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# The Wouthuysen Equation

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## Abstract

**Dedication.** I dedicate this paper to Prof. P.C. Baayen, at the occasion of his retirement on 20 December 1994. The beautiful equation which forms the subject matter of this paper was invented by Wouthuysen after he retired.

The four complex variable Wouthuysen equation arises from an original space-time lattice approach to spinor waves and elementary particles. Here the complete space of solutions is described. It consists of one isolated point and one branched  $S_4$ -covering-space over the circle with 8 branching points of order 6, 24 branching points of order 4 and 12 "turning points". The 24 branching points of order 4 are also turning points for two of the four branches.

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## 1. THE EQUATIONS

The equations are for four complex variables of unit norm

$$\begin{aligned} 2 - (z_1^2 + z_2^2 + z_3^2 + z_4^2) - (z_1 + z_2 + z_3 + z_4) \\ + (z_1 z_2 + z_1 z_3 + z_1 z_4 + z_2 z_3 + z_2 z_4 + z_3 z_4) = 0 \end{aligned} \tag{1.1}$$

$$\|z_1\| = \|z_2\| = \|z_3\| = \|z_4\| = 1 \tag{1.2}$$

with in addition a stationary phase condition

$$z_1 z_2 z_3 z_4 = 1 \tag{1.3}$$

In terms of real parameters. There are 8 parameters and (1.1), (1.2) together give 6 conditions (2 from (1.1) and 1 each from  $\|z_i\| = 1$ ,  $i = 1, \dots, 4$ ). Given (1.2), (1.3) only gives one extra condition. So by equation counting one could expect 1-dimensional families of solutions. This does indeed turn out to be the case.

Note that the equations (1.1) - (1.3) are symmetric in  $z_1, z_2, z_3, z_4$ . So there is a natural action of the symmetric group on 4 letters,  $S_4$ , and the solutions fall into  $S_4$ -orbits.

## 2. A NUMBER OF SPECIAL SOLUTIONS

*2.1 Solutions with at least one  $z_i$  equal to 1.* These are

$$(1, 1, 1, 1), \text{ a single solution invariant under } S_4 \quad (2.2)$$

$$(1, \zeta_3, \zeta_3, \zeta_3), (\zeta_3, 1, \zeta_3, \zeta_3), (\zeta_3, \zeta_3, 1, \zeta_3), (\zeta_3, \zeta_3, \zeta_3, 1) \quad (2.3)$$

$$(1, \zeta_3^2, \zeta_3^2, \zeta_3^2), (\zeta_3^2, 1, \zeta_3^2, \zeta_3^2), (\zeta_3^2, \zeta_3^2, 1, \zeta_3^2), (\zeta_3^2, \zeta_3^2, \zeta_3^2, 1) \quad (2.4)$$

Here  $\zeta_3 = -\frac{1}{2} + \frac{1}{2}i\sqrt{3}$  is a primitive 3-rd root of unity. These form two  $S_4$ -orbits of size 4 each.

$$(1, 1, \zeta_3, \zeta_3^2), (1, 1, \zeta_3^2, \zeta_3), (1, \zeta_3, 1, \zeta_3^2), (1, \zeta_3^2, 1, \zeta_3) \quad (2.5)$$

$$(1, \zeta_3, \zeta_3^2, 1), (1, \zeta_3^2, \zeta_3, 1), (\zeta_3, 1, 1, \zeta_3^2), (\zeta_3^2, 1, 1, \zeta_3)$$

$$(\zeta_3, 1, \zeta_3^2, 1), (\zeta_3^2, 1, \zeta_3, 1), (\zeta_3, \zeta_3^2, 1, 1), (\zeta_3^2, \zeta_3, 1, 1)$$

This set of solutions forms a single  $S_4$  orbit of size 12. As it turns out (2.2) - (2.5) are the only solutions with at least one  $z_i = 1$ ; see section 3 below for details.

### 2.6 Solutions with additional symmetry (besides those in 2.1)

$$z_i = \pm \frac{1}{3}\sqrt{3} \pm \frac{1}{3}j\sqrt{6}, \quad j = \sqrt{-1} \quad (2.7)$$

This solution satisfies (up to permutations),  $z_2 = -z_1$ ,  $z_4 = -z_3$  and is in fact the only solution with the property. It also satisfies (up to permutations),  $z_2 = \bar{z}_1$ ,  $z_4 = \bar{z}_3$ .

$$\begin{aligned} z_{1,2} &= \left(-\frac{1}{8} + \frac{3}{8}\sqrt{5}\right) \pm j\left(\frac{1}{8}\sqrt{15} + \frac{1}{8}\sqrt{3}\right), \\ z_{3,4} &= \left(-\frac{1}{8} - \frac{3}{8}\sqrt{5}\right) \pm j\left(\frac{1}{8}\sqrt{15} - \frac{1}{8}\sqrt{3}\right) \end{aligned} \quad (2.8)$$

(up to permutation). This solution also has  $\bar{z}_2 = z_1$ ,  $\bar{z}_4 = z_3$  and there is in fact, besides (2.2), (up to permutation) one one-dimensional family of such solutions on which both (2.7) and (2.8) are located.

