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## ► To cite this version:

Leandro Farina, Marcos Ferreira, Victor Péron. The Airfoil equation on near disjoint intervals: Approximate models and polynomial solutions. *Journal of Computational and Applied Mathematics*, 2016, 10.1016/j.cam.2015.11.024 . hal-01253227

**HAL Id: hal-01253227**

**<https://inria.hal.science/hal-01253227>**

Submitted on 11 Jan 2016

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# The Airfoil equation on near disjoint intervals: Approximate models and polynomial solutions

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## Abstract

The airfoil equation is considered over two disjoint intervals. Assuming the distance between the intervals is small an approximate solution is found and relationships between this approximation and the solution of the classical airfoil equation are obtained. Numerical results show the convergence of the solution of the original problem to the approximation. Polynomial solutions for an approximate model are obtained and a spectral method for the generalized airfoil equation on near disjoint intervals is proposed.

*Keywords:* airfoil equation, singular integral equations, singular perturbation, orthogonal polynomials, spectral method

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## 1. Introduction

Several works deal with the airfoil equation over an interval and its generalizations, see e.g. [1, 2, 3, 4]. In its original form, this equation can be written as

$$\frac{1}{\pi} \int_{-1}^1 \frac{f(t)}{x-t} dt = g(x), \quad x \in (-1, 1), \quad (1.1)$$

and it models the flow over an infinitely thin airfoil without viscosity and in the bidimensional case [5]. Here  $f$  is the local circulation density and it can be

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shown to be equal to the difference in induced velocity over the upper and lower side of the airfoil. The right-hand side  $g$  is given by the product of  $2\pi$ , the onset velocity and the slope of airfoil which in case of a flat plate is nothing but the product of  $2\pi$ , the onset velocity and the angle of incidence. The case when  $g$  is an odd function includes for instance an airfoil with zero angle of incidence and parabolic camber distribution. Applications in elasticity and surface wave scattering are also described by this equation [6].

In this work, we consider the airfoil equation with a Cauchy type of singularity and set in close disjoint intervals (2.1); that is, in two intervals with a small aperture of size  $2\varepsilon > 0$ . Tricomi [2] derived analytical solutions for the airfoil equation set in two disjoint intervals. Dutta and Banerjea [7] presented this solution in a slightly different form and have used it to deduce a solution of the associated hypersingular integral equation.

We investigate formally and numerically the asymptotic behavior for the solution  $f_\varepsilon$  of the airfoil equation when the small parameter  $\varepsilon$  tends to zero. We first identify the formal limit of  $f_\varepsilon$  as  $\varepsilon$  tends to zero : The background model  $f_0$  is given by a Cauchy singular integral. We compare the formal limit with the solution of the airfoil equation set in an interval  $(-1, 1)$ , in Section 3.2. We exhibit the first two terms of an expansion in power series of  $\varepsilon$  for particular analytical solutions  $f_\varepsilon$  and we specify a functional framework in weighted Sobolev spaces, Section 3.3. We illustrate numerically convergence results of  $f_\varepsilon$  towards  $f_0$  in  $\varepsilon^2$  in this framework, Section 4. We then find polynomials as solutions for the approximate model and we exhibit a spectral method to solve a generalized airfoil equation set on close disjoint intervals, in Section 5.

## 2. The mathematical model

We consider the airfoil equation with Cauchy type singularity and set in the union of two disjoint intervals with a small hole of size  $2\varepsilon > 0$ ,  $G_\varepsilon = (-1, -\varepsilon) \cup (\varepsilon, 1)$

$$\frac{1}{\pi} \int_{-1}^{-\varepsilon} \frac{f_\varepsilon(t)}{x-t} dt + \frac{1}{\pi} \int_{\varepsilon}^1 \frac{f_\varepsilon(t)}{x-t} dt = -\psi(x) , \quad x \in G_\varepsilon . \quad (2.1)$$

Here,  $f_\varepsilon$  is the unknown and  $\psi$  represents the data of the problem. We assume that  $\psi$  is Hölder continuous for  $x \in G_\varepsilon$ ,  $\psi \in \mathcal{C}^{0,\alpha}(G_\varepsilon)$ .

Let  $\varepsilon > 0$  be a fixed parameter. It is possible to solve the airfoil equation (2.1) by the method of Tricomi [2] (see also e.g. [7]). The solution writes

$$f_\varepsilon(x) = \begin{cases} \frac{1}{\pi R_\varepsilon(x)} [C_{1,\varepsilon} + C_{2,\varepsilon}x + \Psi_\varepsilon(x)] , & x \in (-1, -\varepsilon) \\ -\frac{1}{\pi R_\varepsilon(x)} [C_{1,\varepsilon} + C_{2,\varepsilon}x + \Psi_\varepsilon(x)] , & x \in (\varepsilon, 1) \end{cases} \quad (2.2)$$

where  $\Psi$  is given by the Cauchy integrals

$$\Psi_\varepsilon(x) = \int_{-1}^{-\varepsilon} \frac{\psi(t)R_\varepsilon(t)}{x-t} dt - \int_{\varepsilon}^1 \frac{\psi(t)R_\varepsilon(t)}{x-t} dt , \quad (2.3)$$

$C_{1,\varepsilon}$  and  $C_{2,\varepsilon}$  are two arbitrary constants, and  $R_\varepsilon(x) = \sqrt{(1-x^2)(x^2-\varepsilon^2)}$ ,  $x \in G_\varepsilon$ .

