

An Atlas of 12-Link, 1-Freedom Simple Jointed Kinematic Chains and Mechanisms

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Abstract – Simple Jointed Kinematic chains have long since been established as an important conceptual entity useful in the creative synthesis of mechanisms, machines and power transmission systems. The task of generating and analysing kinematic chains, popularly termed as the structural synthesis and analysis of chains is a mammoth task especially when there are more than nine links in the chain. By reporting all the structural variants of the simple jointed kinematic chains (SJ KCs) belonging to 12-link, 1-freedom category along with the distinct mechanisms derivable from each, the results of this work mainly serves to relieve machine designers from the efforts of performing structural synthesis and analysis of chains, and also from getting into the intricacies of the isomorphism problem associated with the number synthesis of the chains. Instead, they can direct their efforts towards finding ways to convert SJ KCs to the desired mechanisms having different machine elements. A total of 6856 chains were generated using a computer program developed by the author followed by detection of 75397 distinct mechanisms from the given category of chains. These findings are reported in this paper by employing a concise notation for representing the chains. The paper also discusses the findings that emerged by applying characteristics polynomial based isomorphism tests on all the 6856 chains using the link-adjacency, degree and structural matrices. It reports two cases where the degree- and structural matrix based isomorphism tests yield identical counter examples.

Keywords– Kinematic chain, structural synthesis, mechanisms, isomorphism, Degree matrix, Structural matrix.

I. INTRODUCTION

One possible reason which can be attributed to non-availability of the complete collection of the structural variants of 12-link, 1-freedom simple jointed kinematic chains (SJ KCs) in the published literature is the large volume of associated data required to be published [1]. Owing to its potential use in the preliminary design phase of the product design cycle, which is the phase during which the machine design engineer has to bring out innovation in the artefact that is being designed, kinematic chains have been found to assist in the creative synthesis of solutions in an objective and systematized manner [2]. It is also found to help in spawning newer ideas and novel mechanical configurations regardless of the complexity of the underlying mechanism. It has been shown in literature that the chains, which in its primitive form consist of simple links connected by means of the turning joints, can be transformed into mechanisms consisting of gears, cams, belts, chains, and so on [3].

Several researchers in the past have attempted structural synthesis of chains, and have proposed various methods to enumerate them [4-17]. But for very few instances [13,16] wherein the drawing of the kinematic chain

structures are reported, the results reported thus far is predominantly restricted to describing the methodology of synthesis, their application to several cases of links and degree of freedom, followed by the tabulations of the total number of chains that could be generated in each category of SJ KCs. The mechanism designers, on the other hand, would prefer to have all the structural variants presented to them so that they can further work upon the chains to produce actual mechanisms.

One possible reason for the non-availability of a chain catalogue – as a sketch or an alternative representation of the chain – is the sheer difficulty to report the substantial results given the page-space constraints. This paper chooses to provide the complete structural information about the chains and the number of mechanisms that each kinematic chain can yield in a form that enables easy sketching of the structure of SJ KCs and identification of the links which yield distinct mechanisms (or alternatively, the links which yield identical mechanism). To this end a concise notation for the chain is proposed. The notation enables representation of the chain and the possible distinct mechanisms derivable from it by means of an alpha-numeric string of 12 characters length. A short FORTRAN program that can decode the chain into a form that is convenient to sketch, as compared to the link adjacency matrix representation, is also included in the paper.

While searching across all the 6856 chains for cospectral examples it is found that when characteristic polynomial of link adjacency matrix [18] is employed as an isomorphism index there were 15 triplets of 12-link, 1-freedom SJ KCs, and 183 instances of pairs of cospectral chains. A similar search for cospectral examples using the degree matrix [20] and structural matrix [19] representations revealed two pairs of counter-examples to isomorphism tests. A surprising discovery in the study was that both the tests failed to distinguish the same pairs of kinematic chains. These chains are also reported in this paper.

II. BRIEF REVIEW OF LITERATURE

Referring to "Table 1: Current status of enumeration of kinematic chains" in the review paper by Mruthyunjaya [1], it may be observed that several researchers have in the past attempted enumeration of chains adopting different approaches and have reported nearly identical results.

