w). \) It follows that

\[ F(z, w) = \begin{cases} G(z, w) & (z, w) \in M_1 \\ H(z, w) & (z, w) \in M_2 \end{cases} \]
is a well defined continuous function on $M_1 \cup M_2$ which is holomorphic on each holomorphic leaf of $M_1$ and on each holomorphic leaf of $M_2$.

Our aim is to show that $F$ depends only on $z$ which will imply that $f$ is holomorphic on $\text{Int} Q_1 \cup \text{Int} Q_2$.

8. INTEGRALS OF CR FUNCTIONS ON $M$

Denote by $\pi_1$ the projection $\pi_1(z, w) = z$. With no loss of generality assume that $\lambda(0) = 0$. Our assumptions imply that there is an $\eta > 0$ such that if

$$\Sigma = \{ t + is : \lambda(t) - \eta < s < \lambda(t) + \eta, \ \alpha < t < \beta \},$$

then $L(z) \cap M = L(z) \cap N$ for all $z \in \Sigma$, that is, $\pi_1^{-1}(\Sigma) \cap M = \pi_1^{-1}(\Sigma) \cap N$. Put $\Sigma_1 = \{ z \in \Sigma, \mathbb{R}z < 0 \}, \Sigma_2 = \{ z \in \Sigma, \mathbb{R}z > 0 \}$. Recall that for $z \in \Sigma_1$ the set $E(z)$ is the boundary of $Y(z) = P_1 \cap L(z)$ in $L(z)$ and for $z \in \Sigma_2$ the set $E(z)$ is the boundary of $Y(z) = P_2 \cap L(z)$ in $L(z)$. Let

$$A_j = \bigcup \{ Y(z) : z \in \Sigma_j \} = \pi_1(\Sigma_j) \cap P_j \ (j = 1, 2).$$

For each $j = 1, 2$, $A_j$ is an open subset of $\Sigma_j \times \mathbb{C}$ whose relative boundary is $N \cap (\Sigma_j \times \mathbb{C})$. Using Proposition 5.1 we see that the complement of $\overline{A_j}$ in $\Sigma_j \times \mathbb{C}$ is connected, $j = 1, 2$.

We shall prove that the function $F$ extends holomorphically into $A_1$ and into $A_2$. We begin to follow the reasoning of H. Lewy. In [7] this was done for smooth functions on smooth manifolds and for more general, including continuous, functions on smooth manifolds this was done in [8]. We cannot refer to these results directly since in our case the manifold is not smooth but consists of two smooth pieces. However, these two pieces are both foliated by analytic discs which simplifies the situation. We provide the details to make the proof self-contained.

Let $\Delta(u, r)$ be contained in either $\Sigma_1$ or $\Sigma_2$ and assume that $\Theta$ is a continuous function on $\pi_1^{-1}(\Delta(u, r)) \cap N$ which is holomorphic on each holomorphic leaf. The function

