

## A COUNTEREXAMPLE TO ANALYTICITY IN FRICTIONAL DYNAMICS\*

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**Abstract.** We consider the motion of a particle acted on by dry friction and a force that is an analytic function of time. We give a counterexample to the claim that such motions are given by analytic functions of time. Several published arguments concerning existence and uniqueness in unilateral dynamics with friction rely on the analyticity of such motions. The counterexample invalidates those arguments for motions in three or more dimensions.

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### 1. INTRODUCTION

Contact and impact are typically modelled with *unilateral constraints*: inequalities involving the coordinates of some bodies, which are satisfied when those bodies do not interpenetrate. Such constraints are essential components of models of robots [7, 10] and other systems [6], and it is natural to enquire about the existence and uniqueness of solutions to initial value problems for such models [3]. In the 1960s, it was discovered that the motion of a unilaterally constrained particle acted on by an external force is in general non-unique, even if the force is an infinitely differentiable function of time [1, 4, 14]. However, in the 1990s, it was shown that such motions are unique if there is no friction and the force is an analytic function [1, 13]. (A function  $f$  is *analytic* if for every point  $x_0$  of its domain, the Taylor series of  $f$  at  $x_0$  converges to  $f(x)$  for all points  $x$  in some neighbourhood of  $x_0$ .)

Several authors have explored how such results might be extended to models involving friction. Ballard and Basseville [2] presented arguments for the existence and uniqueness of solutions to initial value problems for a unilaterally constrained particle acted on by an analytic force and dry friction. Charles and Ballard [5] extended those arguments to finite collections of particles. A key step of those arguments is to derive a local solution given by a power series, and to claim that it corresponds to an analytic function.

In this paper, we present a simple counterexample to that claim. The counterexample invalidates the existence and uniqueness arguments presented in Ballard and Basseville [2] and Charles and Ballard [5] for unilaterally constrained particles in dimension  $d > 2$ , although those arguments are correct for  $d = 2$  to the best of our knowledge. Consequently for  $d > 2$ , the only general existence result about unilateral dynamics with friction is that of Monteiro Marques [11], which only addresses situations with a single constraint and perfectly inelastic

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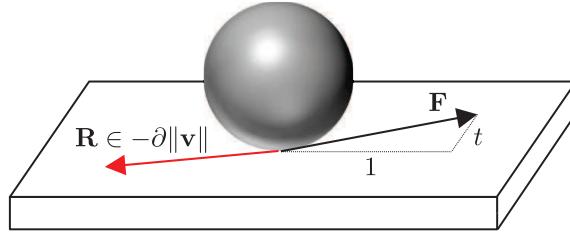


FIGURE 1. The tangential force and reaction acting on the particle in Counterexample 1.

impacts (zero restitution coefficient); and the question of finding sufficient conditions for uniqueness is largely open.

### 1.1. Counterexample

Consider a particle in contact with a flat surface, acted on by a force and friction. The particle's position is an element of  $\mathbb{R}^d$ , but a normal force holds it in contact with the surface, so we describe its motion in  $\mathbb{R}^{d-1}$  using an orthogonal coordinate system tangent to that surface. The particle's tangential velocity  $\mathbf{v} : [0, T] \rightarrow \mathbb{R}^{d-1}$  satisfies Newton's second law:

$$m\dot{\mathbf{v}} = \mathbf{F} + \mathbf{R},$$

where  $m$  is the particle's mass, the dot denotes the time derivative,  $\mathbf{F} : [0, T] \rightarrow \mathbb{R}^{d-1}$  is the tangential force, and  $\mathbf{R} : [0, T] \rightarrow \mathbb{R}^{d-1}$  is the tangential reaction. This reaction satisfies Coulomb's law of friction:

$$\mathbf{R}(t)\|\mathbf{v}(t)\| = -\mu N(t)\mathbf{v}(t) \quad \text{and} \quad \|\mathbf{R}(t)\| \leq \mu N(t),$$

where  $\mu > 0$  is the friction coefficient, and  $N(t)$  is the magnitude of the force normal to the surface. As discussed in Moreau [12], Ballard and Charles [3], we may write this compactly as

$$\mathbf{R}(t) \in -\mu N(t) \partial\|\mathbf{v}(t)\|,$$

where  $\partial f$  denotes the subdifferential of a convex function  $f$ . For simplicity, we assume the particle has unit mass and that  $\mu N(t) = 1$ . The velocity then satisfies the differential inclusion

$$\dot{\mathbf{v}} \in \mathbf{F} - \partial\|\mathbf{v}\|. \quad (1.1)$$

(This is equivalent to requiring that the differential equation  $\dot{\mathbf{v}}(t) = \mathbf{F}(t) - (\mathbf{v}(t)/\|\mathbf{v}(t)\|)$  holds at times when  $\mathbf{v}(t) \neq 0$ , and that the constraint  $\|\dot{\mathbf{v}}(t) - \mathbf{F}(t)\| \leq 1$  holds at times when  $\mathbf{v}(t) = 0$ .)

The following counterexample shows that even if the force  $\mathbf{F}$  is an analytic function of time and the final time  $T > 0$  is tiny, differential inclusion (1.1) need not have an analytic solution  $\mathbf{v}$ . The force appearing in this counterexample is illustrated in Figure 1. The magnitude of this force initially equals the friction limit, but a component of the force orthogonal to its initial direction increases, causing the particle to slip.

**Counterexample 1.** Suppose the dimension is  $d > 2$ , the final time is  $T > 0$ , and the velocity  $\mathbf{v} : [0, T] \rightarrow \mathbb{R}^{d-1}$  is an absolutely continuous function with  $\mathbf{v}(0) = 0$  that satisfies differential inclusion (1.1) for the force

$$\mathbf{F}(t) = (1, t, 0, \dots, 0)^\top \in \mathbb{R}^{d-1},$$

for almost all  $t \in [0, T]$ . Then  $\mathbf{v}$  is not an analytic function.

To prove the velocity  $\mathbf{v}(t)$  is not analytic, we derive its Taylor series at  $t = 0$  and show that this series diverges for any  $t > 0$ .

**Remark 1.1.** It is not uncommon for differential equations to have divergent series solutions [9]. However, the initial condition  $\mathbf{v}(0) = 0$  is necessary for a series solution of differential inclusion (1.1) to diverge for all  $t > 0$ , when  $\mathbf{F}$  is analytic. Indeed, if  $\mathbf{v}(0) \neq 0$  then the tangential reaction is  $\mathbf{R}(t) = -\mathbf{v}(t)/\|\mathbf{v}(t)\|$  on a neighbourhood of  $t = 0$ , and this is an analytic function of  $\mathbf{v}(t)$  on a neighbourhood of  $\mathbf{v}(0)$ , so the Cauchy–Kovalevskaya theorem [8] guarantees the existence of a unique analytic solution  $\mathbf{v}(t)$  on a neighbourhood of  $t = 0$ .