Restricting the survey of literature to those contributions that emphasized computer-based methodologies of number synthesis and also to those that deal with SJ KCs possessing greater than 9 links, Tuttle et al. [3,4] introduced group theory to the study of kinematic structure for the enumeration of chains and mechanisms. Mruthyunjaya [11-13, 16] presented the method

based on transformation of binary chains for structural synthesis of simple- and multiple-jointed chains with positive, zero or negative freedom. Complete collection of 9-link, 2-freedom and 10-link, 1-freedom chains were derived in this work through a computer program implementing the method. Mruthyunjaya et al. [16] have reported the sketches of all 11-link, two-freedom chains, derived by applying transformation of binary chains for structural synthesis. The complete collection of 839 simple-jointed chains found in the category including 65 with total freedom, 688 with partial freedom and 86 with fractionated freedom were presented. References [13,16] illustrates the amount of space required to publish the kinematic structure of mechanisms.

III. SYNTHESIS METHODOLOGY ADOPTED IN THIS WORK

In his doctoral dissertation, the corresponding author Vijayananda [17] had developed a structural synthesis method in which a chain having a given number of links and degree of freedom is built up by augmenting a specially constructed assemblage of links called the *link-patterns* to a valid chain having fewer number of links called the *parent kinematic chain*. The parent kinematic chain is a closed chain with positive freedom and free from immobile sub-chains while the link-pattern is either an open structure with two free elements or a quasi-closed structure with one free element. The interrelation among the degrees of freedom and amongst the number of links of the chain to be derived, the parent kinematic chain and the link pattern to be added are presented and the rules to be followed while adding the link patterns are formulated. The method is applicable for synthesis of chains with positive, zero or negative freedom. It has been expressed in analytical terms using concepts from graph theory and computerized to enable synthesis of chains with positive freedom incorporating an isomorphism test developed by the corresponding author [17]. The program has been applied to generate chains with up to 13 links and having different freedoms. Another advantage of this method is that it also generates valuable information required to identify type of freedom of the derived chains. See also Mruthyunjaya [1].

IV. STRUCTURAL SYNTHESIS OF 12-LINK, 1 FREEDOM SJKC

As mentioned in the above section, synthesis of 12-link, 1 freedom SJKCs are generated using the complete collection of 10-link, 1 freedom and 11-link, 2-freedom parent kinematic chains. It should be observed that the number synthesis being dealt with and reported in this work is restricted to generating closed and connected chains possessing no redundant sub-chains having zero or negative freedom.

By using a *dyad* link-pattern (two binary links in series) that adds two binary links and three simple joints to the 10-link, 1 freedom parent chains, SJKCs having 12-link and 1 freedom can be generated. Note that by applying Gruebler's criterion, this augmentation will not alter the number of degrees of freedom of the parent chain. This operation is performed in turn on each of the complete

collection of 10-link, 1-dof chains. Chains so produced will have at least one dyad in it.

Similarly, by adding one binary link to 11-link, 2-dof chain, two additional joints will be introduced. Now by applying Gruebler's criterion, one dof ($3 \times 1 - 2 \times 2 = -1$) will be removed from the original 2-dof chain rendering the final chain to possess 12-link and 1-dof. It may be observed that addition of one binary link need be done to only those 11-link 2-dof chains that will yield chains without dyads. The latter lends a significant computational time saving avenue.

V. RESULTS OF NUMBER SYNTHESIS & COSPECTRAL CASES AMONG 12-LINK, 1-FREEDOM CHAINS

This paper reports the structure of 6856 SJKCs, and the 75397 distinct mechanisms that can be derived from the complete collection of 12-link, 1-freedom chains (Table 4). These chains are arranged column-wise in blocks of 640 chains. For example, chain no. 90 is **J4oA8H8+241**. The order of listing is to be particularly noted since the cospectral chain numbers shown in Tables 1 and 2 is as per the stated order.

As a further exercise, characteristic polynomial of the degree matrix proposed in [20] and that of the structural matrix proposed in [19] was examined by applying it to all the 12-link, 1-freedom chains. The intent of the study was to check for the existence of any counter examples. It was found that there existed two pairs of chains wherein both the tests failed to distinguish the two structures. A surprising discovery from this exercise is that both of the above two tests had the same cases of counterexamples. The two cases of counter-examples shown in Fig. 1 were common to both isomorphism tests.

