API BUL 11L2
First Edition
December 1969

API

CATALOG

of

ANALOG COMPUTER DYNAMOMETER CARDS

OFFICIAL PUBLICATION

REG. U.S. PATENT OFFICE

AMERICAN PETROLEUM INSTITUTE

New York, N. Y.

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Issued by
AMERICAN PETROLEUM INSTITUTE
Division of Production
300 Corrigan Tower Bldg.
Dallas, Texas 75201

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INTRODUCTION

In 1954 a group of users and manufacturers of sucker rod pumping equipment undertook a study in depth of the many complex problems associated with this means of lifting fluid from a well. To control and direct the effort, Sucker Rod Pumping Research, Incorporated, a non-profit organization was created. The services of Midwest Research Institute at Kansas City were retained to perform the work necessary to achieve the objectives of the organization.

As a part of this project, more than 1100 polished rod dynamometer cards were taken with the electronic analog simulator at Midwest Research Institute. These were reorganized and presented in catalog form as *Summary Report Vol. II of II, January 1 - December 31, 1960, M.R.I. Project No. 2376-E.* Sucker Rod Pumping Research, Incorporated, before its dissolution, released this catalog of cards to the American Petroleum Institute. It was determined by the Committee on Standardization of Production Equipment at the Midyear Standardization Conference and reported in Circ PS-1382 dated August, 1969 that the catalog would be published by the API Dallas office for the cost of reproduction.

Nomenclature is that used in API RP 11L: *Recommended Practice for Design Calculations for Sucker Rod Pumping Systems.* The cards were derived for many combinations of the independent non-dimensional parameters Fo/Sk_r and N/Nó. The cards are published for information and reference.

A discussion of the information presented, including an explanation of the numbers and material on the card sheets, may be found in the following paragraphs. Suggestions for card use are also given. This discussion is included through the courtesy of Mr. M. H. Halderson, Phillips Petroleum Company.

NOMENCLATURE AND SUGGESTIONS FOR USE

The reference line on analog cards is the weight of rods in the fluid, Wrf. The distance from the reference line to the peak load is F_1/Sk_r, and the distance from the reference line to the minimum load is F_2/Sk_r. The vertical scale is one inch equals 1.0. There has been a slight shrinkage in reproduction in some cases.

Tubing was anchored on all tests made with the electronic analog computer.

All of the dynamometer cards were taken under conditions which simulated full filling of the pump barrel. There was no fluid or gas pound. Therefore, the card shapes are representative of good bottom hole pumping conditions. Deviations in shape of cards occur when wells are pounding fluid or when pumps are handling gas or for other reasons such as plunger sticking, tubing buckling, excessive paraffin deposits, worn plungers, leaking valves, etc.

Dynamometer cards taken in the field are compared with typical cards from the analog by calculating Fo/Sk_r and N/Nó for the conditions that prevailed when the card was taken and then observing analog dynamometer cards for the same conditions.

On field tests, the variables S, k, N, and Nó can usually be determined quite accurately, but often the true Fo (differential plunger load) cannot be determined from information that is available. It is therefore well to compare field cards with analog cards for values of Fo/Sk_r other than calculated for the field test.

The typical dynamometer cards can sometimes be used in a reverse manner to determine Fo. The value of N/Nó is calculated for the test conditions. Then the field card is compared to analog cards with different values of Fo/Sk_r but actual N/Nó to find the group with the greatest similarity to the field card. The value of Fo/Sk_r for this group is then used to determine Fo.

Of particular significance is the similarity of all of the dynamometer cards on each page which in each case are cards for a given Fo/Sk_r and N/Nó. For each Fo/Sk_r and N/Nó there is a unique general card shape which is only slightly modified by the other system variables studied. These variables and the tests related to the study of the variables are:

Second harmonic in polished rod motion .... Tests A, B, H

Comparison of pump damping and string damping .... Tests B, C, D

Comparison of pump damping .... Tests B, C

Study of string damping .... Tests C, E, F

Tapered rod string .... Tests C, J, I; L, M, N; O, P, Q

Prime mover slip and inertia .... Tests C, L, O; J, M, P; I, N, Q

Each card is designated by the letter of the particular test series. The percentages of second harmonic, the string damping, and the pump damping are designated respectively by the three top numbers. For example, the notation 6-10-0 signifies

6 percent second harmonic
10 percent string damping
0 percent pump damping

Analog dynamometer cards on any page are for the same N/Nó, that is, the cards are for a given ratio of pumping speed to the natural frequency of the particular rod string. Because the natural frequencies of tapered rod strings are higher than straight strings, tapered strings will be operating at higher strokes per minute than straight strings with the same N/N6 in wells of the same depth. Higher actual strokes per minute result in more work done in given time and this is obtained with higher peaks, lower minimums, and greater load ranges. For example, refer to dynamometer cards O, P, and Q for $Fo/Sk_r = 0.3$, $N/N6 = 0.5$. Here it is seen that load range increases significantly in going from a straight rod string to a two-way taper and from a two-way taper to a three-way taper. The frequency factors, Fc, for the rod strings simulated on these tests were respectively 1.00, 1.095, and 1.16. This means that in a given well, the two-way tapered string would be pumping 9.5 percent faster than the straight string and the three-way tapered string would be pumping 16 percent faster than the straight string for the same N/N6.