**Remark 1.2.** When working with unilateral constraints, the velocity must in general be formulated as a discontinuous function, so as to allow for impacts [2, 5]. Such formulations simplify to ours in the special case that a normal force holds the particle in contact with a surface. In this special case, the unilateral constraint is equivalent to a *bilateral constraint*: an equality constraint on the particle’s coordinates. The existence and uniqueness of a solution to Counterexample 1 therefore follow from general results about bilaterally constrained problems with friction – specifically, Proposition 3.3 of [2] or Proposition 3.1 of [5].

## 1.2. Outline

First, we derive an algorithm to compute the Taylor series of  $\mathbf{v}$  (Sect. 2). We provide numerical evidence that this series diverges (Fig. 2) and explain the divergence intuitively. Then we discuss the specific results that our counterexample invalidates, and pinpoint the error in the arguments leading to those results (Sect. 3). Appendix A gives a proof of divergence, and the supplementary material contains a Python implementation of our algorithm and Maxima code to verify our algebra.

## 2. COMPUTING THE TAYLOR SERIES

In this section, we derive an algorithm for computing the Taylor series of the velocity in Counterexample 1, and provide evidence and an intuitive argument for the divergence of that series. We restrict attention to dimension  $d = 3$ . (We may obtain the velocity for  $d > 3$  from that for  $d = 3$ , simply by setting the  $d - 3$  additional components to zero.) We write the Taylor series at  $t = 0$  of the velocity  $\mathbf{v}$  in the form

$$\mathbf{v}(t) = \begin{pmatrix} t^p u(t) \\ t^q v(t) \end{pmatrix} \quad \text{where} \quad u(t) := \sum_{n=0}^{\infty} u_n t^n, \quad v(t) := \sum_{n=0}^{\infty} v_n t^n \quad (2.1)$$

for some real coefficients  $u_n, v_n$  with  $u_0, v_0 \neq 0$ , and some non-negative integers  $p, q$ .

### 2.1. Solving for the leading orders

First we show that  $p = 3$  and  $q = 4$ . It follows from the initial condition  $\mathbf{v}(0) = 0$  that  $p, q \geq 1$ . Also, for  $\mathbf{v}(t) \neq 0$  differential inclusion (1.1) reads

$$\frac{d}{dt}(t^p u) = 1 - \frac{t^p u}{\sqrt{t^{2p} u^2 + t^{2q} v^2}}, \quad (2.2)$$

$$\frac{d}{dt}(t^q v) = t - \frac{t^q v}{\sqrt{t^{2p} u^2 + t^{2q} v^2}}. \quad (2.3)$$

Substituting the series expansions (2.1) and matching the coefficients of  $t^0$  in (2.3) gives

$$\mathbf{1}_{q=1} v_0 = -\mathbf{1}_{p=q} \frac{v_0}{\sqrt{u_0^2 + v_0^2}} - \mathbf{1}_{p>q} \frac{v_0}{|v_0|},$$

where  $\mathbf{1}_.$  is the indicator function. If  $p = q$ , then this expression cannot be satisfied for  $v_0 \neq 0$ . Thus, we have  $p \neq q$ . Using this fact, matching the coefficients of  $t^0$  in (2.2) gives

$$\mathbf{1}_{p=1}u_0 = 1 - \mathbf{1}_{p < q} \frac{u_0}{|u_0|}.$$

If  $p > q \geq 1$ , then this expression cannot be satisfied. So, we must have  $p < q$ , in which case this expression reads  $\mathbf{1}_{p=1}u_0 = 1 - u_0/|u_0|$ . As this cannot be satisfied for  $p = 1$ , it follows that  $p > 1$  and  $u_0 > 0$ . Matching the coefficients of  $t^1$  in (2.3), and using  $1 < p < q$  (so that  $q \neq 2$ ) gives

$$0 = 1 - \mathbf{1}_{q=p+1} \frac{v_0}{|u_0|},$$

which is only satisfied if  $q = p + 1$  and  $v_0 = |u_0|$ . As  $q = p + 1$ , Taylor expanding each side of (2.2) gives

$$\frac{d}{dt}(t^p u) = p t^{p-1} u_0 + O(t^p) \quad \text{and} \quad 1 - \frac{u}{\sqrt{u^2 + t^2 v^2}} = \frac{v_0^2}{2u_0^2} t^2 + O(t^3) \quad \text{as } t \rightarrow 0.$$

As the terms involving  $t^{p-1}$  and  $t^2$  have non-zero coefficients, they must be equal, and we conclude that

$$p = 3, \quad q = 4, \quad \text{and} \quad u_0 = v_0 = \frac{1}{6}. \quad (2.4)$$

## 2.2. Algorithm

For the values of  $p, q$  in (2.4), functions  $u, v$  should satisfy the differential equations

$$\frac{d}{dt}(t^3 u) = 1 - \frac{u}{\sqrt{u^2 + t^2 v^2}}, \quad \frac{d}{dt}(t^4 v) = t - \frac{tv}{\sqrt{u^2 + t^2 v^2}}.$$

We write these equations in the form

$$d + e = 1, \quad f + g = t, \quad (2.5)$$

in terms of the intermediate functions

$$\begin{aligned} a &= u^2 + t^2 v^2, & b &= \sqrt{a}, & c &= 1/b, \\ d = uc, & e = \frac{d}{dt}(t^3 u), & f = tvc, & g = \frac{d}{dt}(t^4 v). \end{aligned}$$