We will take the constants  $C_{1,\varepsilon}$  and  $C_{2,\varepsilon}$  as zero and will call the associated solution as the *null-circulation solution*. The physical meaning and motivation for choosing homogeneous constants is due to the fact that this case relates to the solution of the Airfoil equation on an interval when the circulation around the airfoil is zero. We will see more details of this in section 3.2.

### 3. Convergence results

In this section, we present convergence results and approximate models for the solution  $f_\varepsilon$  of (2.1) when  $\varepsilon$  tends to 0 (Prop. 3.2). We derive the background model  $f_0$  which is nothing but the pointwise limit of  $f_\varepsilon$  as  $\varepsilon$  tends to 0. We compare the background model  $f_0$  with the solution of the airfoil equation over an interval (1.1) (Prop. 3.4). Finally, we exhibit the first two terms of an asymptotic expansion of  $f_\varepsilon$  in power series of  $\varepsilon$  when the right hand side is a Chebyshev polynomial.

#### 3.1. Asymptotic behavior. Background model

We first investigate the behavior of the solution of the airfoil equation (2.1) when  $\varepsilon$  goes to 0.

**Lemma 3.1.** *Let  $x \in G_\varepsilon$  and  $\psi \in \mathcal{C}^{0,\alpha}(-1,1)$ . Define the function  $g_\varepsilon$  on  $G_\varepsilon \setminus \{x\}$  as*

$$g_\varepsilon(t) = \frac{\psi(t)R_\varepsilon(t)}{x-t}\mathbf{1}_{(-1,-\varepsilon)}(t) - \frac{\psi(t)R_\varepsilon(t)}{x-t}\mathbf{1}_{(\varepsilon,1)}(t) . \quad (3.1)$$

*Then,  $g_\varepsilon$  satisfies the pointwise convergence result : for a.e.  $t \in (-1,1)$ ,*

$$g_\varepsilon(t) \longrightarrow -\frac{\sqrt{1-t^2}}{x-t}t\psi(t)\mathbf{1}_{(-1,1)}(t) \quad \text{as } \varepsilon \rightarrow 0 . \quad (3.2)$$

**Proof.**

For all  $t \in G_\varepsilon \setminus \{x\}$ ,  $g_\varepsilon(t) = \frac{\psi(t)R_\varepsilon(t)}{x-t}(\mathbf{1}_{(-1,-\varepsilon)} - \mathbf{1}_{(\varepsilon,1)})(t)$ . Observe that  $R_\varepsilon(t) \longrightarrow |t|\sqrt{1-t^2}$  as  $\varepsilon \rightarrow 0$  for all  $t \in G_\varepsilon$  and  $(\mathbf{1}_{(-1,-\varepsilon)} - \mathbf{1}_{(\varepsilon,1)})(t) \longrightarrow -\text{sgn}(t)\mathbf{1}_{(-1,1)}(t)$  as  $\varepsilon \rightarrow 0$  for a.e.  $t \in (-1,1)$ . As a consequence, there holds for a.e.  $t \in (-1,1)$

$$R_\varepsilon(t)(\mathbf{1}_{(-1,-\varepsilon)} - \mathbf{1}_{(\varepsilon,1)})(t) \longrightarrow -\sqrt{1-t^2}t\mathbf{1}_{(-1,1)}(t) \quad \text{as } \varepsilon \rightarrow 0 .$$

We infer the convergence result (3.2) ■

In the framework of Lemma 3.1, one can not conclude in general that

$$\int_{-1}^1 g_\varepsilon(t) dt \longrightarrow - \int_{-1}^1 \frac{\sqrt{1-t^2}}{x-t} t\psi(t) dt \quad \text{when } \varepsilon \rightarrow 0 \quad (3.3)$$

for such function  $\psi \in \mathcal{C}^{0,\alpha}(-1,1)$ .

Nevertheless, when we restrict our considerations to a class of functions  $\psi \in \mathcal{C}^{0,\alpha}(-1,1)$  such that

$$|g_\varepsilon(t)| \leq g(t) \quad \text{for a.e. } t \in (-1,1)$$

where  $g \in L^1(-1,1)$  is a given function independent of  $\varepsilon$ , then as a consequence of the Lebesgue's Dominated Convergence Theorem the convergence result (3.3) holds. We then infer the following result.