$$z \mapsto Q(z) = \int_{\Lambda(z)} \Theta(z, w)dw$$

is, as we know, well defined and by Proposition 6.1 it is continuous on $\Delta(u, r)$. Recall that there are at most finitely many real values $\tau$ such that $\tau + i\mathbb{R}$ is not transverse to $bD$. So, if we want to prove that $Q$ is holomorphic on $\Delta(u, r)$ it is enough to prove that $Q$ is holomorphic in a neighbourhood of each $z_0 \in \Delta(u, r)$ such that $z_0 + i\mathbb{R}$ intersects $bD$ transversely. Let $z_0$ be such a point. Let $\rho > 0$ be such that for each $z \in \Delta(z_0, \rho), z + i\mathbb{R}$ meets $bD$ transversely. Passing to a smaller $\rho$ if necessary we may assume that there is a $\gamma > 0$ such that whenever $U$ is a closed disc contained in $\Delta(z_0, \rho)$ of radius not exceeding $\gamma$, the circle $bU + it, t \in \mathbb{R}$, either misses $bD$ or meets $bD$ in one point or in two points. Let $U$ be such a disc. By transversality, there is a positive integer $\nu$ such that for each $z \in U$ the set $L(z) \cap N = L(z) \cap M$ consists of $\nu$ pairwise disjoint simple closed curves, each being the union of two smooth arcs with endpoints on $\{ z \} \times b\Delta$, one having its interior contained in $\{ z \} \times \Delta$, and the other having its interior contained in $\{ z \} \times (\mathbb{C} \setminus \overline{\Delta})$, which change smoothly with $z$. So $\pi_1^{-1}(U) \cap N = \pi_1^{-1}(U) \cap M = \bigcup \{ L(z) \cap N : z \in U \}$ is an open subset of $N$ which has $\nu$ components whose closures are pairwise disjoint; the boundary of this set is $\pi_1^{-1}(bU) \cap N = \bigcup \{ L(z) \cap N : z \in bU \}$. Let $\Omega$ be one of these components. Write $T = bN_1 = bN_2$. The set $\Omega$ consists of three
pairwise disjoint parts: the domains \( \Omega_1 = \Omega \cap \text{Int} N_1, \Omega_2 = \Omega \cap \text{Int} N_2 \) and the two dimensional surface \( \Omega \cap T \). For each \( z \in bU \), \( L(z) \cap b\Omega \) is a simple closed curve, so \( b\Omega \) is a torus and \( \Omega \) is a solid torus in \( N \).

We now want to show that

\[
(8.1) \quad \int_{b\Omega} \Theta(z, w) dz \wedge dw = 0.
\]

Note first that \( \Omega \cap T \) is the common part of \( b\Omega_1 \) and \( b\Omega_2 \), so to prove (8.1) it is enough to prove that

\[
(8.2) \quad \int_{b\Omega_1} \Theta(z, w) dz \wedge dw = 0
\]

and

\[
(8.3) \quad \int_{b\Omega_2} \Theta(z, w) dz \wedge dw = 0.
\]

Consider (8.2). The properties of \( U \) imply that \( \Omega_1 \) can be written as the union of a continuous family of pairwise disjoint analytic discs

\[
A_t = \{ (\zeta + it, \Phi(\zeta)) : \zeta \in D, \zeta + it \in U \} = \{ (\zeta, \Phi(\zeta)) + it : \zeta \in D \cap (-it + U) \},
\]

and \( b\Omega_1 \) is the union of their pairwise disjoint boundaries

\[
bA_t = \{ (\zeta, \Phi(\zeta)) + it : \zeta \in b(D \cap (-it + U)) \}.
\]

These analytic discs, if nonempty, are of two sorts: either their boundaries are smooth simple closed curves which meet \( \Omega \cap T \) in at most one point (which happens if \( U \subset D + it \)), or their boundaries are simple closed curves consisting of two arcs, one contained in \( \text{Int} N_1 \) and the other contained in \( T \) (which happens if \( U \) meets \( D + it \) but is not contained in \( D + it \)). Recall that \( N_1 = \{ (\Upsilon(w) + it, w) : w \in \overline{\Delta}, t \in \mathbb{R} \} \), where the conformal map \( \Upsilon = \Phi^{-1} \) extends to a biholomorphic map from \( R\Delta \) for some \( R > 1 \) to a neighbourhood of \( \overline{D} \). Define the function \( \rho \) by \( \rho(z, w) = (1/i)(z - \Upsilon(w)) \) and notice that \( \rho \) is real on \( N_1 \). Then \( \Theta(z, w) dz \wedge dw = d\rho \wedge \mu \), where \( \mu = -(1/i)(\Theta(z, w)/\Upsilon'(w)) dz \) which, by using the Fubini theorem on each of the three smooth pieces of \( b\Omega_1 \) and adding the results, implies that

\[
(8.4) \quad \int_{b\Omega} \Theta(z, w) dz \wedge dw = \int_{I} \left[ \int_{bA_t} \mu \right] dt,
\]

