"Balance": a computer program for two plane rigid rotor balancing written for the hewlett-packard 41C calculator

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SUBJECT "BALANCE" - A COMPUTER PROGRAM FOR TWO PLANE RIGID ROTOR BALANCING WRITTEN FOR THE HEWLETT-PACKARD 41C CALCULATOR

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ISSUED TO

TABLE OF CONTENTS

APPENDICES

1. INTRODUCTION

On many occasions it is necessary to perform dynamic balancing in the field as an in-situ balancing application. In-situ field balancing is one of the most practical and effective balancing methods because it is not necessary to remove the rotor from the assembly and transport it to the balancing machine location, and then to machine the adaptor housings to fit to the balancing machine, etc. Two-plane dynamic balancing can be used for most rigid rotor balancing, and unless the rotor is flexible, multiplane dynamic balancing with more than two planes is seldom needed.

Until recently, it was impractical if not impossible, for staff of the Engine Laboratory to perform two-plane dynamic balancing in the field. The hand calculation method is very long, and therefore is prone to mistakes. Although a computer program for multiple plane dynamic balancing is available, the time-sharing computer system of NRC is not accessible in the field unless a portable time-sharing terminal as well as a telephone line to the NRC Computation Center are at hand.

These difficulties have been overcome by the purchase of a HP41-C hand-held programmable calculator and the suitable accessories. The accessories are 2 extra memory modules and a card reader. The memory modules provide sufficient memory space and the card reader provides back-up for the program so that the program can be re-entered in case the calculator memory is accidentally changed or erased.

2. DISCUSSION

The two-plane balancing problem has been solved by the Exact Point-Speed Influence Coefficient Method and the result has been programmed for the HP41-C hand-held programmable calculator.

The mathematical detail is given in Appendix I and the program is listed in Appendix II. Though the two-plane case has been solved in Appendix I, the theory is identical to the multiplane balancing problem except for the size of matrices involved. The program used the Exact Point-Speed Method, as described in reference 4 as opposed to the Least Square Method of reference 3. Since its effectiveness is under examination, the Error Correction Method of reference 5 is not used in the present program. To adopt the "Error Correction Method", more memory modules would be necessary.

A total number of 18 subroutines are built into the program, and complex subtraction, multiplication and division were named CSUB, CMULT and CDIV, respectively.

2.1 INPUT DATA

The calculator is programmed to stop and ask for each input value by an alphanumeric prompt.

After pressing the ON key to turn on the calculator, the following keys should be pressed in the order listed:

i) XEQ
ii) ALPHA
iii) B A L A N C E
iv) ALPHA

1) The first prompt is "AMP1 AS IS ?" This means that the calculator is ready to accept the input value of the "amplitude #1 as is", that is, ONLY the amplitude value (not the phase angle) of the original unbalance response at the probe #1, namely W_1^0 (see Appendix I for the notations). Key in the value, then press the R/S key. After keying in each input value, the key R/S should be pressed to resume the calculation.

2) The second prompt is "AMP2 AS IS ?" Key in the amplitude value, not the phase angle, of the original unbalance response at the probe #2, namely W_2^0, then press the key R/S .

3) The third prompt is "TRIAL WEIGHT1 ?" Key in the weight of the first trial weight at the balancing plane #1, then press the key R/S .

4) Similarly, the next five prompts are:

i) "AMP1 TRIAL1 ?"
ii) "AMP2 TRIAL1 ?"
iii) "TRIAL WEIGHT2 ?"
iv) "AMP1 TRIAL2 ?"
v) "AMP2 TRIAL2 ?"

They mean "Please key in the values of:

i) Amplitude at probe #1 with the trial weight at plane #1,
ii) Amplitude at probe #2 with the trial weight at plane #1,
iii) Trial weight at the balancing plane #2,
iv) Amplitude at probe #1 with the trial weight at plane #2,
v) Amplitude at probe #2 with the trial weight at plane #2,
respectively.

5) The next 8 prompts ask for the phase angles:

i) "PHASE1 AS IS ?"
ii) "PHASE2 AS IS ?"
iii) "TRIAL ANGLE1 ?"
iv) "PHASE1 TRIAL1 ?"
v) "PHASE2 TRIAL1 ?"
vi) "TRIAL ANGLE2 ?"
vii) "PHASE1 TRIAL2 ?"
viii) "PHASE2 TRIAL2 ?"