**Proposition 3.2.** *Let  $x \in G_\varepsilon$  and  $\psi \in \mathcal{C}^{0,\alpha}(-1,1)$ . Assume that there exists a function  $g \in L^1(-1,1)$  such that*

$$|g_\varepsilon(t)| \leq g(t) \quad \text{for a.e. } t \in (-1,1), \quad (3.4)$$

where  $g_\varepsilon$  is defined by (3.1). Then, in the framework of Sec. 2, the null-circulation solution  $f_\varepsilon$  of the airfoil equation (2.1) satisfies the following point-wise convergence result when  $\varepsilon \rightarrow 0$  :

$$f_\varepsilon(x) \longrightarrow f_0(x) . \quad (3.5)$$

Here the function  $f_0$  is defined as

$$f_0(x) = -\frac{1}{\pi x \sqrt{1-x^2}} \Psi_0(x) \quad \text{for all } x \in G_0 = (-1, 1) \setminus \{0\} , \quad (3.6)$$

where  $\Psi_0$  is defined by a Cauchy type singular integral

$$\Psi_0(x) = -\int_{-1}^1 \frac{\sqrt{1-t^2}}{x-t} t\psi(t) dt . \quad (3.7)$$

**Proof.**

The proof is a consequence of Lemma 3.1 together with Lebesgue's Dominated Convergence Theorem. As a consequence of Lemma 3.1, there holds for a.e.  $t \in (-1, 1)$  :

$$g_\varepsilon(t) \longrightarrow -\frac{\sqrt{1-t^2}}{x-t} t\psi(t) \mathbb{1}_{(-1,1)}(t) \quad \text{as } \varepsilon \rightarrow 0 .$$

Using the condition (3.4), we can apply Lebesgue's Dominated Convergence Theorem to obtain the following result

$$\int_{-1}^1 g_\varepsilon(t) dt \longrightarrow -\int_{-1}^1 \frac{\sqrt{1-t^2}}{x-t} t\psi(t) dt \quad \text{when } \varepsilon \rightarrow 0$$

According to Section 2, there holds

$$f_\varepsilon(x) = \frac{1}{\pi R_\varepsilon(x)} \left( \mathbb{1}_{(-1, -\varepsilon)} - \mathbb{1}_{(\varepsilon, 1)} \right) (x) \int_{-1}^1 g_\varepsilon(t) dt$$

Since  $R_\varepsilon(x) \longrightarrow |x| \sqrt{1-x^2}$  as  $\varepsilon \rightarrow 0$ , we infer the convergence result (3.5) for all  $x \in G_\varepsilon$ . ■

The following proposition provides a convergence result that will be relevant in section 5.2, in the discussion on spectral methods for the generalized Airfoil equation on disjoint intervals.

**Proposition 3.3.** *Let  $x \in G_\varepsilon$  and assume that there exists a function  $v \in L^1(-1, 1)$  such that the null-circulation solution  $f_\varepsilon$  of the airfoil equation (2.1) satisfies*

$$\left| \frac{f_\varepsilon(t)}{x-t} \mathbf{1}_{G_\varepsilon}(t) \right| \leq v(t) \quad \text{for a.e. } t \in (-1, 1) . \quad (3.8)$$

*Then, for  $f_0$  given by (3.6), there holds*

$$\int_{G_\varepsilon} \frac{f_\varepsilon(t)}{x-t} dt \longrightarrow \int_{G_0} \frac{f_0(t)}{x-t} dt \quad \text{as } \varepsilon \rightarrow 0. \quad (3.9)$$

**Proof.**

As a consequence of Prop. 3.2 there holds for a.e.  $t \in (-1, 1)$

$$\frac{f_\varepsilon(t)}{x-t} \mathbf{1}_{G_\varepsilon}(t) \longrightarrow \frac{f_0(t)}{x-t} \mathbf{1}_{(-1,1)}(t) \quad \text{as } \varepsilon \rightarrow 0 .$$

Then using the condition (3.8) we can apply Lebesgue's Dominated Convergence Theorem to obtain the convergence result (3.9). ■

### 3.2. Comparison with the solution of the airfoil equation set on an interval

When  $\psi$  is Hölder continuous in  $(-1, 1)$ , the general solution of (1.1) with a data  $g = -\psi$  writes (see e.g. [2, pp. 173-180] or [8])

$$f(x) = \frac{1}{\pi} \int_{-1}^1 \sqrt{\frac{1-t^2}{1-x^2}} \frac{\psi(t)}{x-t} dt + \frac{A}{\sqrt{1-x^2}} . \quad (3.10)$$

Here  $A$  is an arbitrary constant. The constant  $A$  physically represents the circulation around the airfoil [5]. We consider that the circulation vanishes. Thus,  $A = 0$ , and the solution  $f$  is unique, given by

$$f(x) = \frac{1}{\pi} \int_{-1}^1 \sqrt{\frac{1-t^2}{1-x^2}} \frac{\psi(t)}{x-t} dt . \quad (3.11)$$

Therefore, for all  $x \in (-1, 1) \setminus \{0\}$  there holds

$$f(x) = f_0(x) + \frac{1}{x} \frac{1}{\pi} \int_{-1}^1 \sqrt{\frac{1-t^2}{1-x^2}} \psi(t) dt \quad (3.12)$$

where  $f_0$  is given by (3.6) as an approximation of  $f_\varepsilon$ .