where \( I \subset \mathbb{R} \) is the segment of all \( t \) such that \( \Omega_1 \cap \{ (\zeta + it, \Phi(\zeta)) : \zeta \in D \} \) is not empty. For each \( t \in I \) we have

\[
\int_{bA_t} \mu = -\frac{1}{i} \int_{bA_t} \Theta(z, w) \frac{1}{\Upsilon'(w)} dz,
\]

where the integral on the right vanishes by the Cauchy theorem since the function \( (z, w) \mapsto \Theta(z, w)/\Upsilon'(w) \) is continuous on \( \overline{A_t} \) and holomorphic on \( A_t \). This proves that the integral on the left in (8.4) vanishes. We repeat the reasoning for \( N_2 \) to get (8.3). This proves (8.1). Thus,

\[
\int_{bU} \left[ \int_{bA(z)} \Theta(z, w) dw \right] dz = 0
\]

for every disc \( U \subset \Delta(z_0, \rho) \), which, by the Morera theorem, implies that the function \( Q \) is holomorphic on \( D(z_0, \rho) \). This proves that \( Q \) is holomorphic on \( \Sigma_1 \cup \Sigma_2 \).
9. Holomorphic Extensions of $F$ and the Completion of the Proof

We continue to follow the reasoning of H. Lewy. For each $z \in \Sigma_1 \cup \Sigma_2$ and each $w \in \mathbb{C} \setminus \Lambda(z)$ (that is, for each $w$ such that $(z, w) \not\in N$) define
\[
\Xi(z, w) = \frac{1}{2\pi i} \int_{\Lambda(z)} \frac{F(z, \zeta)}{\zeta - w} d\zeta.
\]
For a fixed $z$ the function $w \mapsto \Xi(z, w)$ is holomorphic on $\mathbb{C} \setminus \Lambda(z)$. Now, fix $z_0 \in \Sigma_1$ and $w \in \mathbb{C} \setminus \Lambda(z_0)$. We show that $z \mapsto \Xi(z, w)$ is holomorphic in a neighbourhood of $z_0$. There is a $\rho > 0$ such that $\Delta(z_0, \rho) \subseteq \Sigma_1$ and $(z, w) \not\in N$ ($z \in \Delta(z_0, \rho)$), so the function $(z, \zeta) \mapsto F(z, \zeta)/(\zeta - w)$ is continuous on $\bigcup\{L(z) \cap N : z \in \Delta(z_0, \rho)\}$ and holomorphic on each holomorphic leaf. By the reasoning in Section 8 it follows that $z \mapsto \Xi(z, w)$ is holomorphic on $\Delta(z_0, \rho)$. This shows that $\Xi$ is holomorphic on $\pi_1^{-1}(\Sigma_1) \setminus N$. Fix a large $w$. We know that $z \mapsto \Xi(z, w)$ is continuous on $\Sigma_1 \cup \{\alpha + i(\delta, \beta)\}$ and holomorphic on $\Sigma$. Since $\Lambda(\alpha)$ is a finite set it follows that $\Xi(z, w)$ approaches 0 as $z$ approaches a point of $\alpha + i(\delta, \beta)$. It follows that $\Xi(z, w) \equiv 0$ ($z \in \Sigma_1$). Since this holds for all sufficiently large $w$, the connectedness of $(\Sigma_1 \times \mathbb{C}) \setminus \mathcal{T}_1$ implies that $\Xi \equiv 0$ on $(\Sigma_1 \times \mathbb{C}) \setminus \mathcal{T}_1$, so
\[
\frac{1}{2\pi i} \int_{\Lambda(z)} F(z, \zeta) \frac{d\zeta}{\zeta - w} = 0 \quad (z \in \Sigma_1, w \in \mathbb{C} \setminus Y(z)).
\]
It follows, in particular, that for all $z \in \Sigma_1$ the function $w \mapsto F(z, w)$, defined on $E(z) = bY(z)$, has a continuous extension into $Y(z) \cup bY(z)$ which is holomorphic on $Y(z)$. The same reasoning shows this for all $z \in \Sigma_2$.