The unit of phase angle is "degree". Corresponding values to be keyed in after each prompt listed above are:

i) The value of original or "as is" phase angle at probe #1.
ii) The value of original or "as is" phase angle at probe #2.
iii) Phase angle of the trial weight at balancing plane #1.
iv) Phase angle at probe #1 with trial weight at plane #1.
v) Phase angle at probe #2 with trial weight at plane #1.
vi) Phase angle of the trial weight at balancing plane #2.
vii) Phase angle at probe #1 with trial weight at plane #2.
viii) Phase angle at probe #2 with trial weight at plane #2.

After keying in all the values, one at a time followed by the R/S key, the "program execution symbol" will appear on the display and will travel from the left end to the right end of the display. The motion of the "program execution symbol" on the display of the calculator means that the program is being executed. After the symbol traverses the display approximately five times from left to right, the first computed correction weight is displayed. After the figures stop in the display, the R/S key should be pressed to proceed to the next computed correctional weight.

The program has been tested both by comparison with cases in numerous references (Refs. 1 and 2) and by actual balancing trials. An example from Ref. 1 is given in Appendix III.

3. CONCLUSION

A computing program for two plane balancing has been completed and stored in the HP41-C hand-held programmable calculator for field balancing purposes. This program permits 2 plane balancing calculations in the field within a fraction of a minute.

REFERENCES

(1) Thearle, E.L. — "Dynamic Balancing in the Field", Trans. ASME, 56(10), pp. 745-753 (1934).

(2) Macduff, J.N. — "A Procedure for Field Balancing Rotating Machinery", Sound and Vibration, 1(7), July 1967.

(3) Goodman, T.P. — "A Least-Squares Method for Computing Balance Corrections", Trans. ASME, J. Eng. for Ind., pp. 273-279, Aug. 1964.

(4) Tessarzik, J.M. Badgley, R.H. Anderson, W.J. — "Flexible Rotor Balancing by the Exact Point-Speed Influence Coefficient Method", Trans. ASME, J. Eng. for Ind., pp. 148-158, Feb. 1972.

(5) Lund, J.W. Tonnesen, J. — "Analysis and Experiments on Multi-Plane Balancing of a Flexible Rotor", ASME Paper No. 71-Vibr-74.

APPENDIX A

Let us denote the unbalance response vector as $\{W_1^0, W_2^0\}^t$, the unbalance vector as $\{U_1, U_2\}^t$, and the influence coefficient matrix as $\begin{bmatrix} \alpha_{11}, & \alpha_{12} \\ \alpha_{21}, & \alpha_{22} \end{bmatrix}$, then we have

$$\begin{Bmatrix} W_1^0 \\ W_2^0 \end{Bmatrix} = \begin{bmatrix} \alpha_{11}, & \alpha_{12} \\ \alpha_{21}, & \alpha_{22} \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \end{Bmatrix} \qquad (1)$$

where all the terms are complex numbers, and

W_1^0 is the original or "as is" unbalance response measured at the probe #1,
W_2^0 is the original or "as is" unbalance response measured at the probe #2,
U_1 is the unknown unbalance at the balancing plane #1,
U_2 is the unknown unbalance at the balancing plane #2,
$\alpha_{11}, \alpha_{12}, \alpha_{21}, \alpha_{22}$ are influence coefficients, for example, α_{ij} is an unbalance response at probe #i due to the unit unbalance at balancing plane #j,
$\{\ \}^t$ means transpose of the matrix.
Subscripts stand for probe locations or balancing planes, and superscripts stand for number of trials, for example, zero (0) means zeroth trial weight application which in turn, indicates original or "as is" situation while 1 or 2 means 1st or 2nd trial weight application, in the first or second balancing plane, respectively.

Suppose we have readings of unbalance responses of W_1^1 and W_2^1 at the probes #1 and #2 locations respectively, when we applied the first trial weight T_1 at the balancing plane #1. Then, the terms W_1^0, W_2^0 and U_1 in equation (1) can be replaced to W_1^1, W_2^1 and (U_1+T_1) respectively, that is,

$$\begin{Bmatrix} W_1^1 \\ W_2^1 \end{Bmatrix} = \begin{bmatrix} \alpha_{11}, & \alpha_{12} \\ \alpha_{21}, & \alpha_{22} \end{bmatrix} \begin{Bmatrix} U_1+T_1 \\ U_2 \end{Bmatrix} \qquad (2)$$

Similarly, we can get the following equation when we put the second trial weight T_2 at the balancing plane #2,

$$\begin{Bmatrix} W_1^2 \\ W_2^2 \end{Bmatrix} = \begin{bmatrix} \alpha_{11}, & \alpha_{12} \\ \alpha_{21}, & \alpha_{22} \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2+T_2 \end{Bmatrix} \qquad (3)$$

Note that the first trial weight T_1 has been removed from the balancing plane #1 before the second trial weight T_2 is applied to the balancing plane #2. Now we have 6 linearly independent equations for 6 unknowns namely, α_{11}, α_{12}, α_{21}, α_{22}, U_1 and U_2. Therefore, the system becomes mathematically deterministic and can be solved as below.