### 3.2.1. Particular cases of the function $\psi(t)$

For some choices of the right hand side  $\psi$ , the solution  $f_\varepsilon$  of the airfoil equation (2.1) (set in  $G_\varepsilon$ ) coincides with the solution  $f$  of the airfoil equation set in  $(-1, 1)$ , modulo a residual term and when  $\varepsilon$  is small enough.

**Proposition 3.4.** *Let  $\psi \in \{T_m, U_n, \quad m \in \mathbb{Z}^+ \setminus \{0, 2\}, n \in \mathbb{Z}^+ \setminus \{0\}\}$  or let  $\psi$  be an odd function in  $\mathcal{C}^{0,\alpha}(-1, 1)$ . Here  $T_n$  and  $U_n$  are the Chebyshev polynomials of the first and second types, respectively. Then, in the framework of section 2,*

$$f(x) = f_0(x) \quad \text{for all } x \in (-1, 1) \setminus \{0\}. \quad (3.13)$$

Moreover, setting  $x \in G_\varepsilon$  and assuming (3.4), then the null-circulation solution  $f_\varepsilon$  of the airfoil equation (2.1) satisfies the following convergence result

$$f_\varepsilon(x) \rightarrow f(x) \quad \text{when } \varepsilon \rightarrow 0. \quad (3.14)$$

#### Proof.

From (3.12), we can write

$$f(x) = f_0(x) + \frac{1}{\pi x \sqrt{1-x^2}} I \quad (3.15)$$

where  $I = \int_{-1}^1 \sqrt{1-t^2} \psi(t) dt$ . Thus, it is obvious that (3.13) holds when  $\psi$  is odd. In order to show that (3.13) is also valid when  $\psi$  is equal to  $T_m$  or  $U_n$ ,  $m \in \mathbb{Z}^+ \setminus \{0, 2\}$ ,  $n \in \mathbb{Z}^+ \setminus \{0\}$ , we will look into the integral on the right hand side of (3.15). Note that for  $\psi(t) = T_n(t)$  we have

$$I = \int_0^\pi \sin^2(\theta) T_n(\cos(\theta)) d\theta$$

, using the change of variables  $t = \cos(\theta)$ .

Now, using  $\sin^2(\theta) = \frac{1 - \cos(2\theta)}{2}$  and  $T_n(\cos(\theta)) = \cos(n\theta)$ , we obtain

$$I = \underbrace{\frac{1}{2} \int_0^\pi \cos(n\theta) d\theta}_{I_1} - \underbrace{\frac{1}{2} \int_0^\pi \cos(2\theta) \cos(n\theta) d\theta}_{I_2}$$

Note that

$$I_1 = \begin{cases} \frac{\pi}{2} & , \text{ for } n = 0 \\ 0 & , \text{ elsewhere} \end{cases} \quad \text{and} \quad I_2 = \begin{cases} -\frac{\pi}{4} & , \text{ for } n = 2 \\ 0 & , \text{ elsewhere.} \end{cases}$$



Thus, when  $\psi = T_n$  and  $n \in \mathbb{N} \setminus \{0, 2\}$ ,  $I = 0$  and then  $f(x) = f_0(x)$ .

Analagously, for  $\psi(t) = U_n(t)$  we have

$$J = \int_{-1}^1 \sqrt{1-t^2} U_n(t) dt = \int_0^\pi \sin^2(\theta) U_n(\cos(\theta)) d\theta.$$

As  $U_n(\cos(\theta)) = \frac{\sin((n+1)\theta)}{\sin(\theta)}$ , we get

$$J = \int_0^\pi \sin(\theta) \sin((n+1)\theta) d\theta = \begin{cases} \frac{\pi}{2} & , \text{ for } n = 0 \\ 0 & , \text{ elsewhere.} \end{cases}$$

Thus, when  $\psi = U_n$  and  $n \in \mathbb{N} \setminus \{0\}$  there holds  $J = 0$  and again  $f(x) = f_0(x)$ .

Finally, as a consequence of the convergence result (3.5) we obtain (3.14). ■

### 3.3. First two terms of an asymptotic expansion for particular analytical solutions $f_\varepsilon$

In this section, we derive the first two terms of an asymptotic expansion for the solution  $f_\varepsilon$  of the airfoil equation (2.1) (set on  $G_\varepsilon$ ) when the right hand side  $\psi$  is a Chebyshev polynomial, Prop. 3.5. As a consequence, we exhibit weight functions together with weighted Sobolev spaces for the first two terms of this expansion.