Recall that $\Lambda(0) \cup \{\infty\}$ consists of finitely many pairwise disjoint simple closed curves on the Riemann sphere, one of which passes through infinity. By transversality, $\Lambda(t)$ changes continuously with $t$ near 0 and contains $\infty$ only if $t = 0$. As $t \nearrow 0$ the open sets $Y(t)$ and their oriented boundaries converge to a domain $Y^-$ and its oriented boundary $bY^-$ which, as a set, coincides with $\Lambda(0)$. As $t \searrow 0$ the open sets $Y(t)$ and their oriented boundaries $\Lambda(t)$ converge to a domain $Y^+$ and its oriented boundary $bY^+$ which, as a set, coincides with $\Lambda(0)$. We have $Y_- \cup \Lambda(0) \cup Y^+ = \mathbb{C}$. Since the function $F$ is bounded and continuous on $M$ it follows that as $t \nearrow 0$, the holomorphic extensions of $F|M \cap L(t + i\lambda(t))$ converge to the holomorphic extension of $F|M \cap L(0)$, a bounded continuous function on $\{0\} \times \overline{Y^-}$, holomorphic on $\{0\} \times \overline{Y^+}$. In particular, $F|M \cap L(0)$ extends to a bounded continuous function on $\{0\} \times \overline{Y^-}$ which is holomorphic on $\{0\} \times Y^-$. Similarly, $F|M \cap L(0)$ extends to a bounded continuous function on $\{0\} \times \overline{Y^+}$ which is holomorphic on $\{0\} \times Y^+$. Consequently $F|M \cap L(0)$ extends to a bounded continuous function on $\{0\} \times \mathbb{C}$ which is holomorphic on $\{0\} \times [Y^- \cup Y^+]$. This function extends holomorphically across $\{0\} \times \Lambda(0)$ to a bounded entire function on $L(0)$, which, by the Liouville theorem, must be constant. This implies that $F|M \cap L(0)$ is a constant. In the same way we show that $F|M \cap L(0)$ is constant for each $s, -\eta < s < \eta$. It follows that there is an $r > 0$ such that on $r\Delta$ the holomorphic extensions of all functions $f(it + bD)$ to $it + D$, for all $t$ such that $r\Delta \subset it + D$, coincide, and that on $r\Delta$ the holomorphic extensions of all functions $f(it + bD^*)$ to $it + D^*$, for all $t$ such that $r\Delta \subset it + D^*$, coincide. This implies first that $f$ is holomorphic on $\bigcup\{(it + bD) : r\Delta \subset it + D, a < t < b\} \cap \text{Int} S$, and then, by translating $bD$ further along $\mathbb{R}$, that $f$ is holomorphic on $\bigcup\{(it + bD) : a < t < b\} \cap \text{Int} S = \text{Int}Q_1$. Similarly, we show that $f$ is holomorphic on $\text{Int}Q_2$. The proof is complete.
10. Remarks

It remains an open problem to prove Theorem 2.1 without the assumption that Ω is symmetric with respect to the real axis. It is known that one cannot drop the assumption that \((\overline{\Omega} - ir) \cap (\overline{\Omega} + ir) = \emptyset\). In fact the function

\[
f(z) = \begin{cases} \frac{z^2}{z} & (z \neq 0) \\ 0 & (z = 0) \end{cases}
\]

is continuous on \(\mathbb{C}\) and extends holomorphically from each circle which either surrounds the origin or contains the origin, yet \(f\) is not holomorphic.

After the present paper was submitted for publication the author received the preprint [1] from Mark Agranovsky in which he proves a similar result for real analytic functions for considerably more general families of curves.

Acknowledgements

The author is indebted to Mark Agranovsky for several very stimulating discussions. After these discussions the author found a way to pass from circles to general curves.

This work was supported in part by the Ministry of Higher Education, Science and Technology of Slovenia through the research program Analysis and Geometry, Contract No. P1-0291

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