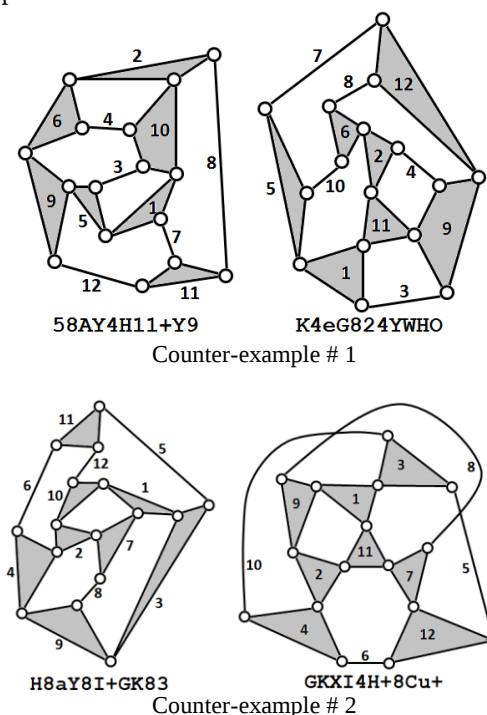


Figure 1: Counter-examples for the degree matrix [3] and structural matrix [2] based approaches

It may be noted that the size of structural matrix (which is equal to the sum of number of links and joints in

the chain) is larger than that of the degree matrix for the same chain (which is the size of the link adjacency matrix). That is, for a 12-link, 1-freedom category the structural matrix is a square matrix of size 28 while it is 12 in the case of degree matrix. Although the degree matrix of a chain is easily derivable from its link adjacency matrix, the former contain some additional information in it. The latter, loaded with extra information, serves as the better starting point for the computation of the characteristic coefficients. It is due to this that the characteristic polynomial of degree matrix has been found to have fewer counter-examples.

In the same manner the structural matrix of the chain, although derivable from link-adjacency matrix, contains a lot more information about the chain in its initial form itself. The method, in fact, generates a matrix which is larger in size than what the representation requires. The objective was to pack as much information about the chain as possible into the matrix representation from which

characteristic polynomial of the matrix is computed. The test based on this matrix is believed to have no counter-examples. The findings of the present work in the 12-link, 1-freedom category reveals that the degree matrix based test [20], despite its smaller size, is computationally as efficient as the method of characteristic polynomial of link adjacency matrix suggested in [18], and as robust as that of structural matrix based method [19].

From the above it can be concluded that despite its relatively smaller size ($N \times N$), isomorphism test based on the degree matrix is as good as the isomorphism test based on structural matrix whose size is $[(N+J) \times (N+J)]$, where N is the number of links, and J is the number of joints in the chain.

Table 1: 15 CASES OF COSPECTRAL TRIPLETS AMONG 12-LINK, 1-FREEDOM CHAINS

[225, 561, 6165], [1522, 4517, 4832], [2166, 2575, 2611], [2167, 2168, 2201], [2193, 2284, 2285]
[2395, 2426, 2600], [2428, 2450, 2618], [2449, 2453, 2475], [3219, 3321, 3863], [3536, 3548, 3642]
[3537, 3551, 3571], [5314, 6678, 6735], [5486, 6817, 6825], [5934, 6720, 6332], [6025, 6725, 6846]