By the Cauchy product formula, the coefficients of the formal power series  $\sum_{n=0}^{\infty} a_n t^n, \dots, \sum_{n=0}^{\infty} g_n t^n$  of these intermediate functions satisfy

$$\begin{cases} a_n = \sum_{p+q=n} u_p u_q + \sum_{p+q=n-2} v_p v_q, \\ b_n = \sqrt{a_0} \mathbf{1}_{n=0} + \frac{\mathbf{1}_{n \geq 1}}{2b_0} \left( a_n - \sum_{p+q=n, p,q>0} b_p b_q \right), \\ c_n = \frac{\mathbf{1}_{n=0}}{b_0} - \frac{\mathbf{1}_{n \geq 1}}{b_0} \sum_{p+q=n, p>0} b_p c_q, \end{cases} \quad \begin{cases} d_n = \sum_{p+q=n} u_p c_q, \\ e_n = (n+1)u_{n-2}, \\ f_n = \sum_{p+q=n-1} v_p c_q, \\ g_n = (n+1)v_{n-3} \end{cases} \quad (2.6)$$

for  $n \geq 0$ . (In our notation, we sum over pairs of non-negative integers  $p, q$ , so that  $\sum_{p+q=n, p>0} b_p c_q = \sum_{p=1}^n b_p c_{n-p} = \sum_{q=0}^{n-1} b_{n-q} c_q$ , and coefficients with negative indices vanish, so that  $a_0 = u_0^2$  and  $e_0 = 0$ .) Moreover, matching the coefficients of  $t^n$  and  $t^{n-1}$  in (2.5) gives

$$d_n + e_n = \mathbf{1}_{n=0}, \quad f_{n-1} + g_{n-1} = \mathbf{1}_{n=2}. \quad (2.7)$$

The idea of our algorithm is to treat  $u_{n-2}, u_{n-1}, u_n, v_{n-2}$  as unknowns, having already determined values for  $u_p, v_p$  for  $p < n - 2$ . Equation (2.6) then provides expressions for  $a_p, b_p, c_p$  for  $p = n - 2, n - 1, n$  and hence for  $d_n, e_n, f_{n-1}, g_{n-1}$  in terms of those unknowns. Substituting these expressions in (2.7) gives a linear equation for  $u_{n-2}, v_{n-2}$ , which has a unique solution. (As the intermediate expressions for  $c_n, c_{n-1}$  involve  $u_{n-1}, u_n$ , it is interesting that the linear equation does not involve those variables.)

We now apply the idea of the previous paragraph, treating  $n = 3, 4$  and  $n \geq 5$  separately, as the formulas have “special cases” for small  $n$ . (For instance, the sum  $\sum_{p+q=n} u_p u_q$  involves the term  $u_{n-2}^2$  for  $n = 4$  but the corresponding term is  $2u_2 u_{n-2}$  for  $n \geq 5$ .) Full details of the following derivations are given in `algebra.txt` in the supplementary material. For  $n = 3$  and 4, we get the linear equations

$$\begin{pmatrix} d_3 + e_3 \\ f_2 + g_2 \end{pmatrix} = \begin{pmatrix} 10 & -6 \\ -6 & 6 \end{pmatrix} \begin{pmatrix} u_1 \\ v_1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad \begin{pmatrix} d_4 + e_4 \\ f_3 + g_3 \end{pmatrix} = \begin{pmatrix} 11 & -6 \\ -6 & 6 \end{pmatrix} \begin{pmatrix} u_2 \\ v_2 \end{pmatrix} + \begin{pmatrix} 3/8 \\ 1/6 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

with the unique solutions

$$u_1 = 0, \quad v_1 = 0, \quad u_2 = -13/120, \quad v_2 = -49/360. \quad (2.8)$$

For  $n \geq 5$ , we get

$$\begin{pmatrix} d_n + e_n \\ f_{n-1} + g_{n-1} \end{pmatrix} = \begin{pmatrix} n+7 & -6 \\ -6 & 6 \end{pmatrix} \begin{pmatrix} u_{n-2} \\ v_{n-2} \end{pmatrix} - \begin{pmatrix} m_n^u \\ m_n^v \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad (2.9)$$

where

$$\begin{cases} m_n^u := -R_{d_n}^n - (R_{c_{n-2}}^n/2) + R_{c_n}^n + (18/5)(R_{b_{n-2}}^n - R_{a_{n-2}}^n) + 18(R_{a_n}^n - R_{b_n}^n), \\ m_n^v := -nv_{n-4} - R_{f_{n-1}}^n + R_{c_{n-2}}^n + 18(R_{a_{n-2}}^n - R_{b_{n-2}}^n), \end{cases} \quad (2.10)$$

in which the terms  $R_{\cdot}^n$  are the parts of the sums in (2.6) that depend neither on the unknowns  $u_{n-2}, u_{n-1}, u_n, v_{n-2}$ , nor on the quantities  $b_p, c_p$  for  $p = n - 2, n - 1, n$  that involve those unknowns:

$$\begin{cases} R_{a_{n-2}}^n = \sum_{\substack{p+q=n-2 \\ p,q>0}} u_p u_q + \sum_{\substack{p+q=n-4 \\ p,q>0}} v_p v_q, & R_{b_{n-2}}^n = \sum_{\substack{p+q=n-2 \\ p,q>0}} b_p b_q, & R_{c_{n-2}}^n = \sum_{\substack{p+q=n-2 \\ p,q>0}} b_p c_q, \\ R_{a_n}^n = \sum_{\substack{p+q=n \\ p,q>2}} u_p u_q + \sum_{\substack{p+q=n-2 \\ p,q>0}} v_p v_q, & R_{b_n}^n = \sum_{\substack{p+q=n \\ p,q>2}} b_p b_q, & R_{c_n}^n = \sum_{\substack{p+q=n \\ p,q>2}} b_p c_q, \\ R_{d_n}^n = \sum_{\substack{p+q=n \\ p,q>2}} u_p c_q, & R_{f_{n-1}}^n = \sum_{\substack{p+q=n-2 \\ p,q>0}} v_p c_q. \end{cases} \quad (2.11)$$

It turns out that  $u_n, v_n, a_n, b_n, c_n$  vanish for all odd  $n$ . We show this by induction. In the base case, equation (2.8) gives  $u_1 = v_1 = 0$ , so (2.6) gives  $a_1 = b_1 = c_1 = 0$ . Otherwise, suppose  $n - 2$  is odd and that  $u_p, v_p, a_p, b_p, c_p$  vanish for all all odd  $p < n - 2$ . Consider any term of any of the sums  $R_{\cdot}^n$  in (2.11). This term is of the form  $x_p y_q$  for appropriate sequences  $x, y \in \{u, v, b, c\}$ , where one of  $p, q$  is odd and less than  $n - 2$ . It follows from the induction hypothesis that one of the factors  $x_p$  or  $y_q$  vanishes. Thus all the sums  $R_{\cdot}^n$  vanish. It also follows from the induction hypothesis that  $v_{n-4} = 0$ . Thus, equation (2.10) gives  $m_n^u = m_n^v = 0$ , so the linear equation (2.9) has the unique solution  $u_{n-2} = v_{n-2} = 0$ . Examining the sums giving  $a_{n-2}, b_{n-2}, c_{n-2}$  in (2.6), we see that their terms are also of the form  $x_p y_q$ , where one of the factors  $x_p$  or  $y_q$  vanishes. Therefore  $a_{n-2}, b_{n-2}, c_{n-2}$  also vanish. This completes the induction.