### 2.9 Solutions with $z_1 + z_2 + z_3 + z_4 = 0$

Under this additional condition  $(z_1 + \dots + z_4)^2 = 0$ , so  $z_1^2 + \dots + z_4^2 = -2(z_1z_2 + \dots + z_3z_4)$ , so

$$z_1z_2 + \dots + z_3z_4 = -\frac{2}{3} \quad (2.10)$$

Also, using  $z_1z_2z_3z_4 = 1$ ,  $z_1z_2z_3 + z_1z_3z_4 + z_1z_2z_4 + z_2z_3z_4 = z_4^{-1} + z_2^{-1} + z_3^{-1} + z_1^{-1} = \bar{z}_4 + \bar{z}_2 + \bar{z}_3 + \bar{z}_1 = 0$  because  $\|z_i\| = z_i\bar{z}_i = 1$ . Hence  $z_1z_2z_3 + z_1z_2z_4 + z_1z_3z_4 + z_2z_3z_4 = 0$ . Thus the  $z_1, \dots, z_4$  are solutions of the equation

$$z^4 - \frac{2}{3}z^2 + 1 = 0 \quad (2.11)$$

The solutions of this are

$$\frac{1}{3} \pm \frac{2}{3}j\sqrt{2} \quad (2.12)$$

and so the  $z_1, z_2, z_3, z_4$  are equal to

$$\pm \sqrt{\frac{1}{3} \pm \frac{2}{3}\sqrt{2}} = \pm \frac{1}{3}\sqrt{3} \pm \frac{1}{3}i\sqrt{6} \quad (2.13)$$

which is again the special solution (2.7).

#### 2.14 Solutions with at least one $z_i$ equal to $-1$ .

There are (up to permutations) three solutions with at least one  $z_i = -1$ . These are

$$z_1 = z_2 = -1, \quad z_{3,4} = (7 + \sqrt{33})^{-1}(3 + \sqrt{33} \pm 2j\sqrt{10 + 2\sqrt{33}}) \quad (2.15)$$

making up one  $S_4$ -orbit of size 12, and

$$-1, \zeta_6^5 = \frac{1}{2} - \frac{1}{2}j\sqrt{3}, \frac{1}{2}\sqrt{3} + \frac{1}{2}j, -\frac{1}{2}\sqrt{3} - \frac{1}{2}j \quad (2.16)$$

$$-1, \zeta_6 = \frac{1}{2} + \frac{1}{2}j\sqrt{3}, \frac{1}{2}\sqrt{3} - \frac{1}{2}j, -\frac{1}{2}\sqrt{3} + \frac{1}{2}j \quad (2.17)$$

and all permutations (making up two complex conjugate  $S_4$  orbits of size 24 each).

### 3. SOLUTIONS WITH AT LEAST ONE $z_i$ EQUAL TO 1.

Permuting the  $z_i$  if necessary, assume  $z_1 = 1$ . Then (1.1) reduces to

$$z_2^2 + z_3^2 + z_4^2 = z_2z_3 + z_2z_4 + z_3z_4 \quad (3.1)$$

This scales. So take  $z = z_2$  and consider

$$1 + z_3^2 + z_4^2 = z_3 + z_4 + z_3z_4 \quad (3.2)$$

Let  $w_3 = z_3 - 1$ ,  $w_4 = z_4 - 1$ . Then (3.2) turns into

$$w_3^2 + w_4^2 = w_3w_4 \quad (3.3)$$

This scales again. So consider

$$1 + w_4^2 = w_4 \quad (3.4)$$

which has the solutions

$$w_4 = \frac{1}{2} \pm \frac{1}{2}j\sqrt{3} = \zeta_6, \zeta_6^5 \quad (3.5)$$

where  $\zeta_6 = \frac{1}{2} + \frac{1}{2}j\sqrt{3}$  is a 6-th root of unity. Thus the solutions of (3.2) are of the form

$$z_3 = 1 + w, \quad z_4 = 1 + w\zeta_6, \quad w \in \mathbb{C} \quad (3.6)$$

(including  $w = 0$ ). And those of (3.3) are

$$w_3 = w, \quad w_4 = w\zeta_6 \quad (3.7)$$

From (3.7) it follows that  $w_4$  and  $w_3$  make an angle of  $60^\circ$  with one another, and that they are of equal length. For  $z_3 = 1 + w_3$ ,  $z_4 = 1 + w_4$  to be on the unit circle,  $w_3$  and  $w_4$  must be on the circle of radius 1 with centre at  $-1$ . Hence they must be conjugate and it readily follows that the only

possibilities are

$$w_3, w_4 = -\frac{3}{2} \pm j\sqrt{3} \quad \text{or} \quad w_3, w_4 = 0$$

(e.g. because the triangle formed by  $0, w_3, w_4$  must have all sides equal) and hence there are only the three possibilities

$$\zeta_3 = \zeta_3, \quad z_4 = \zeta_3^2; \quad z_3 = \zeta_3^2, \quad z_4 = \zeta_3; \quad z_3 = z_4 = 1$$

Thus the possible solutions of (3.1) are

$$(z_2, z_3, z_4) = (z, z, z), (z, \zeta_3 z, \zeta_3^2 z), (z, \zeta_3^2 z, \zeta_3 z)$$

and the solutions of (1.1) - (1.2) with at least one  $z_i$  equal to 1 are (up to permutations):

$$(1, z, z, z), \quad z \in \mathbb{C}; \quad (1, z, \zeta_3 z, \zeta_3^2 z), \quad z \in \mathbb{C}; \quad (1, z, \zeta_3^2 z, \zeta_3 z), \quad z \in \mathbb{C}$$

The requirement (1.3),  $z_1 z_2 z_3 z_4 = 1$ , translates in all these cases to  $z = 1, \zeta_3, \zeta_3^2$  and putting this in gives the 4 solution orbits (2.2) - (2.5) listed above.