Subtracting eq. (1) from eq. (2), we have

$$\begin{Bmatrix} W_1^1 - W_1^0 \\ W_2^1 - W_2^0 \end{Bmatrix} = \begin{bmatrix} \alpha_{11}, & \alpha_{12} \\ \alpha_{21}, & \alpha_{22} \end{bmatrix} \begin{Bmatrix} T_1 \\ 0 \end{Bmatrix}$$

Solving for α_{11} and α_{21}, we have

$$\alpha_{11} = \frac{W_1^1 - W_1^0}{T_1} \tag{4}$$

$$\alpha_{21} = \frac{W_2^1 - W_2^0}{T_1} \tag{5}$$

Similarly, by subtracting eq. (1) from eq. (3) and solving for α_{12} and α_{22}, we have

$$\alpha_{12} = \frac{W_1^0 - W_1^0}{T_2} \tag{6}$$

$$\alpha_{22} = \frac{W_2^2 - W_2^0}{T_2} \tag{7}$$

Substituting eqs. (4) to (7), into eq. (1) and solving for U_1 and U_2, we have

$$\begin{Bmatrix} U_1 \\ U_2 \end{Bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix}^{-1} \begin{Bmatrix} W_1^0 \\ W_2^0 \end{Bmatrix} = \frac{1}{\alpha_{11}\cdot\alpha_{22} - \alpha_{12}\cdot\alpha_{21}} \begin{Bmatrix} \alpha_{22}W_1^0 - \alpha_{12}W_2^0 \\ (-\alpha_{21}W_1^0 + \alpha_{11}W_2^0) \end{Bmatrix}$$

Therefore, the correction weights to be added to the system, namely U_{C1} and U_{C2}, respectively, should be opposite to U_1 and U_2, respectively. That is,

$$U_{C1} = -U_1 = \frac{\alpha_{12}W_2^0 - \alpha_{22}W_1^0}{\alpha_{11}\cdot\alpha_{22} - \alpha_{12}\alpha_{21}} \quad , \text{ and}$$

$$U_{C2} = -U_2 = \frac{\alpha_{21}W_1^0 - \alpha_{11}W_2^0}{\alpha_{11}\alpha_{22} - \alpha_{12}\alpha_{21}}$$