In the light of the above discussion, Algorithm 1 computes the coefficients of the Taylor series of the velocity appearing in Counterexample 1.

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**Algorithm 1.** Determining the coefficients of the Taylor series defined in (2.1).

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1: function TAYLORCOEFFICIENTS( $n_{\max}$ )
2:    $u_0, v_0, b_0, c_0 \leftarrow 1/6, 1/6, 1/6, 6$                                  $\triangleright$  Assume  $n_{\max} \geq 2$  is even
3:    $u_2, v_2 \leftarrow -13/120, -49/360$                                           $\triangleright$  By (2.4) and (2.6)
4:    $u_n, v_n, b_n, c_n \leftarrow 0$  for odd  $n < n_{\max}$                                  $\triangleright$  By (2.8)
5:   for  $n = 6, 8, \dots, n_{\max} + 2$  do
6:      $a_{n-4} \leftarrow \sum_{p+q=n-4} u_p u_q + \sum_{p+q=n-6} v_p v_q$                  $\triangleright$  By (2.6)
7:      $b_{n-4} \leftarrow 3(a_{n-4} - \sum_{p+q=n-4, p,q>0} b_p b_q)$ 
8:      $c_{n-4} \leftarrow -6 \sum_{p+q=n-4, p>0} b_p c_q$ 
9:     Compute the sums  $R^n$  defined in (2.11)
10:    Compute  $m_n^u, m_n^v$  as defined in (2.10)
11:     $u_{n-2} \leftarrow (m_n^u + m_n^v)/(n+1), v_{n-2} \leftarrow u_{n-2} + (m_n^v/6)$        $\triangleright$  This solves (2.9)
12:   end for
13:   return  $u_0, v_0, \dots, u_{n_{\max}}, v_{n_{\max}}$ 
14: end function

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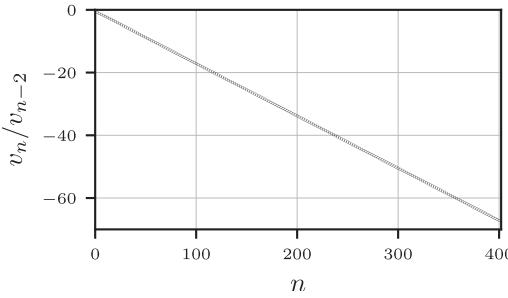


FIGURE 2. The ratio  $v_n/v_{n-2}$  for even  $n$ .

### 2.3. Intuitive argument and numerical evidence for divergence

If  $v_n$  does not vanish for all large enough  $n$ , and each of the sums in (2.11) satisfies  $R^n/v_{n-4} = \text{constant} + O(1/n)$  for even  $n$  as  $n \rightarrow \infty$ , then (2.9) gives

$$\frac{v_{n-2}}{v_{n-4}} = -\frac{n}{6} + \text{constant} + O\left(\frac{1}{n}\right). \quad (2.12)$$

For such a sequence, there is no  $t > 0$  such that  $\sum_{n=0}^{\infty} v_n t^n$  converges.

We implemented the above algorithm using Python's `fractions` module, which provides exact arithmetic for rational numbers, and provide the resulting implementation as `series.py` in the supplementary material. We find the following initial terms of the series:

$$\begin{aligned} u(t) &= \frac{1}{6}t^0 - \frac{13}{120}t^2 + \frac{79}{720}t^4 - \frac{7439}{51840}t^6 + \frac{1289987}{5702400}t^8 - \frac{370576091}{889574400}t^{10} + O(t^{12}) \\ v(t) &= \frac{1}{6}t^0 - \frac{49}{360}t^2 + \frac{23}{144}t^4 - \frac{61297}{259200}t^6 + \frac{7176649}{17107200}t^8 - \frac{772992989}{889574400}t^{10} + O(t^{12}) \end{aligned}$$

as  $t \rightarrow 0$ . Figure 2 plots the ratio  $v_n/v_{n-2}$ , which does indeed decrease nearly linearly, as suggested by (2.12).

### 3. RELATION TO PREVIOUS WORK

Ballard and Basseville [2] argued for the analyticity of the motion of a single particle, under the action of an analytic force and Coulomb friction, and Charles and Ballard [5] extended those arguments to multiple

particles. Both papers apply Lemma 3.4 of [2] to draw this conclusion. This lemma involves a function  $G$  that is hypothesized to be analytic in a neighbourhood of the origin. While both papers claim that the function to which they apply this lemma ( $\tilde{G}$  in [2], p. 70 and  $\tilde{\mathbf{g}}^i$  in [5], p. 13) is analytic in a neighbourhood of the origin, this claim is false in dimension  $d > 2$ , as illustrated in the example below. Moreover, Counterexample 1 shows that it is not possible to circumvent this error: the counterexample directly contradicts the results about the existence of a local analytic solution presented in Proposition 3.5 and Theorem 4.1 of [2] and Proposition 4.1 of [5]. As these existence results are central to the uniqueness arguments presented in Theorem 4.2 of [2] and Theorem 4.2 of [5], the counterexample also invalidates those arguments in dimension  $d > 2$ .

**Example 3.1.** For a single particle  $i$  that is initially at rest but slides immediately thereafter, which is acted on by a tangential force  $\mathbf{F}(t) \in \mathbb{R}^{d-1}$  and normal force  $N(t)$ , the function in Charles and Ballard [5], p. 13 is

$$\tilde{\mathbf{g}}^i(t, \tilde{\mathbf{u}}, \tilde{\mathbf{v}}) := \frac{1}{t^{p_0+1}} \left[ \mathbf{F}(t) - \ddot{\mathbf{S}}_{p_0+2}(t) - \mu|N(t)| \frac{\dot{\mathbf{S}}_{p_0+2}(t) + t^{p_0+1}\tilde{\mathbf{v}}}{\|\dot{\mathbf{S}}_{p_0+2}(t) + t^{p_0+1}\tilde{\mathbf{v}}\|} \right], \quad t \in [0, T], \quad \tilde{\mathbf{u}}, \tilde{\mathbf{v}} \in \mathbb{R}^{d-1},$$