Table 2: 183 CASES OF COSPECTRAL PAIRS AMONG 12-LINK, 1-FREEDOM CHAINS

[27, 3981], [50, 3851], [279, 927], [303, 471], [340, 443], [365, 6070], [382, 3881], [391, 3877]
[400, 428], [409, 499], [437, 5361], [497, 6088], [517, 5011], [522, 6142], [524, 527], [535, 577]
[544, 6146], [576, 5319], [601, 6167], [605, 5573], [775, 1733], [836, 934], [905, 1802], [1061, 1101]
[1125, 4212], [1154, 1363], [1214, 1333], [1306, 5641], [1318, 4172], [1550, 5676], [1559, 5528], [1601, 1636]
[1668, 2029], [1710, 1951], [1731, 1766], [1755, 2742], [1808, 1897], [1921, 2071], [2152, 2153], [2157, 2158]
[2162, 2163], [2203, 2708], [2230, 4423], [2233, 4439], [2240, 5822], [2257, 2315], [2264, 2613], [2286, 2425]
[2291, 4955], [2318, 3339], [2326, 5756], [2329, 2601], [2330, 4546], [2335, 4536], [2386, 2564], [2422, 2616]
[2424, 2604], [2430, 2621], [2439, 2628], [2582, 3736], [2615, 3737], [2643, 5806], [2660, 5085], [2692, 2925]
[2745, 4486], [2937, 6229], [2944, 4457], [2945, 2947], [2946, 5840], [2967, 3056], [2970, 6236], [3088, 4516]
[3120, 3460], [3128, 3466], [3148, 4222], [3157, 4219], [3164, 3190], [3186, 5539], [3196, 4294], [3212, 6679]
[3220, 4290], [3252, 4186], [3253, 6650], [3255, 4184], [3293, 5708], [3304, 4115], [3306, 4141], [3311, 6020]
[3314, 5937], [3320, 4304], [3348, 6216], [3384, 4688], [3389, 4659], [3420, 4698], [3431, 4692], [3439, 3760]
[3440, 4697], [3528, 3533], [3531, 3565], [3535, 3544], [3596, 5100], [3611, 4021], [3635, 3810], [3653, 4493]
[3658, 4492], [3664, 3691], [3678, 6431], [3680, 4778], [3683, 3684], [3685, 4783], [3692, 3694], [3705, 4724]
[3710, 4745], [3735, 3817], [3743, 4702], [3753, 3814], [3761, 4701], [3766, 3789], [3862, 5344], [3864, 5348]
[3886, 5905], [3890, 5907], [3910, 4849], [3923, 4854], [3927, 5986], [3936, 6673], [4329, 5927], [4459, 5094]
[4539, 6254], [4720, 6363], [4780, 6339], [4809, 5977], [4811, 5976], [5001, 5132], [5002, 5152], [5021, 6546]
[5064, 5208], [5066, 5222], [5189, 5276], [5190, 5294], [5205, 6618], [5323, 5326], [5341, 6707], [5365, 6709]
[5369, 5370], [5399, 5400], [5413, 6759], [5415, 6784], [5434, 5436], [5437, 5527], [5456, 5457], [5471, 5510]
[5473, 5512], [5481, 6792], [5493, 5675], [5552, 6168], [5553, 6166], [5901, 6303], [5916, 6163], [5918, 6177]
[5928, 6151], [5934, 6720], [5984, 6332], [5985, 6364], [5990, 6330], [6024, 6726], [6033, 6716], [6461, 6574]
[6481, 6571], [6514, 6604], [6516, 6580], [6517, 6600], [6519, 6605], [6520, 6606], [6562, 6647], [6566, 6839]
[6641, 6737], [6680, 6734], [6681, 6730], [6683, 6732], [6684, 6692], [6724, 6727], [6848, 6853]

VI. CONCISE NOTATION FOR REPORTING SJKCs – A PROPOSAL

A compact notation is proposed to represent SJKCs and the number of distinct mechanisms they yield. The notation helps in greatly reducing the space requirements for reporting the results. To illustrate the notation we consider the example of the 12-link, 3-d.o.f chain shown in Fig. 2 along with its link adjacency matrix.

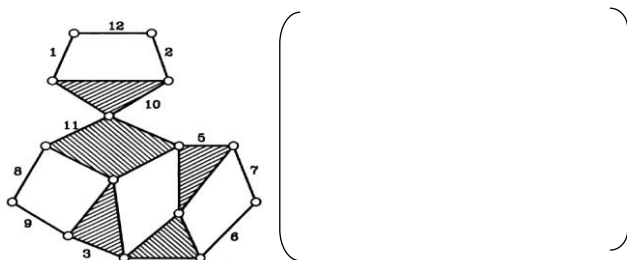


Figure 2: 10-Link, 3-DOF SJKC and its Link-Adjacency Matrix

The compact notation for this chain is $is+A+iAm4K+A4, B$. The letters included in the notation are interpreted by the following procedure.

Commencing from row-1 of the upper triangular link adjacency matrix (diagonal elements excluded), the matrix elements are first written row by row as a single binary string as follows:

```
000000001010000000101100001010110000000100010100000
0000010100001000
```

The above binary string is then divided into smaller units containing six binary digits. A 12-link KC represented by 12×12 matrix will have 66 binary digits ($=11 \times 12 \div 2$) leading to eleven six-bit-units as shown below.

```
[000000] [001010] [000000] [101100] [001010] [110000] [00
0100] [010100] [000000] [001010] [000100]
```

Let $x_1x_2x_3x_4x_5x_6$ represent a six-bit-unit where x_i ($i = 1, 2, \dots, 6$) are the six binary digits. From the x_i 's we can generate an integer d_j as follows.

$$(d_j) = \sum_{i=1}^6 x_i \times 2^{6-i}$$

Depending upon the six-bit-units x_i 's, d_j can take any integer value from 0 (zero) through 63 ($2^6 - 1$). Knowing d_j the following substitution is carried out.