APPENDIX B

Whenever quotation marks (") appear around a character or a string of characters in the program listing, the characters are alphanumeric. To key them in, simply press ALPHA , key in the characters, then press ALPHA again. For example, "SAMPLE" would be keyed in as ALPHA S A M P L E ALPHA.

```
Ø1 *LBL "BALANCE"
Ø2 "AMP1 AS IS ?"
Ø3 PROMPT
Ø4 STO Ø1
Ø5 "AMP2 AS IS ?"
Ø6 PROMPT
Ø7 STO Ø2
Ø8 "TRIAL WEIGHT1 ?"
Ø9 PROMPT
1Ø STO Ø3
11 "AMP1 TRIAL1 ?"
12 PROMPT
13 STO Ø4
14 "AMP2 TRIAL1 ?"
15 PROMPT
16 STO Ø5
17 "TRIAL WEIGHT2 ?"
18 PROMPT
```

```
19 STO Ø6
20 "AMP1 TRIAL2 ?"
21 PROMPT
22 STO Ø7
23 "AMP2 TRIAL2 ?"
24 PROMPT
25 STO Ø8
26 "PHASE1 AS IS ?"
27 PROMPT
28 STO 11
29 "PHASE2 AS IS ?"
30 PROMPT
31 STO 12
32 "TRIAL ANGLE1 ?"
33 PROMPT
34 STO 13
35 "PHASE1 TRIAL1 ?"
36 PROMPT
37 STO 14
38 "PHASE2 TRIAL1 ?"
39 PROMPT
40 STO 15
41 "TRIAL ANGLE2 ?"
42 PROMPT
```

```
43 STO 16
44 "PHASE1 TRIAL2 ?"
45 PROMPT
46 STO 17
47 "PHASE2 TRIAL2 ?"
48 PROMPT
49 STO 18
50 XEQ "W11"
51 XEQ "W1Ø"
52 XEQ "CSUB"
53 XEQ "T1"
54 XEQ "CDIV"
55 STO 21
56 X <> Y
57 STO 31
58 XEQ "W21"
59 XEQ "W2Ø"
60 XEQ "CSUB"
61 XEQ "T1"
62 XEQ "CDIV"
63 STO 22
64 X <> Y
65 STO 32
66 XEQ "W12"
```

```
67 XEQ "W1Ø"
68 XEQ "CSUB"
69 XEQ "T2"
70 XEQ "CDIV"
71 STO 23
72 X <> Y
73 STO 33
74 XEQ "W22"
75 XEQ "W2Ø"
76 XEQ "CSUB"
77 XEQ "T2"
78 XEQ "CDIV"
79 STO 24
80 X <> Y
81 STO 34
82 XEQ "ALPHA12"
83 XEQ "ALPHA21"
84 XEQ "CMULT"
85 STO 29
86 X <> Y
87 STO 39
88 XEQ "ALPHA11"
89 XEQ "ALPHA22"
90 XEQ "CMULT"
```

```
 91 RCL 39
 92 RCL 29
 93 XEQ "CSUB"
 94 STO 25
 95 X <> Y
 96 STO 35
 97 XEQ "ALPHA22"
 98 XEQ "W1Ø"
 99 XEQ "CMULT"
100 STO 26
101 X <> Y
102 STO 36
103 XEQ "ALPHA12"
104 XEQ "W2Ø"
105 XEQ "CMULT"
106 RCL 36
107 RCL 26
108 XEQ "CSUB"
109 XEQ "DENOM"
110 XEQ "CDIV"
111 XEQ "UC1"
112 STOP
113 XEQ "ALPHA11"
```

```
114 XEQ "W2Ø"
115 XEQ "CMULT"
116 STO 27
117 X <> Y
118 STO 37
119 XEQ "ALPHA21"
120 XEQ "W1Ø"
121 XEQ "CMULT"
122 RCL 37
123 RCL 27
124 XEQ "CSUB"
125 XEQ "DENOM"
126 XEQ "CDIV"
127 XEQ "UC2"
128 RTN
129 *LBL "CDIV"
130 1/X
131 X <> Y
132 CHS
133 GTO ØØ
134 *LBL "CDIV"
135 X <> Y
136 *LBL ØØ
137 RDN
```

```
138 *
139 RDN
140 +
141 R↑
142 GTO Ø2
143 *LBL "CSUB"
144 P-R
145 CHS
146 X <> Y
147 CHS
148 RDN
149 RDN
150 P-R
151 R↑
152 +
153 RDN
154 +
155 R↑
156 R-P
157 *LBL Ø2
158 RTN
159 *LBL "UC1"
160 "UC1 = "
161 GTO Ø1
```

```
162 *LBL "UC2"
163 "UC2 = "
164 *LBL Ø1
165 ARCL X
166 " |- GRAMS,"
167 AVIEW
168 STOP
169 ARCL Y
170 " |- DEG"
171 AVIEW
172 RTN
173 *LBL "W11"
174 RCL 14
175 RCL Ø4
176 RTN
177 *LBL "W1Ø"
178 RCL 11
179 RCL Ø1
180 RTN
181 *LBL "W12"
182 RCL 17
183 RCL Ø7
184 RTN
185 *LBL "W21"
```