where  $\mathbf{S}_{p_0+2}(t) = \sum_{k=0}^{p_0+2} \mathbf{u}_k t^k$  is the truncated Taylor series for the tangential position of the particle for suitable coefficients  $\mathbf{u}_k \in \mathbb{R}^{d-1}$ , and  $p_0$  is the integer such that  $\dot{\mathbf{S}}_{p_0+2}(t)$  has a single non-zero term. Now, if the force satisfies  $\mathbf{F}(t) = (2, 0)^\top$  and  $\mu|N(t)| = 1$ , then the solution for the tangential velocity is  $\mathbf{v}(t) = (t, 0)^\top$ , so the truncated Taylor series satisfies  $\dot{\mathbf{S}}_{p_0+2}(t) = (t, 0)^\top$  with  $p_0 = 0$ . It follows that

$$\tilde{\mathbf{g}}^i(t, \tilde{\mathbf{u}}, \tilde{\mathbf{v}}) = \frac{1}{t} \left[ \begin{pmatrix} 1 \\ 0 \end{pmatrix} - \frac{\begin{pmatrix} 1 \\ 0 \end{pmatrix} + \tilde{\mathbf{v}}}{\left\| \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \tilde{\mathbf{v}} \right\|} \right],$$

which has a simple pole at  $t = 0$  whenever the second component of  $\tilde{\mathbf{v}}$  does not vanish. Thus  $\tilde{\mathbf{g}}^i$  is not analytic on any neighbourhood of the origin.

## APPENDIX A. PROOF OF COUNTEREXAMPLE 1

The proof is based on Algorithm 1. It is straightforward, but laborious as the algorithm involves many intermediate sums, each of which must be bounded. The file `algebra.txt` in the supplementary material contains computer algebra code for all calculations involved.

Let  $B_p := |b_p|$ ,  $C_p := |c_p|$ ,  $U_p := |u_p|$  and  $V_p := |v_p|$ . The proof proceeds by induction with the hypothesis:

$$H_p : \left\{ \begin{array}{ll} |b_{p-2}/v_{p-6} + 1/6| \leq k_b/(p-2), & \text{where } k_b := 20, \quad \text{if } p \geq 6, \\ |c_{p-2}/v_{p-6} - 6| \leq k_c/(p-2), & \text{where } k_c := 746, \quad \text{if } p \geq 6, \\ B_{p-2} \leq V_{p-2}/4, & \text{if } p \geq 6, \\ C_{p-2} \leq 8V_{p-2}, & \text{if } p \geq 6, \\ |u_p/v_{p-2} + 1| \leq K/p^2, & \text{where } K := 60, \quad \text{if } p \geq 2, \\ |v_p/v_{p-2} + (p+2.9)/6| \leq K_v/p, & \text{where } K_v := 5, \quad \text{if } p \geq 2, \\ U_p \leq V_p, & \text{and} \\ V_{p-2}/V_{p-4} \leq V_p/V_{p-2} & \text{if } p \geq 4. \end{array} \right.$$

We refer to the four lines concerning  $b_{p-2}, c_{p-2}, B_{p-2}, C_{p-2}$  as  $H_p^{bc}$ , and we define the hypothesis

$$H_{\leq n} : \quad n \text{ is even and } H_p \text{ holds for all even } p \text{ with } 0 \leq p \leq n.$$

Before giving the proof itself, we present three lemmas: Lemmas A.1 and A.2 are simple bounds on ratios involving  $V_n$ ; and Lemma A.3 gives upper bounds of the form  $\frac{\text{constant}}{n}$  on the sums defining  $a_n, b_n, c_n$  and  $R^n$ .

**Lemma A.1.** Suppose  $k \geq 6$  and  $n \geq k + 10$  are even integers and that  $H_{\leq n-4}$  holds. Then

$$\frac{V_{n-k}}{V_{n-4}} \leq \prod_{q=4, q \text{ even}}^{k-2} \frac{6}{n-q} =: \rho(n, k).$$

*Proof.* As  $H_{\leq n-4}$  holds, for even  $p$  with  $2 \leq p \leq n-4$ , we have  $\frac{V_p}{V_{p-2}} \geq \frac{p+2.9}{6} - \frac{K_v}{p}$ . For  $p \geq 12$ , the right-hand side is greater than  $p/6$ . As  $12 \leq n-k+2 \leq n-4$ , it follows that

$$\frac{V_{n-k}}{V_{n-4}} = \frac{V_{n-k}}{V_{n-k+2}} \frac{V_{n-k+2}}{V_{n-k+4}} \cdots \frac{V_{n-6}}{V_{n-4}} \leq \frac{6}{n-k+2} \frac{6}{n-k+4} \cdots \frac{6}{n-4}$$

as claimed.  $\square$

**Lemma A.2.** Suppose  $p \geq 182$  is even and  $H_p$  holds. Then  $V_p/V_{p-2} \leq p/5.9$ .

*Proof.* As  $H_p$  holds, we have  $\frac{V_p}{V_{p-2}} \leq \frac{p+2.9}{6} + \frac{K_v}{p}$ . The result follows as  $(\frac{1}{5.9} - \frac{1}{6})p \geq \frac{2.9}{6} + \frac{5}{p}$  for  $p \geq 182$ .  $\square$

The following lemma involves the function

$$S_{\alpha, \beta}^{X, x, Y, y}(n) := \left( \frac{xy}{2} (n_{\min} - \beta - 18) V_{10} \rho(n_{\min}, \beta + 10) + \sum_{p=\alpha+2}^8 (xY_p + yX_p) \rho(n_{\min}, \beta + p) \right) \frac{n_{\min}}{n},$$

in which  $X, Y$  are real sequences,  $x, y$  are real numbers,  $\alpha, \beta, n$  are even integers, and  $\rho(n, k)$  is as in Lemma A.1. We used  $n_{\min} = 200$  to obtain numerical values.

**Lemma A.3.** Suppose that  $(X, x), (Y, y) \in \{(U, 1), (V, 1), (B, 1/4), (C, 8)\}$ , that  $\alpha, \beta \in \{0, 2, 4, 6\}$  with  $\alpha + \beta \geq 4$ , that  $n - 4 \geq 200$ , and that  $H_{\leq n-4}$  holds. Then

$$\sum_{p+q=n-\beta, p, q > \alpha} \frac{X_p Y_q}{V_{n-4}} \leq S_{\alpha, \beta}^{X, x, Y, y}(n).$$

*Proof.* As  $H_{\leq n-4}$  holds, we have  $B_{n-6} \leq V_{n-6}/4$ , and more generally for  $4 \leq p \leq n-6$ , we have

$$X_p \leq xV_p, \quad Y_p \leq yV_p.$$

For the hypothesized  $\alpha, \beta, n$ , it follows that

$$\sum_{p+q=n-\beta, p, q > \alpha} X_p Y_q \leq \sum_{p+q=n-\beta, p, q > \alpha} (X_p \mathbf{1}_{p \leq 8} + xV_p \mathbf{1}_{p > 8})(Y_q \mathbf{1}_{q \leq 8} + yV_q \mathbf{1}_{q > 8}).$$