#### 4. SOLUTIONS WITH NO $z_i$ EQUAL TO 1.

To study the solutions of (1.1) - (1.3) for which no  $z_i$  is equal to 1, first use the transformation

$$w_i = z_i - 1, \quad i = 1, 2, 3, 4 \quad (4.1)$$

(which has already proved to be useful above). This turns equation (1.1) into

$$w_1^2 + w_2^2 + w_3^2 + w_4^2 = w_1 w_2 + w_1 w_3 + w_1 w_4 + w_2 w_3 + w_2 w_4 + w_3 w_4 \quad (4.2)$$

The second tool is the Cayley transform  $\phi: \mathbb{R} \rightarrow S^1 = \{z \in \mathbb{C} : \|z\| = 1\}$  given by

$$\phi(r) = \frac{r - j}{r + j}, \quad j = \sqrt{-1} \quad (4.3)$$

This mapping is 1-1 and onto  $S^1 \setminus \{1\}$ .

Let

$$z_i = \frac{r_i - j}{r_i + j}, \quad i = 1, \dots, 4 \quad (4.4)$$

Then

$$w_i = \frac{-2j}{r_i + j}, \quad i = 1, \dots, 4 \quad (4.5)$$

Set

$$w_i = r_i + j, \quad i = 1, \dots, 4 \quad (4.6)$$

Then the equation (4.2) becomes

$$v_1^{-2} + v_2^{-2} + v_3^{-2} + v_4^{-2} = v_1^{-1}v_2^{-1} + v_1^{-1}v_3^{-1} + \dots + v_3^{-1}v_4^{-1} \quad (4.7)$$

Multiply this with  $v_1^2 v_2^2 v_3^2 v_4^2$ , to obtain

$$v_2^2 v_3^2 v_4^2 + v_1^2 v_3^2 v_4^2 + v_1^2 v_2^2 v_4^2 + v_1^2 v_2^2 v_3^2 = v_1 v_2 v_3 v_4 (v_3 v_4 + \dots + v_1 v_2) \quad (4.8)$$

Let  $e_1, e_2, e_3, e_4$  be the elementary symmetric functions in the  $v_1, \dots, v_4$ ; i.e.

$$\begin{aligned} e_1 &= v_1 + v_2 + v_3 + v_4, \quad e_2 = v_1 v_2 + \dots + v_3 v_4, \\ e_3 &= v_1 v_2 v_3 + \dots + v_2 v_3 v_4, \quad e_4 = v_1 v_2 v_3 v_4 \end{aligned} \quad (4.9)$$

Then (4.8) becomes

$$e_3^2 = 3e_2 e_4 \quad (4.10)$$

Now let  $f_1, f_2, f_3, f_4$  be the elementary symmetric functions in the  $r_1, r_2, r_3, r_4$ , i.e.  $f_1 = r_1 + r_2 + r_3 + r_4$ , etc. Then

$$e_1 = f_1 + 4j, \quad e_2 = f_2 + 3j f_1 - 6 \quad (4.11)$$

$$e_3 = f_3 + 2j f_2 - 3f_1 - 4j, \quad e_4 = f_4 + j f_3 - f_2 - j f_1 + 1.$$

Putting this into (4.10) gives the following equations for the  $f_1, f_2, f_3, f_4$

$$\begin{aligned} f_3^2 + 3f_1 f_3 - f_2^2 - 5f_2 + 2 - 3f_2 f_4 + 18f_4 &= 0 \\ f_2 f_3 + 10f_3 - 3f_1 - 9f_1 f_4 &= 0 \end{aligned} \quad (4.12)$$

Now

$$z_1 z_2 z_3 z_4 = \frac{(r_1 - j)(r_2 - j)(r_3 - j)(r_4 - j)}{(r_1 + j)(r_2 + j)(r_3 + j)(r_4 + j)} \quad (4.13)$$

Let

$$w = (r_1 - j)(r_2 - j)(r_3 - j)(r_4 - j) = f_4 - j f_3 - f_2 + j f_1 + 1 \quad (4.14)$$

By (4.13), equation (1.3) means  $\bar{w} = w$  and by (4.14) this means

$$f_1 = f_3 \quad (4.15)$$

Putting this in (4.12) we see that there are two possibilities

$$f_1 = f_3 = 0 \quad (4.16A)$$

$$f_2 = 9f_4 - 7 \quad (4.16B)$$

In case A, the first equation of (4.12) becomes



$$f_2^2 + (5 + 3f_4)f_2 - (18f_4 + 2) = 0 \quad (4.17A)$$

and in case B, the first equation of (4.12) becomes

$$f_1^2 = 27f_4^2 - 30f_4 + 3 = 3(9f_4 - 1)(f_4 - 1) \quad (4.17B)$$

So, to find all solutions of (1.1) - (1.3) for which no  $z_i$  is equal to 1 it is necessary and sufficient to consider the equation

$$r^4 + f_1r^3 + f_2r^2 + f_3r + f_4 = 0 \quad (4.18)$$

under the conditions

$$\text{Family A : } f_1 = f_3 = 0 \text{ and } f_2^2 + (5 + 3f_4)f_2 - (18f_4 + 2) = 0$$

$$\text{Family B : } f_1 = f_3, f_2 = 9f_4 - 7, f_1^2 = 27f_4^2 - 30f_4 + 3 = 3(9f_4 - 1)(f_4 - 1)$$

and to find out for which cases all four roots of (4.18) are real.

