

# A GENERALIZATION OF THE CATALAN IDENTITY AND SOME CONSEQUENCES

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(Submitted June 1993)

## 1. INTRODUCTION

The Catalan identity

$$F_{n-r}F_{n+r} - F_n^2 = (-1)^{n-r+1} F_r^2 \quad (1.1)$$

has several generalizations. Here we obtain a new generalization and use it to generalize the Gelin-Cesàro identity

$$F_n^4 - F_{n-2}F_{n-1}F_{n+1}F_{n+2} = 1, \quad (1.2)$$

which was stated by Gelin and proved by Cesàro (see [1], p. 401). Furthermore, we establish that a certain expression arising from three-term recurrence relations is a perfect square, and this generalizes previous work.

Using the notation of Horadam [2], let

$$W_n = W_n(a, b; p, q) \quad (1.3)$$

so that

$$W_n = pW_{n-1} - qW_{n-2}, \quad W_0 = a, \quad W_1 = b, \quad n \geq 2. \quad (1.4)$$

If  $\alpha, \beta$ , assumed distinct, are the roots of

$$\lambda^2 - p\lambda + q = 0, \quad (1.5)$$

we have the Binet form [2]

$$W_n = \frac{A\alpha^n - B\beta^n}{\alpha - \beta}, \quad (1.6)$$

in which

$$\begin{cases} A = b - a\beta \\ B = b - a\alpha. \end{cases} \quad (1.7)$$

Write

$$e = pab - qa^2 - b^2 = -AB. \quad (1.8)$$

As usual,  $U_n = W_n(0, 1; p, q)$  is the fundamental sequence of Lucas [4].

## 2. THE MAIN RESULT

We now generalize the Catalan identity and obtain some consequences.

**Theorem:** For  $W_n = W_n(a, b; p, q)$  and  $Y_n = W_n(a_1, b_1; p, q)$ ,

$$W_n Y_{n+r+s} - W_{n+r} Y_{n+s} = \Psi(s) q^n U_r, \quad (2.1)$$

where

$$\Psi(s) = (pa_1b - qaa_1 - bb_1)U_s + (ab_1 - a_1b)U_{s+1}.$$

**Proof:** Using the Binet forms for  $W_n$  and  $Y_n$  we obtain, after some algebra,

$$W_n Y_{n+r+s} - W_{n+r} Y_{n+s} = \frac{(AB_1\beta^s - A_1B\alpha^s)q^n U_r}{\alpha - \beta},$$

where, in the Binet form for  $Y_n$ ,

$$\begin{cases} A_1 = b_1 - \alpha_1\beta, \\ B_1 = b_1 - \alpha_1\alpha. \end{cases} \quad (2.2)$$

Now, using (1.7) and (2.2) we see, after simplifying, that  $\frac{AB_1\beta^s - A_1B\alpha^s}{\alpha - \beta}$  reduces to  $\Psi(s)$ .  $\square$

In (2.1), replacing  $n$  by  $n-r$  and  $s$  by  $r$  gives

$$W_{n-r} Y_{n+r} - W_n Y_n = \Psi(r)q^{n-r} U_r. \quad (2.3)$$

Replacing  $r$  by  $r+1$  in (2.3), we have

$$W_{n-r-1} Y_{n+r+1} - W_n Y_n = \Psi(r+1)q^{n-r-1} U_{r+1}. \quad (2.4)$$

Adding (2.3) and (2.4) gives

$$W_{n-r} Y_{n+r} + W_{n-r-1} Y_{n+r+1} = 2W_n Y_n + \Psi(r)q^{n-r} U_r + \Psi(r+1)q^{n-r-1} U_{r+1}. \quad (2.5)$$

Subtracting (2.4) from (2.3) gives

$$W_{n-r} Y_{n+r} - W_{n-r-1} Y_{n+r+1} = \Psi(r)q^{n-r} U_r - \Psi(r+1)q^{n-r-1} U_{r+1}. \quad (2.6)$$