As  $H_{\leq n-4}$  holds, we have  $V_p/V_{p-2} \leq V_{q+2}/V_q$  for any even integers  $2 \leq p \leq q+2 \leq n-4$ . So for any even integers  $8 < p \leq q+2$  appearing in this sum, we have

$$V_p V_q \leq V_{p-2} V_{q+2} \leq \cdots \leq V_{10} V_{n-\beta-10}.$$

As the sum  $\sum_{p+q=n-\beta, p, q > 8} \cdots$  involves  $(n - \beta - 18)/2$  terms with even  $p$ , it follows that

$$\sum_{p+q=n-\beta, p, q > \alpha} \frac{X_p Y_q}{V_{n-4}} \leq \frac{xy}{2} (n - \beta - 18) \frac{V_{10} V_{n-\beta-10}}{V_{n-4}} + \sum_{p=\alpha+2}^8 (X_p y + xY_p) \frac{V_{n-\beta-p}}{V_{n-4}}. \quad (\text{A.1})$$

By Lemma A.1, we have

$$\frac{V_{n-\beta-p}}{V_{n-4}} \leq \rho(n, \beta + p) \quad \text{for even } \beta + p \text{ with } 6 \leq \beta + p \leq n - 10.$$

As  $\alpha + \beta \geq 4$ , the condition  $6 \leq \beta + p$  applies to all appearances of  $V_{n-\beta-p}$  in (A.1), giving

$$\sum_{p+q=n-\beta, p,q>\alpha} \frac{X_p Y_q}{V_{n-4}} \leq \frac{xy}{2}(n - \beta - 18)V_{10}\rho(n, \beta + 10) + \sum_{p=\alpha+2}^8 (X_p y + x Y_p)\rho(n, \beta + p). \quad (\text{A.2})$$

Let  $f$  be any of the functions  $n \mapsto \rho(n, \beta + p)$  for  $\alpha + 2 \leq p \leq 8$ , or  $n \mapsto (n - \beta - 18)\rho(n, \beta + 10)$ . By the definition of  $\rho$  and the hypotheses on  $\alpha, \beta$ , the function  $nf(n)$  is decreasing for  $n \geq n_{\min}$ . Therefore,  $f(n) \leq n_{\min}f(n_{\min})/n$  for  $n \geq n_{\min}$ . Applying this to (A.2) completes the proof.  $\square$

*Proof of Counterexample 1.* First, we consider the base case,  $H_{\leq 200}$  (in Step 1). Next, we show that if  $n - 4 \geq 200$  and  $H_{\leq n-4}$  holds, then  $H_{n-2}^{bc}$  and  $H_{n-2}$  hold (Steps 2 and 3). Finally, we conclude (Step 4).

**Step 1: Base case ( $H_{\leq 200}$ ).** Our implementation of Algorithm 1, which uses exact arithmetic for rational numbers from Python's `fractions` module, gives

$$\begin{aligned} \max_{6 \leq p \leq 200} (p-2)|b_{p-2}/v_{p-6} + 1/6| &= 1.466 \dots \leq k_b, & \max_{2 \leq p \leq 200} p^2|u_p/v_{p-2} + 1| &= 10.913 \dots \leq K, \\ \max_{6 \leq p \leq 200} (p-2)|c_{p-2}/v_{p-6} - 6| &= 37.089 \dots \leq k_c, & \max_{2 \leq p \leq 200} p|v_p/v_{p-2} + (p+2.9)/6| &= 1.881 \dots \leq K_v, \\ \max_{6 \leq p \leq 200} (p-2)B_{p-2}/V_{p-2} &= 0.043 \dots \leq 1/4, & \max_{0 \leq p \leq 200} U_p/V_p &= 1, \\ \max_{6 \leq p \leq 200} (p-2)C_{p-2}/V_{p-2} &= 1.073 \dots \leq 8, & \max_{4 \leq p \leq 200} V_{p-2}^2/(V_p V_{p-4}) &= 0.990 \dots \leq 1, \end{aligned}$$

in which each maximum is taken only over even values of  $p$ . Therefore  $H_{\leq 200}$  holds. (While one might find a proof involving a “smaller” base case, for instance  $H_{\leq 50}$ , we do not pursue this as we believe it would still require computer algebra.)

**Step 2: Showing that  $H_{\leq n-4} \Rightarrow H_{n-2}^{bc}$ .** Suppose that  $H_{\leq m}$  holds where  $m := n - 4 \geq 200$ . As  $H_m$  holds, we have  $|u_m/v_{m-2} + 1| \leq K/m^2$ , so Lemma A.2 gives

$$\frac{|u_0 u_m + v_0 v_{m-2}|}{V_{m-4}} \leq \left| u_0 \left( \frac{u_m}{v_{m-2}} + 1 \right) - u_0 + v_0 \right| \frac{V_{m-2}}{V_{m-4}} \leq \left( \frac{U_0 K}{m^2} + |v_0 - u_0| \right) \frac{m-2}{5.9} \leq \frac{U_0 K}{5.9m} =: r_{u_m}.$$

Similarly, we have

$$\left| u_2 \frac{u_{m-2}}{v_{m-4}} + v_2 + \frac{1}{36} \right| \leq \frac{U_2 K}{(m-2)^2} + \left| v_2 + \frac{1}{36} - u_2 \right| = \frac{U_2 K}{(m-2)^2} =: r_{u_{m-2}}$$

and Lemma A.1 gives

$$\frac{|u_4 u_{m-4} + v_4 v_{m-6}|}{V_{m-4}} \leq \left( \frac{U_4 K}{(m-4)^2} + |v_4 - u_4| \right) \rho(m, 6) =: r_{u_{m-4}}.$$

So the definition of  $a_m$  in (2.6), Lemma A.3, and the fact that  $m \mapsto m(r_{u_m} + r_{u_{m-2}} + r_{u_{m-4}})$  is decreasing give

$$\left| \frac{a_m}{v_{m-4}} + \frac{1}{18} \right| \leq 2 \frac{|u_0 u_m + v_0 v_{m-2}|}{V_{m-4}} + \left| 2u_2 \frac{u_{m-2}}{v_{m-4}} + 2v_2 + \frac{1}{18} \right| + 2 \frac{|u_4 u_{m-4} + v_4 v_{m-6}|}{V_{m-4}}$$

$$\begin{aligned}
& + \sum_{p+q=m, p,q>4} \frac{U_p U_q}{V_{m-4}} + \sum_{p+q=m-2, p,q>4} \frac{V_p V_q}{V_{m-4}} \\
& \leq \frac{2}{m} [m(r_{u_m} + r_{u_{m-2}} + r_{u_{m-4}})]_{m=200} + S_{4,0}^{U,1,U,1}(m) + S_{4,2}^{V,1,V,1}(m) \leq \frac{6.5}{m}.
\end{aligned} \tag{A.3}$$