To conclude this section let's find out whether the families A and B can intersect. For an intersection we have  $f_1 = 0 = f_3$  and, hence from (4.17B),  $f_4 = 1/9, f_2 = -6; f_4 = 1, f_2 = 2$  Then and only then are all four of (4.16) - (4.17) satisfied.

If  $f_4 = 1, f_2 = 2, f_1 = f_3 = 0$ , The solutions of (4.18) are

$$j, j, -j, -j \quad (4.19)$$

i.e. two pairs of coinciding non real solutions. This gives no solution to the Wouthuysen equation, but will still be usefull later.

If  $f_4 = 1/9, f_2 = -6, f_1 = f_3 = 0$ , the solutions of (4.18) are

$$\pm\left(\frac{1}{3}\sqrt{15} + \frac{2}{3}\sqrt{3}\right), \pm\left(\frac{1}{3}\sqrt{15} - \frac{2}{3}\sqrt{3}\right) \quad (4.20)$$

which are all four real and which give the special solution (2.8):

$$\begin{aligned} z_{1,2} &= \left(-\frac{1}{8} + \frac{3}{8}\sqrt{15}\right) \pm j\left(\frac{1}{8}\sqrt{15} + \frac{1}{8}\sqrt{3}\right), \\ z_{3,4} &= \left(-\frac{1}{8} - \frac{3}{8}\sqrt{15}\right) \pm j\left(\frac{1}{8} - \frac{3}{8}\sqrt{15}\right) \end{aligned} \quad (4.21)$$

## 5. THE FAMILY A

In this case the equation becomes

$$r^4 + f_2r^2 + f_4 = 0.$$

with

$$f_2^2 + (5 + 3f_4)f_2 - (18f_4 + 2) = 0 \quad (5.2)$$

We shall use  $f_4$  as the main parameter. This will turn out to be the right choice, even though (5.2) suggests that  $f_2$  might be easier to work with.

For (5.1) to have four real roots, it is necessary and sufficient that  $f_4 \geq 0$ ,  $f_2 \leq 0$ ,  $f_2^2 \geq 4f_4$  (besides  $f_2$  real). The conditions  $f_4 \geq 0$  and  $f_2 \leq 0$  imply that only the solution

$$f_2 = -\frac{5}{2} - \frac{3}{2}f_4 - \frac{1}{2}\sqrt{9f_4^2 + 132f_4 + 33} \quad (5.3)$$

of (5.2) qualifies. If  $f_2$  is given by (5.3) then

$$f_2^2 \geq \frac{1}{4}(9f_4^2 + 132f_4 + 33) > 4f_4$$

So, the family A consists of precisely one family of solutions parametrized by  $f_4 \geq 0$ . Because  $f_2^2 > f_4$ , the two solutions of

$$y^2 + f_2y + f_4 = 0 \quad (5.4)$$

are unequal. So the only case in which the four solutions of (5.1) can have two or more equal is when  $f_4 = 0$ . Then

$$r_1 = r_2 = 0, \quad r_{3,4} = \pm \frac{1}{2} \sqrt{10 + 2\sqrt{33}} \quad (5.5)$$

corresponding to the special solution (2.10) of the Wouthuysen equations.

## 6. THE FAMILY B

In this case the equation becomes

$$r^4 + f_1r^3 + f_2r^2 + f_1r + f_4 = 0 \quad (6.1)$$

subject to following conditions on the coefficients

$$f_2 = 9f_4 - 7, \quad f_1^2 = 3(f_4 - 1)(9f_4 - 1) \quad (6.2)$$

and the question is when (6.1) will have all solutions real. This certainly requires  $f_1$  to be real, which by (6.2) implies that  $f_4 \leq 1/9$ , or  $f_4 \geq 1$ . Thus there are four subfamilies to be considered

$$f_4 \geq 1, \quad f_1 = \sqrt{27f_4^2 - 30f_4 + 3} \quad (B1)$$

$$f_4 \geq 1, \quad f_1 = -\sqrt{27f_4^2 - 30f_4 + 3} \quad (B2)$$

$$f_4 \leq \frac{1}{9}, \quad f_1 = \sqrt{27f_4^2 - 30f_4 + 3} \quad (B3)$$

$$f_4 \leq \frac{1}{9}, \quad f_1 = -\sqrt{27f_4^2 - 30f_4 + 3} \quad (\text{B4})$$

Under  $(r_1, r_2, r_3, r_4) \mapsto (-r_1, -r_2, -r_3, -r_4)$ ,  $f_2$  and  $f_4$  remain the same and  $f_1$  and  $f_3$  change sign. Hence (B1) (for a given value of  $f_4$ ) gives four real solutions iff (B2) does so (for the same value of  $f_4$ ). Similarly for (B3) and (B4). Thus it suffices to examine (B3) and (B1).