**Proposition 3.5.** *Let  $\psi \in \{T_m, \quad m \in \{0, 1, 2, 3\}\}$  (where  $T_n$  are the Chebyshev polynomials of the first types). Then, in the framework of section 2, the solution of the airfoil equation (2.1) set in  $G_\varepsilon$  admits the following asymptotic expansion*

$$f_\varepsilon \approx f_0 + \varepsilon^2 f_2 \quad \text{when } \varepsilon \rightarrow 0. \quad (3.16)$$

Here, for all  $x > 0$ ,  $f_0(x)$  and  $f_2(x)$  are given by :

$$f_0(x) = \frac{x^2 - \frac{1}{2}}{x\sqrt{1-x^2}} \quad \text{and} \quad f_2(x) = \frac{-1}{x^3\sqrt{1-x^2}} \quad \text{when} \quad \psi = T_0, \quad (3.17a)$$

$$f_0(x) = \frac{x^2 - \frac{1}{2}}{\sqrt{1-x^2}} \quad \text{and} \quad f_2(x) = \frac{-1}{4x^2\sqrt{1-x^2}} \quad \text{when} \quad \psi = T_1, \quad (3.17b)$$

$$f_0(x) = \frac{2x^4 - 2x^2 + \frac{1}{4}}{x\sqrt{1-x^2}} \quad \text{and} \quad f_2(x) = \frac{-1}{8x^3\sqrt{1-x^2}} \quad \text{when} \quad \psi = T_2, \quad (3.17c)$$

$$f_0(x) = \frac{4x^4 - 5x^2 + 1}{\sqrt{1-x^2}} \quad \text{and} \quad f_2(x) = \frac{1}{2x^2\sqrt{1-x^2}} \quad \text{when} \quad \psi = T_3. \quad (3.17d)$$

**Proof.**

The proof of this proposition is based on the derivation of the first two terms of an asymptotic expansion in power series of  $\varepsilon$  for the analytical solution  $f_\varepsilon$  of the airfoil equation (2.1) when  $\psi \in \{T_m, \quad m \in \{0, 1, 2, 3\}\}$ . This derivation is based on the following closed-form expressions, obtained in [9].

$$f_\varepsilon(x) = \frac{\text{sgn}(x)}{R_\varepsilon(x)} \left( x^2 - \frac{1 + \varepsilon^2}{2} \right) \quad \text{when} \quad \psi = T_0 \quad (3.18)$$

$$f_\varepsilon(x) = \frac{x \text{sgn}(x)}{R_\varepsilon(x)} \left( x^2 - \frac{1 + \varepsilon^2}{2} \right) \quad \text{when} \quad \psi = T_1 \quad (3.19)$$

$$f_\varepsilon(x) = \frac{\text{sgn}(x)}{R_\varepsilon(x)} \left( -2x^4 + (2 + \varepsilon^2)x^2 + \frac{\varepsilon^4 - 4\varepsilon^2 - 1}{4} \right) \quad \text{when} \quad \psi = T_2 \quad (3.20)$$

$$f_\varepsilon(x) = \frac{x \text{sgn}(x)}{R_\varepsilon(x)} \left( 4x^4 - (5 + 2\varepsilon^2)x^2 + \frac{-\varepsilon^4 + 5\varepsilon^2 + 2}{2} \right) \quad \text{when} \quad \psi = T_3 \quad (3.21)$$

Observe that the function  $R_\varepsilon^{-1}$  has the following asymptotic expansion when  $\varepsilon \rightarrow 0$  : for all  $x \in G_\varepsilon$ ,

$$R_\varepsilon^{-1}(x) = \frac{1}{|x|\sqrt{1-x^2}} \left( 1 + \frac{1}{2} \frac{\varepsilon^2}{x^2} + \mathcal{O}(\varepsilon^4) \right) \quad (3.22)$$

Substituting the expansion (3.22) into (3.18) (and (3.19), (3.20), (3.21), respectively) and performing the identification of terms with the same power of  $\varepsilon$  we infer the expressions of  $f_0$  and  $f_2$  given by (3.17a) (and (3.17b), (3.17c), (3.17d), respectively). ■

As a consequence of Prop. 3.5, it is possible to specify a functional framework for  $f_2$ . We define two weight functions  $w_0$  and  $w_1$  as  $w_0(x) := |x|^{11/2}\sqrt{1-x^2}$  and  $w_1(x) := |x|^{7/2}\sqrt{1-x^2}$ , and we denote by  $L_{w_0}^2(G_0)$  and  $L_{w_1}^2(G_0)$  the associated  $L^2$ - weighted Sobolev spaces.