As  $H_m$  and  $H_{m-2}$  hold, Lemma A.1 gives

$$\frac{B_{m-2}}{V_{m-4}} \leq \left( \frac{1}{6} + \frac{k_b}{m-2} \right) \rho(m, 6) =: r_{B_{m-2}}, \quad \frac{B_{m-4}}{V_{m-4}} \leq \left( \frac{1}{6} + \frac{k_b}{m-4} \right) \rho(m, 8) =: r_{B_{m-4}}.$$

So the definition of  $b_m$ , inequality (A.3), and Lemma A.3 give

$$\begin{aligned}
\left| \frac{b_m}{v_{m-4}} + \frac{1}{6} \right| & \leq 3 \left( \left| \frac{a_m}{v_{m-4}} + \frac{1}{18} \right| + 2B_2 \frac{B_{m-2}}{V_{m-4}} + 2B_4 \frac{B_{m-4}}{V_{m-4}} + \sum_{p+q=m, p,q>4} \frac{B_p B_q}{V_{m-4}} \right) \\
& \leq 3 \left( \frac{6.5}{m} + \frac{1}{m} [m(2B_2 r_{B_{m-2}} + 2B_4 r_{B_{m-4}})]_{m=200} + S_{4,0}^{B,\frac{1}{4},B,\frac{1}{4}}(m) \right) = \frac{19.8 \dots}{m} \leq \frac{k_b}{m}.
\end{aligned} \tag{A.4}$$

As  $H_m$  and  $H_{m-2}$  hold, Lemma A.1 gives

$$\frac{C_{m-2}}{V_{m-4}} \leq \left( 6 + \frac{k_c}{m-2} \right) \rho(m, 6) =: r_{C_{m-2}}, \quad \frac{C_{m-4}}{V_{m-4}} \leq \left( 6 + \frac{k_c}{m-4} \right) \rho(m, 8) =: r_{C_{m-4}},$$

so that

$$\begin{aligned}
\left| \frac{c_m}{v_{m-4}} - 6 \right| & \leq 6 \left( \left| \frac{c_0 b_m}{v_{m-4}} - 1 \right| + B_2 \frac{C_{m-2}}{V_{m-4}} + C_2 \frac{B_{m-2}}{V_{m-4}} + B_4 \frac{C_{m-4}}{V_{m-4}} + C_4 \frac{B_{m-4}}{V_{m-4}} + \sum_{p+q=m, p,q>4} \frac{B_p C_q}{V_{m-4}} \right) \\
& \leq 6 \left( \frac{6k_b}{m} + \frac{1}{m} [m(B_2 r_{C_{m-2}} + C_2 r_{B_{m-2}} + B_4 r_{C_{m-4}} + C_4 r_{B_{m-4}})]_{m=200} + S_{4,0}^{B,\frac{1}{4},C,\frac{1}{4}}(m) \right) \\
& = \frac{745.2 \dots}{m} \leq \frac{k_c}{m}.
\end{aligned} \tag{A.5}$$

Applying Lemma A.1 to inequalities (A.4) and (A.5) gives

$$\frac{B_m}{V_m} \leq \left[ \left( \frac{1}{6} + \frac{k_b}{m} \right) \frac{6}{m-2} \right]_{m=200} \frac{6}{m} \leq \frac{0.05}{m} \leq \frac{1}{4}, \quad \frac{C_m}{V_m} \leq \left[ \left( 6 + \frac{k_c}{m} \right) \frac{6}{m-2} \right]_{m=200} \frac{6}{m} \leq \frac{1.8}{m} \leq 8. \tag{A.6}$$

Together inequalities (A.4)–(A.6) imply that  $H_{n-2}^{bc}$  holds.

**Step 3: Showing that  $H_{\leq n-4} \Rightarrow H_{n-2}$ .** Suppose  $n-4 \geq 200$  and that  $H_{\leq n-4}$  holds. We now bound the sums  $R^n$  defined in (2.11). Lemma A.1 gives

$$\begin{aligned}
|u_4 u_{n-4} + v_4 v_{n-6} + u_6 u_{n-6}| \frac{1}{V_{n-4}} & \leq \left( |u_4 - v_4| + U_4 \frac{K}{(n-4)^2} + U_6 \left( 1 + \frac{K}{(n-6)^2} \right) \frac{6}{n-6} \right) \frac{6}{n-4} =: T_1^n, \\
|u_2 u_{n-4} + v_2 v_{n-6} + u_4 u_{n-6}| \frac{1}{V_{n-4}} & \leq \left( |u_2 - v_2| + U_2 \frac{K}{(n-4)^2} + U_4 \left( 1 + \frac{K}{(n-6)^2} \right) \frac{6}{n-6} \right) \frac{6}{n-4} =: T_2^n, \\
\frac{U_{n-4}}{V_{n-4}} & \leq \left( 1 + \frac{K}{(n-4)^2} \right) \frac{6}{n-4} =: T_3^n,
\end{aligned}$$

and the penultimate steps of (A.6) give

$$\frac{B_{n-4}}{V_{n-4}} \leq \frac{0.05}{n-4} =: T_4^n, \quad \frac{C_{n-4}}{V_{n-4}} \leq \frac{1.8}{n-4} =: T_5^n.$$