The discriminant of (6.1) is equal to

$$D = \prod_{i < k} (r_i - r_k)^2 \quad (\text{6.3})$$

where  $r_1, r_2, r_3, r_4$  are the four roots of (6.1). It turns out that under (6.2)

$$D = -2^{10}(2f_4^3 - 7f_2^2 + 8f_4 - 3) = -2^{10}(f_4 - 1)^2(2f_4 - 3). \quad (\text{6.4})$$

This is a substantial calculation but it is less surprising than it maybe looks. First,  $D$  is of course a polynomial in the  $f_1, f_2, f_3, f_4$  and it is homogeneous of degree 12 where  $f_i$  has weight  $i$ ,  $i = 1, \dots, 4$ . Under  $r_i \mapsto -r_i$ ,  $i = 1, \dots, 4$ ,  $D$  remains invariant. As  $f_1, f_3$  change sign under  $r_i \mapsto -r_i$  and  $f_2, f_4$  remain invariant,  $f_1$  and  $f_3$  can only occur in the monomials in  $D$  in the forms  $f_1^2, f_1 f_3, f_3^2$ . However, the substitutions (6.2) are not homogeneous so that the degree could become as high as 12. The monomials in the discriminant of a fourth degree polynomial are of maximal degree 6 in  $f_1, f_3$  combined. Thus a polynomial of degree 6 in  $f_4$  could occur. A final drop in degree of 3 occurs because there are three coinciding roots at  $f_4 = \infty$ . Finally because there are coinciding roots of (6.1) at  $f_4 = 1$  one of the roots of  $D$  must be 1.

For the subfamily (B3) (and (B4)) we have that at  $f_4 = 1/9$  there are four different real solutions, see (4.20). Because  $D \neq 0$  for  $-\infty < f_4 < 1/9$ , this must remain so for the whole family. Thus (B3) and (B4) represent two one dimensional families of solutions to the Wouthuysen equations parametrized by  $f_4 \leq \frac{1}{9}$ .

For  $f_4 \geq 1$ , i.e. the families (B1) and (B2),  $D = 0$  at  $f_4 = 3/2$ . For this value of  $f_4$  (6.1) becomes (for (B1))

$$r^4 + \frac{5}{2}\sqrt{3} r^3 + 6\frac{1}{2} r^2 + \frac{5}{2} \sqrt{3} r + \frac{3}{2} = 0 \quad (\text{6.5})$$

with the solutions

$$-\sqrt{3}, -\sqrt{3}, -\frac{1}{4}\sqrt{3} + \frac{1}{4}j\sqrt{5}, -\frac{1}{4}\sqrt{3} - \frac{1}{4}j\sqrt{5} \quad (\text{6.6})$$

At  $f_4 = 1$ , equation (6.1) has four non real solutions, viz.  $j, j, -j, -j$ . So for  $1 < f_4 < 3/2$ , it remains the case that (6.1) has four non real solutions (because for this to change  $D$  must assume the value zero). As  $D \neq 0$  for  $3/2 < f_4 < \infty$ , the family (B1) and (B2) have for these values of  $f_4$  either four non real solutions or two real and two non real (complex conjugate) solutions. As it turns out the latter is the case. A numerical check shows e.g. that at  $f_4 = 10$  the four solutions are approximately

$$-47.287, -0.606, -0.564 \pm 0.177j$$

In both cases (B1) and (B2) do not contribute to solutions of the Wouthuysen equation.

For later use we also need the solutions of the (B3) and (B4) families at  $f_4 = 0$ . The equation for the (B3) case then becomes

$$r^4 + \sqrt{3}r^3 - 7r^2 + \sqrt{3}r = 0 \quad (6.7)$$

with solutions

$$0, \sqrt{3}, 2 - \sqrt{3}, -2 - \sqrt{3} \quad (6.8)$$

## 7. MATCHING THE SOLUTIONS WITH A $z_i$ EQUAL TO 1 TO THE A, B3, B4 FAMILIES

Under  $\phi : \mathbb{R} \rightarrow S^1$ ,  $+\infty$  goes to 1, and so does  $-\infty$ . (So the true parameters space is the circle  $\phi(\mathbb{R}) = \phi(\{f_4\})$ ). To see how the solutions with a  $z_i$  equal to 1 fit with the A, B3 and B4 families, it therefore suffices to study what happens to the corresponding solutions as  $f_4 \rightarrow \infty$  (for the A-family) and as  $f_4 \rightarrow -\infty$  (for the B3 and B4 families).