**Proposition 3.6.** *In the framework of Prop. 3.5, the solution of the airfoil equation (2.1) satisfies at least formally the following expansion*

$$(f_\varepsilon - f_0) \approx \varepsilon^2 f_2, \quad \text{when } \varepsilon \rightarrow 0 \quad (3.23)$$

with

$$f_2 \in L_{w_0}^2(G_0) \text{ when } \psi \in \{T_0, T_2\}$$

and

$$f_2 \in L_{w_1}^2(G_0) \text{ when } \psi \in \{T_1, T_3\}$$

**Proof.**

Let  $\psi \in \{T_0, T_2\}$ . As a consequence of (3.17a) and (3.17c), the function  $f_2$  belongs to the space  $L_{w_0}^2(G_0)$ . When  $\psi \in \{T_1, T_3\}$ , (3.17b) and (3.17d) imply that the function  $f_2$  belongs to the space  $L_{w_1}^2(G_0)$ . ■

The validation of this asymptotic expansion (3.23) consists to prove uniform estimates when  $\varepsilon$  is small enough

$$\|f_\varepsilon - f_0\|_{L_{w_0}^2} = \mathcal{O}(\varepsilon^2) \quad \text{when } \psi \in \{T_0, T_2\}$$

and

$$\|f_\varepsilon - f_0\|_{L_{w_1}^2} = \mathcal{O}(\varepsilon^2) \quad \text{when } \psi \in \{T_1, T_3\}.$$

This part of the work is investigated numerically in Sec. 4 and illustrated with numerical convergence rates.

#### 4. Numerical results

In this section, we show a number of numerical results in corroboration with our asymptotic analysis above. Thus, numerical values of  $\|f_\varepsilon - f_0\|_{L_{w_0}^2}$  are shown

in a table and figures presenting the graphs of the functions  $f_0(t)$  and  $f_\varepsilon(t)$  for different values of  $\varepsilon$  are also given.

In figures 1 and 2 the asymptotic behavior of  $f_\varepsilon$  and its convergence to  $f_0$  is depicted for several cases of the function  $\psi$ .

The numerical convergence of  $f_\varepsilon(t)$  to  $f_0(t)$  is clearly seen in table 4 for  $T_j$ ,  $j = 1, \dots, 7$ .

The plots of  $\log(\|f_\varepsilon - f_0\|_{L^2_{w_0}})$  against  $\log(\varepsilon)$  in figure 3, demonstrate numerically  $\|f_\varepsilon - f_0\|_{L^2_{w_0}} = \mathcal{O}(\varepsilon^2)$  for  $\psi \in \{T_0, T_1, T_6\}$  and indicate a convergence rate of order one for  $\psi \in \{T_4, T_7\}$ .

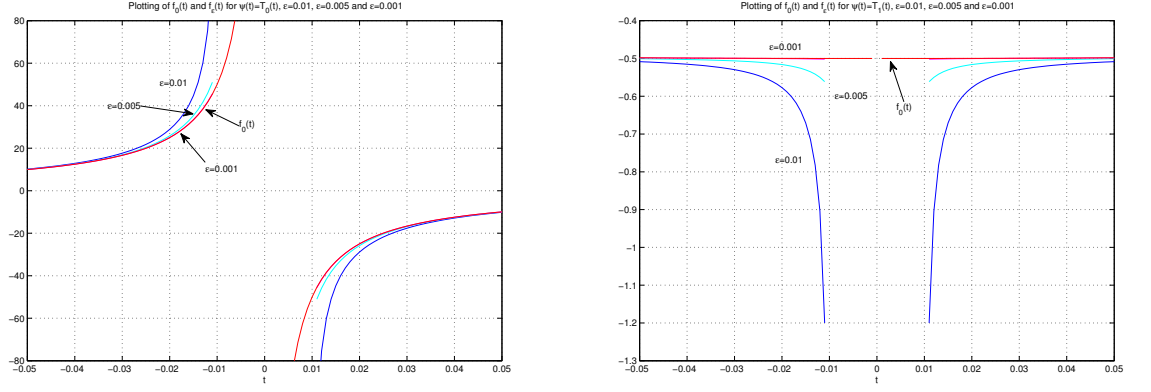


Figure 1: On the left,  $f_\varepsilon(t)$  and  $f_0(t)$ (red) for  $\psi(t) = 1$ . On the right figure,  $f_\varepsilon(t)$  and  $f_0(t)$ (red) for  $\psi(t) = t$ . In both figures,  $\varepsilon = 0.01$  (blue),  $\varepsilon = 0.005$  (cyan),  $\varepsilon = 0.001$  (magenta).