Applying Lemma A.3 to the sums in the following expressions, we obtain

$$\begin{aligned}
\left| \frac{R_{a_n}^n}{v_{n-4}} + \frac{49}{180} \right| &\leq 2T_1^n + \sum_{p+q=n, p,q>6} \frac{U_p U_q}{V_{n-4}} + \left| 2v_2 + \frac{49}{180} \right| + \sum_{p+q=n-2, p,q>4} \frac{V_p V_q}{V_{n-4}} \leq \frac{1.33\cdots}{n}, \\
\left| \frac{R_{a_{n-2}}^n}{v_{n-4}} - \frac{1}{3} \right| &\leq 2T_2^n + \sum_{p+q=n-2, p,q>4} \frac{U_p U_q}{V_{n-4}} + \left| 2v_0 - \frac{1}{3} \right| + \sum_{p+q=n-4, p,q>2} \frac{V_p V_q}{V_{n-4}} \leq \frac{0.519\cdots}{n}, \\
\left| \frac{R_{b_n}^n}{v_{n-4}} \right| &\leq 2B_4 T_4^n + \sum_{p+q=n, p,q>4} \frac{B_p B_q}{V_{n-4}} \leq \frac{0.035\cdots}{n}, \\
\left| \frac{R_{b_{n-2}}^n}{v_{n-4}} \right| &\leq 2B_2 T_4^n + \sum_{p+q=n-2, p,q>2} \frac{B_p B_q}{V_{n-4}} \leq \frac{0.024}{n}, \\
\left| \frac{R_{c_n}^n}{v_{n-4}} \right| &\leq B_4 T_5^n + C_4 T_4^n + \sum_{p+q=n, p,q>4} \frac{B_p C_q}{V_{n-4}} \leq \frac{1.23\cdots}{n}, \\
\left| \frac{R_{c_{n-2}}^n}{v_{n-4}} \right| &\leq B_2 T_5^n + C_2 T_4^n + \sum_{p+q=n-2, p,q>2} \frac{B_p C_q}{V_{n-4}} \leq \frac{0.645\cdots}{n}, \\
\left| \frac{R_{d_n}^n}{v_{n-4}} \right| &\leq C_4 T_3^n + U_4 T_5^n + \sum_{p+q=n, p,q>4} \frac{U_p C_q}{V_{n-4}} \leq \frac{12.765\cdots}{n}, \\
\left| \frac{R_{f_{n-1}}^n}{v_{n-4}} - \frac{9}{10} \right| &\leq \left| c_2 - \frac{9}{10} \right| + V_2 T_5^n + \sum_{p+q=n-2, p,q>2} \frac{V_p C_q}{V_{n-4}} \leq \frac{9.295\cdots}{n}.
\end{aligned}$$

As the solution to linear equation (2.9) for  $u_{n-2}$  is

$$\begin{aligned}
u_{n-2} &= \frac{m_n^u + m_n^v}{n+1} \\
&= \frac{1}{n+1} \left( -nv_{n-4} - R_{f_{n-1}}^n - R_{d_n}^n + \frac{1}{2} R_{c_{n-2}}^n + R_{c_n}^n - \frac{72}{5} R_{b_{n-2}}^n - 18R_{b_n}^n + \frac{72}{5} R_{a_{n-2}}^n + 18R_{a_n}^n \right)
\end{aligned}$$

and we have  $\frac{9}{10} - \frac{72}{5} \times \frac{1}{3} + \frac{49}{10} = 1$ , substituting the above bounds on  $R^n$  gives

$$\begin{aligned}
\left| \frac{u_{n-2}}{v_{n-4}} + 1 \right| &\leq \frac{1}{n+1} \left( \left| \frac{R_{f_{n-1}}^n}{v_{n-4}} - \frac{9}{10} \right| + \left| \frac{R_{d_n}^n}{v_{n-4}} \right| + \frac{1}{2} \left| \frac{R_{c_{n-2}}^n}{v_{n-4}} \right| + \left| \frac{R_{c_n}^n}{v_{n-4}} \right| + \frac{72}{5} \left| \frac{R_{b_{n-2}}^n}{v_{n-4}} \right| + 18 \left| \frac{R_{b_n}^n}{v_{n-4}} \right| \right. \\
&\quad \left. + \frac{72}{5} \left| \frac{R_{a_{n-2}}^n}{v_{n-4}} - \frac{1}{3} \right| + 18 \left| \frac{R_{a_n}^n}{v_{n-4}} + \frac{49}{180} \right| \right) \\
&= \frac{56.06\cdots}{n(n+1)} \leq \frac{K}{(n-2)^2}.
\end{aligned} \tag{A.7}$$

Similarly, the solution for  $v_{n-2}$  is

$$v_{n-2} = u_{n-2} + \frac{m_n^v}{6}, \quad \text{where} \quad m_n^v = -nv_{n-4} - R_{f_{n-1}}^n + R_{c_{n-2}}^n + 18(R_{a_{n-2}}^n - R_{b_{n-2}}^n),$$

and substituting the above bounds on  $R^n$  and  $u_{n-2}$  into this expression gives

$$\begin{aligned}
\left| \frac{v_{n-2}}{v_{n-4}} + \frac{n-2+2.9}{6} \right| &\leq \left| \frac{u_{n-2}}{v_{n-4}} + 1 \right| + \left| -1 + \frac{1}{6} \left( \frac{m_n^v}{v_{n-4}} + n+0.9 \right) \right| \\
&\leq \frac{K}{(n-2)^2} + \frac{1}{6} \left( \left| \frac{R_{f_{n-1}}^n}{v_{n-4}} - \frac{9}{10} \right| + \left| \frac{R_{c_{n-2}}^n}{v_{n-4}} \right| + 18 \left| \frac{R_{a_{n-2}}^n}{v_{n-4}} - \frac{1}{3} \right| + 18 \left| \frac{R_{b_{n-2}}^n}{v_{n-4}} \right| \right)
\end{aligned}$$

$$= \frac{3.59 \dots}{n} \leq \frac{K_v}{n-2}. \quad (\text{A.8})$$

Coupling inequalities (A.7) and (A.8) gives

$$\frac{U_{n-2}}{V_{n-4}} \leq 1 + \frac{K}{(n-2)^2} \leq \frac{n-2+2.9}{6} - \frac{K_v}{n-2} \leq \frac{V_{n-2}}{V_{n-4}}. \quad (\text{A.9})$$

As inequality (A.8) holds, we may argue as in Lemmas A.2 and A.1 to get

$$\frac{V_{n-2}}{V_{n-4}} \geq \frac{n-2}{5.9} \geq \frac{n-4}{6} \geq \frac{V_{n-4}}{V_{n-6}}. \quad (\text{A.10})$$

As  $H_{n-2}^{bc}$  holds (Step 2), inequalities (A.7)–(A.10) imply  $H_{n-2}$  holds, completing the induction.

**Step 4: Conclusion.** As  $H_p$  holds for all even  $p$ , we have

$$\lim_{p \rightarrow \infty, p \text{ even}} \left| \frac{v_p t^p}{v_{p-2} t^{p-2}} \right| = \lim_{p \rightarrow \infty} \frac{p+2.9}{6} t^2 = \infty$$

for any  $t \neq 0$ . By d'Alembert's ratio test, it follows that the series  $\sum_{p=0, p \text{ even}}^{\infty} v_p t^p$  diverges for all non-zero  $t$ . Therefore this series is not the Taylor series at  $t = 0$  of an analytic function. This completes the proof.  $\square$

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