### 7.1 The A-family for $f_4 \rightarrow \infty$ .

First consider an A-family of solutions

$$r^4 + f_2 r^2 + f_4 = 0 \quad f_2 = -\frac{5}{2} - \frac{3}{2}f_4 - \frac{1}{2}\sqrt{9f_4^2 + 132f_4 + 33} \quad (7.2)$$

As  $f_4 \rightarrow \infty$ ,  $f_4^{-1}f_2$  goes to  $-3$ . Let  $s = r^{-1}$ . Then the equation for  $s$  is

$$s^4 + f_4^{-1}f_2 s^2 + f_4^{-1} = 0 \quad (7.3)$$

which in the limit  $f_4 \rightarrow \infty$ , goes to

$$s^4 - 3s^2 = 0 \quad (7.4)$$

It follows that as  $f_4 \rightarrow \infty$ , two solutions of (7.2) go each to  $-\infty$  or  $+\infty$  and the other two go to  $-\frac{1}{3}\sqrt{3}$ ,  $\frac{1}{3}\sqrt{3}$ . However, the four solutions of (7.2) cannot cross as  $f_4 \rightarrow \infty$  ( $f_4 > 0$ ), therefore the only possibility is that one goes to  $-\infty$  and the other to  $+\infty$ .

So up to permutations the limit solutions are

$$\left(-\infty, -\frac{1}{3}, \sqrt{3}, \frac{1}{3}\sqrt{3}, +\infty\right) \quad (7.5)$$

which under  $\phi : \mathbb{R} \rightarrow S^1$  corresponds to the solutions (2.5)

$$(1, \zeta, \zeta^2, 1) \quad (7.6)$$

where  $\zeta = \zeta_3$ .

And indeed a small numerical check shows that for  $f_4 = 10^3$ ,  $10^5$ , respectively, the solutions of (7.2) are, respectively, approximately equal to

$$\begin{aligned} & -54.890, \quad -0.576, \quad 0.576, \quad 54.890 \\ & -547.735, \quad -0.577, \quad 0.577, \quad 547.735 \end{aligned}$$

while  $\frac{1}{3}\sqrt{3}$  is about 0.577.

7.7 *The B3-family for  $f_4 \rightarrow \infty$ .*

Now let's consider a B3-family of solutions

$$\begin{aligned} r^4 + f_1 r^3 + f_2 r^2 + f_1 r + f_4 &= 0, \\ f_2 = 9f_4 - 7, \quad f_1 &= \sqrt{27f_4^2 - 30f_4 + 3} \end{aligned} \tag{7.8}$$

as  $f_4 \rightarrow \infty$  ( $f_4 \leq 1/9$ ). As  $f_4 \rightarrow \infty$ , because  $f_1 \propto 3\sqrt{3}|f_4|$ ,

$$f_4^{-2} f_2 \rightarrow 9, \quad f_4^{-1} f_1 \rightarrow -3\sqrt{3} \tag{7.9}$$

Let  $s = r^{-1}$ . Then the equation for  $s$  is

$$s^4 + f_4^{-1} f_1 s^3 + f_4^{-1} f_2 s^2 + f_4^{-1} f_1 s + f_4^{-1} = 0 \tag{7.10}$$

which in the limit,  $f_4 \rightarrow \infty$ , goes to

$$s^4 - 3\sqrt{3}s^3 + 9s^2 - 3\sqrt{3}s = s(s - \sqrt{3})^3 = 0 \tag{7.11}$$

with solutions

$$0, \quad \sqrt{3}, \quad \sqrt{3}, \quad \sqrt{3} \tag{7.12}$$

It follows that as  $f_4 \rightarrow \infty$  one of the solutions of (7.8) goes to  $\infty$  or  $-\infty$  and the others to  $\frac{1}{3}\sqrt{3}$ .

Now at  $f_4 = 0$  the solutions of (7.8) are

$$-2 - \sqrt{3}, \quad 0, \quad 2 - \sqrt{3}, \quad \sqrt{3} \tag{7.13}$$

The roots cannot cross as  $f_4 \rightarrow -\infty$ , and the smallest one,  $-(2 + \sqrt{3})$ , cannot cross 0 again (because there are no zero solutions of (7.8) for  $f_4 < 0$ ). It follows that (7.13) must go to

$$\left(-\infty, \frac{1}{3}\sqrt{3}, \frac{1}{3}\sqrt{3}, \frac{1}{3}\sqrt{3}\right) \tag{7.14}$$

which corresponds to the solution

$$(1, \zeta^2, \zeta^2, \zeta^2) \tag{7.15}$$

of the Wouthuysen equation.

A numerical check gives that for  $f_4 = -10^4$ , the four solutions are approximately equal to

$$-51966.143, \quad 0.572, \quad 0.577, \quad 0.583$$

while  $\frac{1}{3}\sqrt{3}$  is about 0.577.

#### 8. THE TOPOLOGICAL STRUCTURE OF THE SPACE OF SOLUTIONS

Apart from the identifications at  $r = \infty, -\infty$ , i.e. at  $z = 1$ , the picture of the solution space is made up of 12 pieces as depicted below

Here all special (intersection) points have been made fat dots and given their  $r$ -coordinates. For the points with an  $r = \pm\infty$  the corresponding  $z$ -coordinates have also been given. A crossing point of families that has not been made fat is not an existing crossing point but an artifact of the drawing. In particular there is no intersection of a B4-family with a B3-family for  $-\infty \leq f_4 < 1/9$ .

There are twelve such pieces. The other eleven are obtained by applying appropriate elements of  $S_4$  to the picture shown above. To get the complete global picture it suffices to identify the points above  $f_4 = \pm\infty$  according to the coordinates attached to them. The complete topological picture is given below.