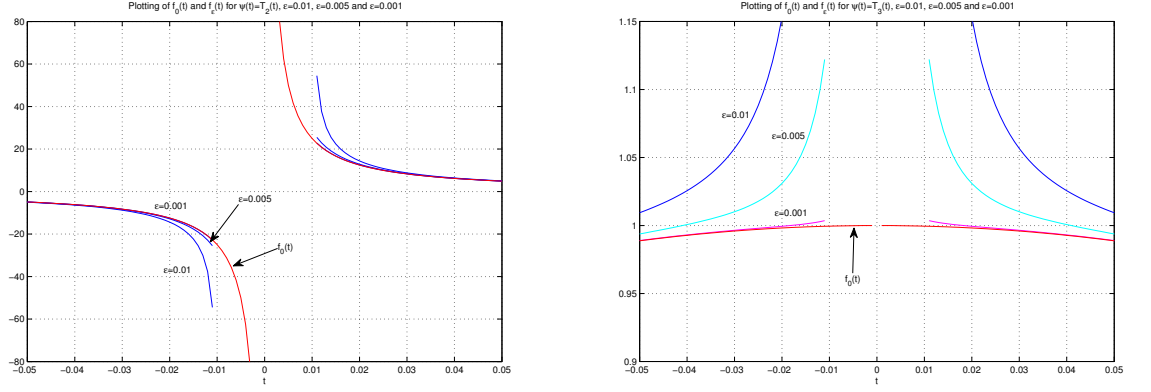


Figure 2: On the left,  $f_\varepsilon(t)$  and  $f_0(t)$ (red) for  $\psi(t) = T_2(t)$ . On the right,  $f_\varepsilon(t)$  and  $f_0(t)$ (red) for  $\psi(t) = T_3(t)$ . In both figures,  $\varepsilon = 0.01$  (blue),  $\varepsilon = 0.005$  (cyan),  $\varepsilon = 0.001$  (magenta)

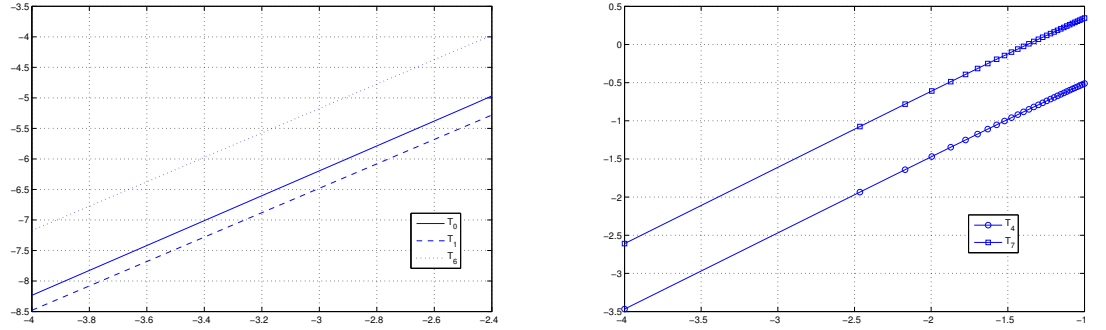


Figure 3:  $\log(\|f_\varepsilon - f_0\|_{L^2_{w_0}})$  plotted against  $\log(\varepsilon)$ .

$\psi(t) \backslash \varepsilon$	0.1	0.01	0.001	0.0001
$T_0$	0.016735069278020	0.000122221398303	0.000000619117636	0.000000005827215
$T_1$	0.003706513707562	0.000033062469290	0.000000330534162	0.000000003305335
$T_2$	0.008133702636602	0.000061094486497	0.000000309558293	0.000000002913607
$T_3$	0.007347436293331	0.000066119977949	0.000000661067827	0.000000006610670
$T_4$	0.307798166131477	0.033680203253810	0.003398455037006	0.000340151486471
$T_5$	0.007174486542688	0.000066106750706	0.000000661066506	0.000000006610670
$T_6$	0.067700651694066	0.000670502998051	0.000006704449030	0.000000067044432
$T_7$	2.220447951981798	0.243445284662592	0.024569234228085	0.002459182003860

Table 1: The norm  $\|f_\varepsilon - f_0\|_{L^2_{w_0}}$  for different values of  $\varepsilon$  and functions  $\psi$ .

## 5. Polynomial solutions

In this section we address the issue of existence of polynomial solutions for the airfoil equation (2.1). We propose to answer partially this question using the approximate solution  $f_0$  given by (3.5).