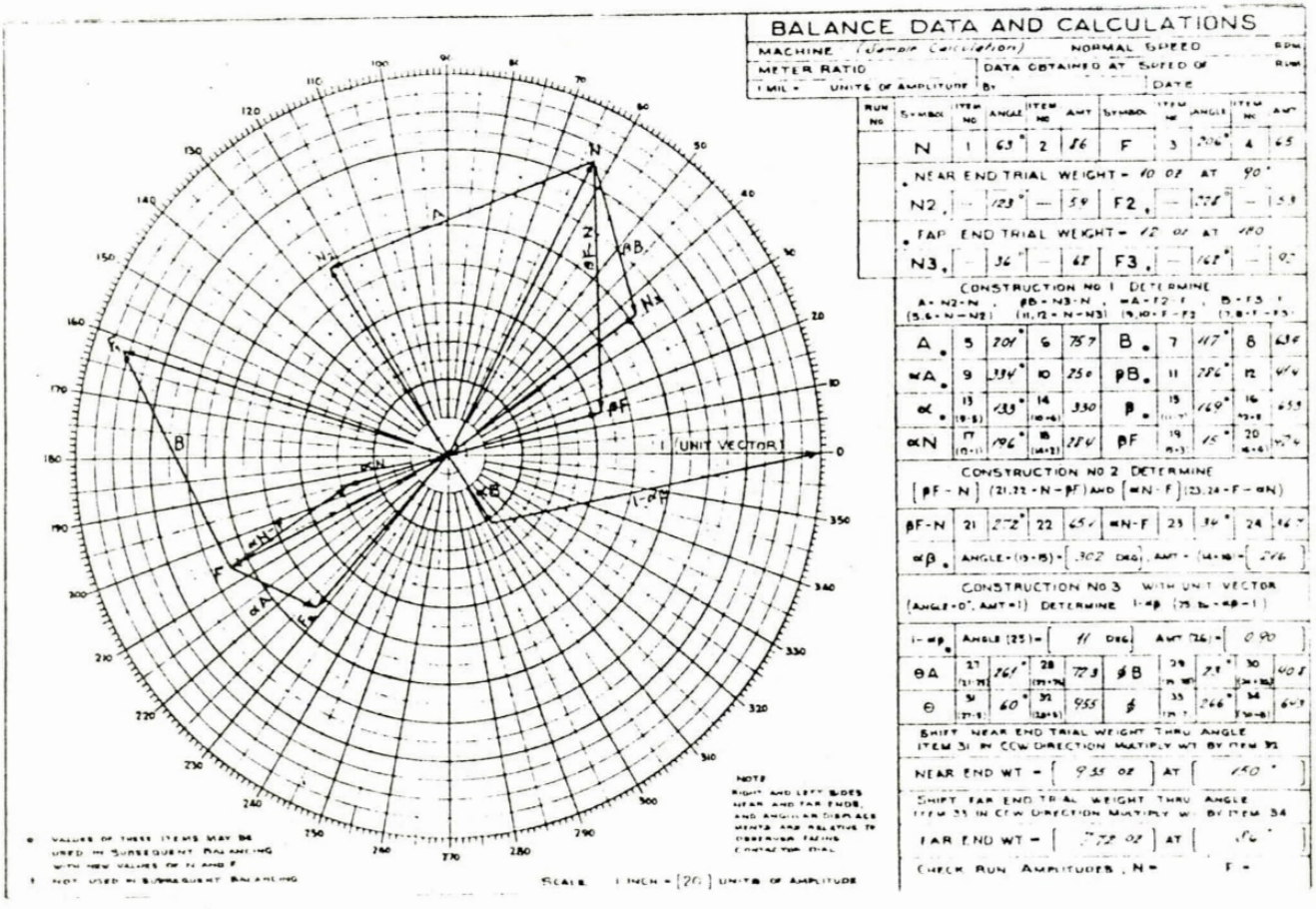
```
186 RCL 15
187 RCL Ø5
188 RTN
189 *LBL "W22"
190 RCL 18
191 RCL Ø8
192 RTN
193 *LBL "W2Ø"
194 RCL 12
195 RCL Ø2
196 RTN
197 *LBL "T1"
198 RCL 13
199 RCL Ø3
2ØØ RTN
2Ø1 *LBL "T2"
2Ø2 RCL 16
2Ø3 RCL Ø6
2Ø4 RTN
2Ø5 *LBL "ALPHA11"
2Ø6 RCL 31
2Ø7 RCL 21
2Ø8 RTN
2Ø9 *LBL "ALPHA12"
```

```
210 RCL 33
211 RCL 23
212 RTN
213 *LBL "ALPHA21"
214 RCL 32
215 RCL 22
216 RTN
217 *LBL "ALPHA22"
218 RCL 34
219 RCL 24
220 RTN
221 *LBL "DENOM"
222 RCL 35
223 RCL 25
224 RTN
225 END
```

NOTE: The asterisk in front of each LBL instruction is only a visual aid to help readers locate labels in the program listings. When a reader keys in the program, he should ignore it.

APPENDIX C: EXAMPLE

The input values of example are shown in the figure below which has been taken from reference 1.



INPUT

AMP1 AS IS	86	
AMP2 AS IS	65	
TRIAL WEIGHT1	10	(oz.)
AMP1 TRIAL1	59	
AMP2 TRIAL1	53	
TRIAL WEIGHT2	12	(oz.)
AMP1 TRIAL2	62	
AMP2 TRIAL2	92	
PHASE1 AS IS	63	
PHASE2 AS IS	206	
TRIAL ANGLE1	90	
PHASE1 TRIAL1	123	
PHASE2 TRIAL1	228	
TRIAL ANGLE2	180	
PHASE1 TRIAL2	36	
PHASE2 TRIAL2	162	

CALCULATED RESULTS

UC1 = 9.61 (oz), -211. degrees (= 149. degrees)
UC2 = 7.69 (oz), 84. degrees