As above let  $\zeta = \zeta_3$

$C_1 = (1, \zeta^2, \zeta^2, \zeta^2)$	$(1, \zeta, \zeta^2, 1)$	$(-t_1, 0, 0, t_1)$
$D_4 = (\zeta, \zeta, \zeta, 1)$	$(1, \zeta^2, \zeta, 1)$	
$C_4 = (\zeta^2, \zeta^2, \zeta^2, 1)$	$(1, \zeta, \zeta^2, 1)$	$(t_1, 0, 0, -t_1)$
$D_1 = (1, \zeta, \zeta, \zeta)$	$(1, \zeta^2, \zeta, 1)$	
$C_1 = (1, \zeta^2, \zeta^2, \zeta^2)$	$(1, \zeta, 1, \zeta^2)$	$(-t_1, 0, t_1, 0)$
$D_3 = (\zeta, \zeta, 1, \zeta)$	$(1, \zeta^2, 1, \zeta)$	
$C_3 = (\zeta^2, \zeta^2, 1, \zeta^2)$	$(1, \zeta, 1, \zeta^2)$	$(t_1, 0, -t_1, 0)$
$D_1 = (1, \zeta, \zeta, \zeta)$	$(1, \zeta^2, 1, \zeta)$	
$C_3 = (\zeta^2, \zeta^2, 1, \zeta^2)$	$(\zeta, \zeta^2, 1, 1)$	$(0, 0, -t_1, t_1)$
$D_4 = (\zeta, \zeta, \zeta, 1)$	$(\zeta^2, \zeta, 1, 1)$	
$C_4 = (\zeta^2, \zeta^2, \zeta^2, 1)$	$(\zeta, \zeta^2, 1, 1)$	$(0, 0, t_1, -t_1)$
$D_3 = (\zeta, \zeta, 1, \zeta)$	$(\zeta^2, \zeta, 1, 1)$	
$C_4 = (\zeta^2, \zeta^2, \zeta^2, 1)$	$(\zeta, 1, \zeta^2, 1)$	$(0, t_1, 0, -t_1)$
$D_2 = (\zeta, 1, \zeta, \zeta)$	$(\zeta^2, 1, \zeta, 1)$	
$C_2 = (\zeta^2, 1, \zeta^2, \zeta^2)$	$(\zeta, 1, \zeta^2, 1)$	$(0, -t_1, 0, t_1)$
$D_4 = (\zeta, \zeta, \zeta, 1)$	$(\zeta^2, 1, \zeta, 1)$	
$C_3 = (\zeta^2, \zeta^2, 1, \zeta^2)$	$(\zeta, 1, 1, \zeta^2)$	$(0, t_1, -t_1, 0)$
$D_2 = (\zeta, 1, \zeta, \zeta)$	$(\zeta^2, 1, 1, \zeta)$	
$C_2 = (\zeta^2, 1, \zeta^2, \zeta^2)$	$(\zeta, 1, 1, \zeta^2)$	$(0, -t_1, t_1, 0)$
$D_3 = (\zeta, \zeta, 1, \zeta)$	$(\zeta^2, 1, 1, \zeta)$	
$C_2 = (\zeta^2, 1, \zeta^2, \zeta^2)$	$(1, 1, \zeta, \zeta^2)$	$(t_1, -t_1, 0, 0)$
$D_1 = (1, \zeta, \zeta, \zeta)$	$(1, 1, \zeta^2, \zeta)$	
$C_1 = (1, \zeta^2, \zeta^2, \zeta^2)$	$(1, 1, \zeta, \zeta^2)$	$(-t_1, t_1, 0, 0)$
$D_2 = (\zeta, 1, \zeta, \zeta)$	$(1, 1, \zeta^2, \zeta)$	

$$f_4 : \quad -\infty \leftarrow \quad 0 \quad 1/9 \quad \rightarrow +\infty$$

The solution  $(1, 1, 1, 1)$  is completely isolated, and all others are connected by the scheme drawn above, where the dotted lines indicate identifications.

In the above

$$Q_1 = \phi(-t_2, -t_3, t_3, t_2) = \left( -\frac{1}{8} + \frac{3}{8}\sqrt{5} + j\left(\frac{1}{8}\sqrt{3}\right), -\frac{1}{8} - \frac{3}{8}\sqrt{5} + j\left(\frac{1}{8}\sqrt{15} - \frac{1}{8}\sqrt{3}\right), \right. \\ \left. -\frac{1}{8} - \frac{3}{8}\sqrt{5} - j\left(\frac{1}{8}\sqrt{15} - \frac{1}{8}\sqrt{3}\right), -\frac{1}{8} + \frac{3}{8}\sqrt{5} - j\left(\frac{1}{8}\sqrt{3}\right) \right)$$

where  $t_2 = \frac{1}{3}\sqrt{15} + \frac{2}{3}\sqrt{3}$ ,  $t_3 = \frac{1}{3}\sqrt{15} - \frac{2}{3}\sqrt{3}$