### 5.1. Approximation of order 1

According to (3.5), we consider  $f_0$  as an approximation of the solution  $f_\varepsilon$  for the integral equation (2.1). Then we look for polynomial solutions for the Cauchy type singular integral (3.6)

$$\frac{1}{\pi x \sqrt{1-x^2}} \int_{-1}^1 \frac{\sqrt{1-t^2}}{x-t} t \psi(t) dt = f_0(x) \quad \text{for all } x \in (-1, 1) \setminus \{0\}. \quad (5.1)$$

It is known that for all  $x \in (-1, 1)$ , and  $n = 0, 1, 2, \dots$ ,

$$\frac{1}{\pi} \int_{-1}^1 \frac{\sqrt{1-t^2}}{x-t} U_n(t) dt = T_{n+1}(x),$$

where  $T_n$  and  $U_n$  are Chebyshev polynomials of the first and second kinds, respectively (see e.g. [8]). Hence, setting

$$\psi(x) = x^{-1} U_n(x) \quad (5.2)$$

for all  $x \in (-1, 1)$  (and  $x \neq 0$  when  $n$  is even) in (5.1), there holds

$$f_0(x) = \frac{1}{x \sqrt{1-x^2}} T_{n+1}(x). \quad (5.3)$$

### 5.2. A spectral method of the generalized airfoil equation in close disjoint intervals

Given the results represented above we can now propose a spectral method for an approximate of the generalized equation [10]

$$\frac{1}{\pi} \int_{G_\varepsilon} \left\{ \frac{1}{x-t} + K(x, t) \right\} f_\varepsilon(t) w(t) dt = h(x), \quad x \in G_\varepsilon, \quad (5.4)$$

where  $K$  is a regular (non strongly singular) function and  $w(t) = \frac{1}{t \sqrt{1-t^2}}$ .

Using (3.5) and Proposition 3.3, we get

$$\frac{1}{\pi} \int_{G_\varepsilon} \frac{f_0(t)}{x-t} dt \approx -\psi(x), \quad x \in G_\varepsilon, \quad \varepsilon \ll 1 \quad (5.5)$$

and from (5.2),(5.3) and (5.5),

$$\frac{1}{\pi} \int_{G_\epsilon} \frac{1}{x-t} T_{n+1}(t) \frac{1}{t\sqrt{1-t^2}} dt \approx -x^{-1} U_n(x), \quad x \in G_\epsilon, \quad \epsilon \ll 1 \quad (5.6)$$

Expand the solution as

$$f_\epsilon(t) \simeq \sum_{n=0}^N a_n T_{n+1}(t). \quad (5.7)$$

Substituting in (5.4) and using (5.6),

$$\sum_{n=0}^N a_n [-x^{-1} U_n(x) + \mathcal{K} T_{n+1}] = \psi(x), \quad (5.8)$$

where  $\mathcal{K}$  is the integral operator given by

$$\mathcal{K}(g) = \frac{1}{\pi} \int_{G_\epsilon} K(x,t) g(t) w(t) dt.$$

Equation (5.8) can be solved by a Galerkin or collocation method.

The spectral method consists of (5.7) and (5.8).

## Acknowledgments

LF acknowledges support by Grant MTM2011-24766 of the MICINN, Spain. LF and VP acknowledge support from EU project FP7-295217-HPC-GA and also by the Basque Government through the BERC 2014-2017 program and by Spanish Ministry of Economy and Competitiveness MINECO: BCAM Severo Ochoa excellence accreditation SEV-2013-0323. MRSF acknowledges financial support from CNPq, Brazil.

## References

- [1] N. I. Muskhelishvili, Singular integral equations. Boundary problems of function theory and their application to mathematical physics, P. Noordhoff N. V., Groningen, 1953, translation by J. R. M. Radok.
- [2] F. G. Tricomi, Integral equations, Pure and Applied Mathematics. Vol. V, Interscience Publishers, Inc., New York, 1957.

- [3] E. O. Tuck, Application and solution of Cauchy singular integral equations, in: Application and numerical solution of integral equations (Proc. Sem., Australian Nat. Univ., Canberra, 1978), Vol. 6 of Monographs Textbooks Mech. Solids Fluids: Mech. Anal., Sijthoff & Noordhoff, Alphen aan den Rijn, 1980, pp. 21–49.
- [4] W. L. Wendland, On applications and the convergence of boundary integral methods, in: Treatment of integral equations by numerical methods (Durham, 1982), Academic Press, London, 1982, pp. 463–476.
- [5] J. P. Breslin, P. Andersen, Hydrodynamics of ship propellers, Vol. 3 of Cambridge Ocean Technology Series, Cambridge University Press, 1994.
- [6] B. N. Mandal, A. Chakrabarti, Applied singular integral equations, Science Publishers, 2011.
- [7] B. Dutta, S. Banerjee, Solution of a hypersingular integral equation in two disjoint intervals, Appl. Math. Lett. 22 (8) (2009) 1281–1285.
- [8] P. A. Martin, Exact solution of a simple hypersingular integral equation, J. Integral Equations Appl. 4 (2) (1992) 197–204.
- [9] M. R. S. Ferreira, Comportamento assintótico para soluções da equação do aerofólio em intervalos disjuntos, Master’s thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil (2015).
- [10] L. Farina, Convergence of spectral methods for singular integral equations and applications, in: The Third BCAM Workshop on Computational Mathematics, Bilbao, 2014.