- If $d_j = 0$, substitute with the '+' character. This is to avoid confusion between '0' (zero) with the alphabet 'O'.
- If $d_j = 1, 2, 3, \dots, 9$, no substitution need be made.
- If $d_j = 10, 11, 12, \dots, 35$, substitute it with the upper case alphabets A, B, C, ..., Z respectively.
- If $d_j = 36, 37, 38, \dots, 61$, substitute it with the lower case alphabets a, b, c, ..., y, z respectively.
- If $d_j = 62, 63$, substitute them with the characters '*', '=' respectively.

After the above substitutions, concatenated d_j ($j = 1, 2, \dots, 11$) obtained from the eleven six-bit-units. The sequence of occurrence of d_j 's is to be retained. The string consisting of eleven characters given above (+A+iAm4K+A4) provides information about the structure of kinematic chain in the condensed notation.

The second part of the notation, **B** (following the comma), provides details about the number of distinct mechanisms possible from the chain, and also which of the links yield structurally identical mechanism upon fixation. The meaning conveyed by each of these codes is tabulated in Table 3.

Table 3: Mechanisms: Symbols and their meaning

Code	Meaning of the symbol
A	All mechanisms are distinct
B	1=2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
C	1=2=3=4, 5=6=7=8, 9=10, 11=12
D	1=2, 3=4, 5=6, 7, 8, 9, 10, 11, 12
E	1=2, 3=4, 5=6, 7=8, 9=10, 11=12
F	1=2=3=4=5=6=7=8, 9=10=11=12
G	1=2, 3=4, 5, 6, 7, 8, 9, 10, 11, 12
H	1=2=3=4, 5=6, 7=8, 9=10, 11=12
I	1=2=3=4=5=6, 7=8, 9=10, 11=12
J	1=2=3=4, 5=6=7=8, 9=10=11=12
K	1=2, 3=4, 5=6, 7=8, 9=10, 11, 12
L	1=2, 3=4, 5=6, 7=8, 9, 10, 11, 12
M	1=2=3=4, 5=6, 7=8, 9=10, 11, 12
N	1=2=3=4=5=6, 7=8, 9=10, 11, 12
O	1=2=3=4, 5=6, 7=8, 9, 10, 11, 12
P	1=2=3, 4=5=6, 7, 8, 9, 10, 11, 12
Q	1=2=3=4, 5=6=7=8, 9=10, 11, 12
R	1=2=3=4=5=6=7=8=9=10, 11=12
S	1=2=3=4, 5=6, 7, 8, 9, 10, 11, 12
T	1=2=3=4=5=6=7=8, 9=10, 11=12
U	1=2=3, 4=5=6, 7=8, 9, 10, 11, 12
V	1=2=3, 4=5=6, 7=8=9, 10, 11, 12
W	1=2=3=4=5=6, 7=8=9, 10=11, 12

In the present example the meaning of letter B is that links 1 and 2 have identical disposition with reference to the remaining 10 links in the chain while the links 3 through 12 have distinct location within the chain. This is indicated in Table 3 as (1=2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12).

VII. FORTRAN PROGRAM FOR DECODING THE NOTATION

In order to facilitate extraction of the chain from its notation, a FORTRAN code block has been included below. The program reads the notation made up with eleven characters from an input text file named 12LINK.INP. The output of the program will list pairs of links which are adjacent to each other. For example, if the input is +A+iAm4K+A4, then the output would be (1,10), (1,12), (2,10), (2,12), (3,4), (3,9), (3,11), (4,5), (4,6), (5,7), (5,11), (6,7), (8,9), (8,11), (10,11)

VIII. SUMMARY AND CONCLUSION

The paper reports the structures of 6856 SJCKs belonging to 12-link, 1-dof category along with 75397 distinct mechanisms. A concise notation developed for the purpose has been used. The paper also reports all the distinct mechanisms possible from each chain. This was made possible through a unique way of labelling of the links of the chain. A FORTRAN program which enables quick decoding of the notation into a form that facilitates easy sketching of chains is also presented. A logical extension of this work is to automate the sketching of the chains. While testing the above chains collection using the characteristic polynomial based tests it is found that there existed 15 triplets and 183 cases of cospectral pairs of chains when link adjacency matrix was used for chain representation. However, with the degree matrix and structural matrix representations of chains there were only two pairs of cospectral chains where the tests could not distinguish. Both tests were found to fail for the same pairs of chains.