And further, using the notation  $\sigma(s_1, s_2, s_3, s_4) = (s_{\sigma(1)}, s_{\sigma(2)}, s_{\sigma(3)}, s_{\sigma(4)})$ ,

$$\begin{aligned} Q_2 &= (23)Q_1 = \phi(-t_2, t_3, -t_3, t_2) \\ Q_3 &= (14)Q_1 = \phi(t_2, -t_3, +t_3, -t_2) \\ Q_4 &= (23)(14)Q_1 = \phi(t_2, +t_3, -t_3, -t_2) \\ Q_5 &= (34)Q_1 = \phi(-t_2, -t_3, t_2, t_3) \\ Q_6 &= (234)Q_1 = \phi(-t_2, t_3, t_2, -t_3) \\ Q_7 &= (143)Q_1 = \phi(t_2, -t_3, -t_2, t_3) \\ Q_8 &= (1423)Q_1 = \phi(t_2, +t_3, -t_2, -t_3) \\ Q_9 &= (123)Q_1 = \phi(-t_3, t_3, -t_2, t_2) \\ Q_{10} &= (13)Q_1 = \phi(t_3, -t_3, -t_2, t_2) \\ Q_{11} &= (1234)Q_1 = \phi(-t_3, t_3, t_2, -t_2) \\ Q_{12} &= (134)Q_1 = \phi(t_3, -t_3, t_2, -t_2) \\ Q_{13} &= (124)Q_1 = \phi(-t_3, t_2, t_3, -t_2) \\ Q_{14} &= (1324)Q_1 = \phi(t_3, t_2, -t_3, -t_2) \end{aligned}$$



$$\begin{aligned}
Q_{15} &= (12)Q_1 = \phi(-t_3, -t_2, t_3, t_2) \\
Q_{16} &= (132)Q_1 = \phi(t_3, -t_2, -t_3, t_2) \\
Q_{17} &= (1243)Q_1 = \phi(-t_3, t_2, -t_2, t_3) \\
Q_{18} &= (13)(24)Q_1 = \phi(t_3, t_2, -t_2, -t_3) \\
Q_{19} &= (12)(34)Q_1 = \phi(-t_3, -t_2, t_2, t_3) \\
Q_{20} &= (1342)Q_1 = \phi(t_3, -t_2, t_2, -t_3) \\
Q_{21} &= (1432)Q_1 = \phi(t_2, -t_2, -t_3, t_3) \\
Q_{22} &= (142)Q_1 = \phi(t_2, -t_2, t_3, -t_3) \\
Q_{23} &= (243)Q_1 = \phi(-t_2, t_2, -t_3, t_3) \\
Q_{24} &= (24)Q_2 = \phi(-t_2, t_2, t_3, -t_3)
\end{aligned}$$

In words, the space of solutions of the Wouthuysen equation consists of one isolated point,  $(1, 1, 1, 1)$ , and a branched curve. This branched curve, and the isolated point, come with a natural projection to the circle. The group  $S_4$  acts on the space of solutions, leaving the isolated point invariant. The projection to the circle is invariant under this action. Let  $S$  denote the solution space and  $\pi : S \rightarrow S^1 = \mathbb{R} \cup \{\infty\}$  this invariant projection.

In terms of the  $r$ -coordinates,  $\mathbb{R} \cup \{\infty\}$ ,  $-\infty = +\infty$ , the picture is as follows

- (i) Above all  $1/9 < y < \infty$ , there are 24 points which form one  $S_4$ -orbit. The inverse under  $\pi$  of a small enough neighborhood of such a points consists of 24 disjoint intervals.

- (ii) Above  $y = \infty$  (corresponding to 1 under the Cayley transform) there are 21 points: the isolated solution point  $(1, 1, 1, 1)$ , which is an invariant point of the  $S^4$ -action, an  $S^4$ -orbit of size 12, and two complex conjugate  $S_4$ -orbits of size 4. These are branching points of order 6. Locally around one of the points of the orbit of size 12, the branched solution curve looks like an interval turning back. Locally around a point of the two  $S_4$ -orbits of size 4 the picture is a six branched star as depicted below. Thus the inverse image of a small interval around the point  $\infty$  of the circle  $\mathbb{R} \cup \{\infty\}$  looks like the disjoint union of 12 intervals, 8 six branched stars and one isolated point.

- (iii) Above  $y = \frac{1}{9}$  there are 24 points which form a single  $S_4$ -orbit. They are all branching points of order 4. The inverse of a small interval around  $y = 1/9$  looks like the disjoint union of 24

4-branched stars like depicted below.

- (iv) Above all  $0 < y < 1/9$  there are 72 points, which from three  $S_4$ -orbits; two of these are complex conjugate, the third is invariant under complex conjugation. The inverse image of a small enough interval around these  $y$  looks like 72 disjoint copies of that interval
- (v) Above  $y = 0$  there are 60 points. They form one orbit of size 12 and two complex conjugate orbits of size 24. The points from the orbit of size 12 are “turning points” in a sense which should be clear from the picture below. The inverse image of a small interval around such a point consists of 60 disjoint intervals of which 12 are “turn back” intervals.
- (vi) Above  $-\infty < y < 0$  there are 48 points which form two complex conjugate orbits of size 24 each. The inverse image of a small interval around these  $y$  looks like the disjoint union of 48 copies of that interval

So, in fact, the group  $\mathbb{Z}/(2) \times S_4$  acts on the space of solutions and  $\pi : S \rightarrow S^1$  is invariant under this action (of a group of order 48).

#### REFERENCES

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