Squaring (2.5) and subtracting the square of (2.6), we obtain

$$\begin{aligned} W_{n-r-1} W_{n-r} Y_{n+r} Y_{n+r+1} &= W_n^2 Y_n^2 + W_n Y_n q^{n-r-1} (q\Psi(r)U_r + \Psi(r+1)U_{r+1}) \\ &\quad + \Psi(r)\Psi(r+1)q^{2n-2r-1} U_r U_{r+1}. \end{aligned} \quad (2.7)$$

Putting  $r = 1$  in (2.7) yields

$$W_{n-2} W_{n-1} Y_{n+1} Y_{n+2} = W_n^2 Y_n^2 + W_n Y_n q^{n-2} (q\Psi(1) + p\Psi(2)) + p\Psi(1)\Psi(2)q^{2n-3}. \quad (2.8)$$

In (2.1), substituting  $r = -1$ ,  $s = m - n + 1$  and noting that  $U_{-1} = -q^{-1}$ , we obtain

$$W_n Y_m - W_{n-1} Y_{m+1} = -\Psi(m-n+1)q^{n-1}. \quad (2.9)$$

Furthermore, if  $n = m - 1$ , then (2.9) yields

$$W_{m-1} Y_m - W_{m-2} Y_{m+1} = -\Psi(2)q^{m-2}. \quad (2.10)$$

Finally, from (2.1), it follows that

$$(W_n Y_{n+r+s} - W_{n+r} Y_{n+s})^2 = \Psi^2(s)q^{2n} U_r^2,$$

so that

$$4W_n W_{n+r} Y_{n+s} Y_{n+r+s} + \Psi^2(s)q^{2n} U_r^2 = (W_n Y_{n+r+s} + W_{n+r} Y_{n+s})^2,$$

thus establishing that

$$4W_n W_{n+r} Y_{n+s} Y_{n+r+s} + \Psi^2(s) q^{2n} U_r^2 \tag{2.11}$$

is a perfect square for nonnegative integers  $n, r, s$  and integers  $a, b, a_1, b_1, p, q$ .

### 3. RELATION TO OTHER GENERALIZATIONS

The results of the previous section generalize results of Horadam and Shannon [3] who, in turn, generalized work of Morgado [5] on the Fibonacci numbers. It suffices then to indicate how our work generalizes that of Horadam and Shannon.

In (2.1), when  $(a_1, b_1) = (a, b)$ , we have  $\{W_n\} = \{Y_n\}$  and  $\Psi(s) = eU_s$ , so that (2.1) becomes

$$W_n W_{n+r+s} - W_{n+r} W_{n+s} = eq^n U_r U_s,$$

which Horadam and Shannon gave as a generalization of the Catalan identity. Under the same circumstances, noting that  $\Psi(1) = e$  and  $\Psi(2) = ep$ , (2.8) reduces to

$$W_{n-2} W_{n-1} W_{n+1} W_{n+2} = W_n^4 + W_n^2 eq^{n-2} (p^2 + q) + e^2 q^{2n-3} p^2,$$

which Horadam and Shannon gave as a generalization of the Gelin-Cesàro identity.

Similarly, (2.9) and (2.10) reduce, respectively, to

$$W_n W_m - W_{n-1} W_{m+1} = -eq^{n-1} U_{m-n+1}$$

and

$$W_n W_{n-1} - W_{n-2} W_{n+1} = -epq^{n-2},$$

which are generalizations of results for Fibonacci numbers due to D'Ocagne (see [1], p. 402).

Finally, the expression (2.11) reduces to

$$4W_n W_{n+r} W_{n+s} W_{n+r+s} + e^2 q^{2n} U_r^2 U_s^2,$$

which was proved by Horadam and Shannon to be a perfect square.

### ACKNOWLEDGMENT

We gratefully acknowledge the comments of an anonymous referee whose suggestions have considerably streamlined the presentation of this paper.

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AMS Classification Numbers: 11B37, 11B39



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Volume 33

Number 1

February 1995

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