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!----- THIS PROGRAM READS THE STRING (For example: +A+iAm4K+A4) AND
!----- OUTPUTS THE LINK LABELS THAT ARE ADJACENT TO EACH OTHER
INTEGER*4 M
CHARACTER KCN*11, MATRIX*66, BINUM*6
OPEN(UNIT=5,FILE='12LINK.INP',STATUS='OLD',ACCESS='SEQUENTIAL')

READ(5,*) KCN                                ! THE STRING IS READ HERE
DO I = 1,11
    M = ICHAR(KCN(I:I))
    IF(M == 43) THEN                            !if '+', set M to 0
        M = 0
    ELSEIF(M >48 .AND. M <58) THEN                !if '1-9' do not change
        M = M - 48
    ELSEIF(M >64 .AND. M <91) THEN                !if 'A-Z' set to '10-35' resp.
        M = M - 55
    ELSEIF(M >96 .AND. M <123) THEN              !if 'a-z' set to '36-61' resp.
        M = M - 61
    ELSEIF(M == 42) THEN                        !if '*' set to 62
        M = 62
    ELSEIF(M == 61) THEN                        !if '=' set to 63
        M = 63
    ENDIF
    BINUM = '000000'
    CALL TOMATRIX(M,BINUM)
    MATRIX(6*(I-1)+1:6*I) = BINUM(1:6)
ENDDO

    IENT = 0
DO I = 1,11
DO J = I+1,12
    IENT = IENT + 1
    IF(MATRIX(IENT:IENT) == '1') THEN
        WRITE(*,*) I,J                        ! OUTPUTS ADJACENT LINKS
    ENDIF
ENDDO
ENDDO
STOP
END

!$$$$$ =====
SUBROUTINE TOMATRIX(M,BINUM)
INTEGER*4 M, IDIV, IREM
CHARACTER BINUM*6
DO J = 1,6
    IDIV = M/2
    IREM = MOD(M,2)
    IF(IREM == 1) THEN
        BINUM(7-J:7-J) = '1'
    ELSE
        BINUM(7-J:7-J) = '0'
    ENDIF
    IF(IDIV /= 0) THEN
        M = IDIV
    ELSE
        RETURN
    ENDIF
ENDDO
END

```

Table 4: 12–LINK, 1–DOF KINEMATIC CHAINS AND MECHANISMS

LGi+G4eW4GX, A LGi+G48G5+Z, A L+i+O48W42Z, A KcEW82C241X, A GGX+W8C159X, G ZGG6+Gg+4KX, A Z+H6+GA+5XX, A Z+G6AGA+5+f, A
 LGi+G4eW41X, A LGi+G48+LGX, A L+i+O48W4+p, A K8eWA2C24GX, A GGX+W8C2LOX, G ZGG6+Gg+45X, A Z+H6+GA+5Wf, A Z+G6AGA+5+Z, A
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Z+G6+Ig+5+Z,A Z+G6+GB+K5X,A I+e+6161XS1,A +01YK114q11,B 1W61Ge2b+XI,E OHWH+eAW4+Z,A OHW1+eg+5GX,A 01W18eAW4+p,B
Z+G6+IAGD+X,A Z+G6+GB+K4f,A G8WX1WK2+Hp,L +01YK114q+9,B 1W61Ge2L1+f,B OHW12eAe4+X,A OHW1+eg+51X,A +A+g4H224q0,D
Z+G6+IAG5GX,A Z+G6+GB+K4Z,A 8WI1G+G8B3E,P +01YK114q+3,B 1W61Ge2L1+Z,B OHW12eAWC+X,A OHW1+eg+5+f,f,A 01W18e9+YK1,B
Z+G6+IAG51X,A Z+G6+GB+4bX,A I+e+4161Xi3,G K2e8Y4e+4+U,C +01YK111Q,C,D OHW12eAW4GX,A OHW1+eg+5+Z,A 01W18e9+Y51,B
Z+G6+IAG5+f,A Z+G6+GB+4af,A 4G9+a5+88HU,Q H8YWA21fa+1,A 1W61Ge25H1X,B OHW12eAW41X,A OHW1+eAG5+X,A 01W18e9+Y49,B
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===== CHAIN NUMBERS 6401 - 6856 =====
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