TEST CONDITIONS

A. Second Harmonic in Polished Rod Motion

Tests A, B and H were conducted to show the effects of second harmonic in the polished rod motion. The polished rod motion is given by:

$$Y_o = -S/2\ (\cos\omega t + b \cos 2\omega t.)$$

Where: Y_o = polished rod position, inches
S = polished rod stroke, inches
b = amplitude of second harmonic relative to 1.0 for the fundamental
ω = angular velocity of crank, radians/sec
t = time, seconds

Test	Coefficient b
A	0.00
B	0.06
H	0.12

A straight rod string with 10 percent damping and a pump with no fluid damping were used for the three tests.

Except for tests A and H, the cards were taken with 6 percent second harmonic, which is normal for conventional pumping units.

B. Comparison of Pump Damping and String Damping

Tests B, C, and D illustrate the effect of pump plunger damping and compare it to an increasing rod string damping. From field data available, it was concluded that a power loss in the fluid column equal to the power loss in the rod string would best simulate the average field conditions. A ratio of three to one between upstroke and downstroke damping on the plunger was chosen as a representative value. Test C was completed under these conditions. For comparison, Test D was run with no pump damping, but with the string damping increased from 10 percent to 20 percent. A straight rod string and a polished rod motion containing 6 percent second harmonic were used for these three tests. In general, moderate increases in damping smooth the card and increase its area somewhat without changing the general character or shape.

C. Rod String Damping

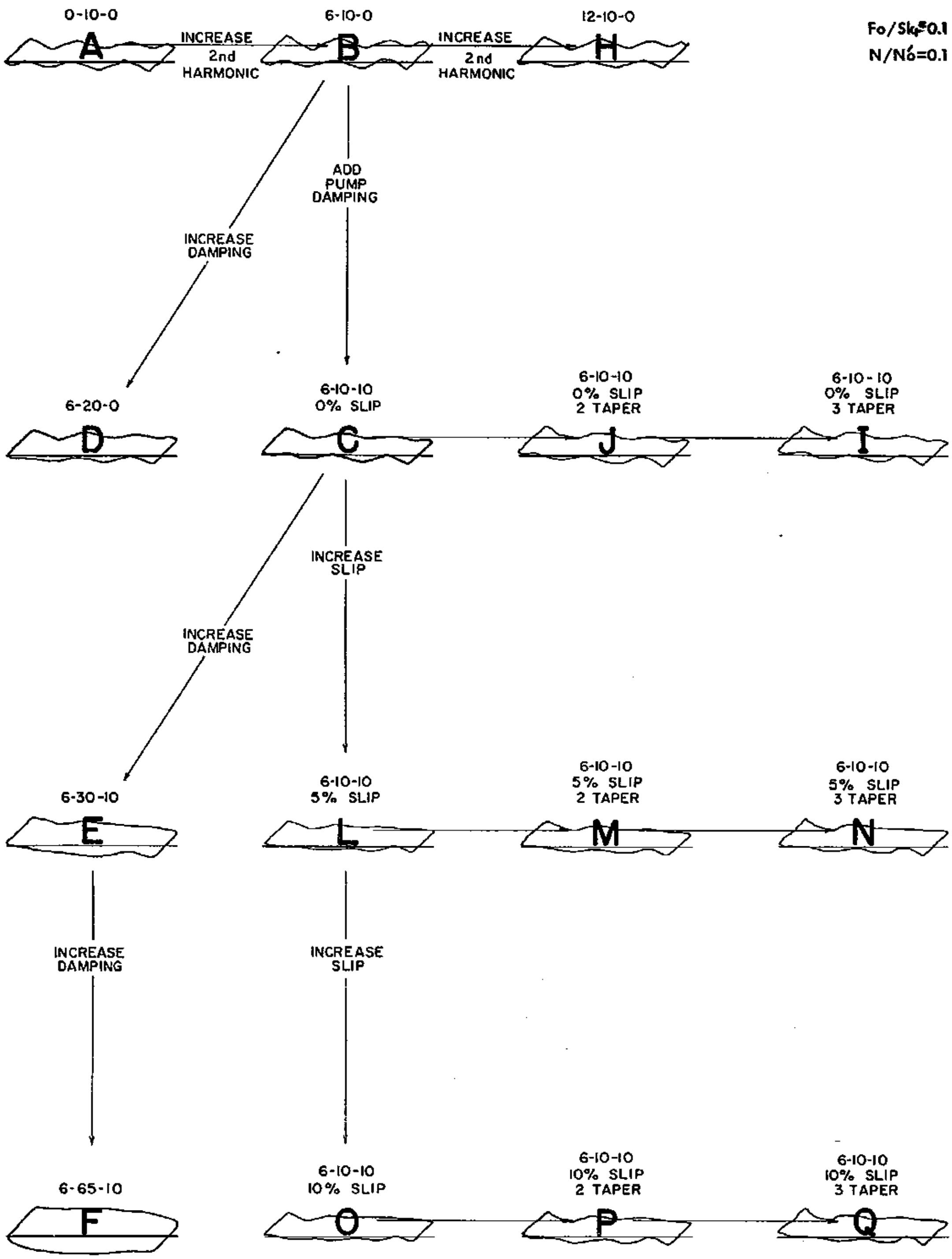
Tests C, E, and F show the effect of increased string damping. The pump damping was held constant for all tests and the string damping was set successively to 10 percent, 30 percent and 65 percent. High string damping tends to round out the cards and appreciably increase the card area, particularly when N/N6 exceeds 0.20. A straight string and a polished rod motion containing 6 percent second harmonic were used for all of these tests.

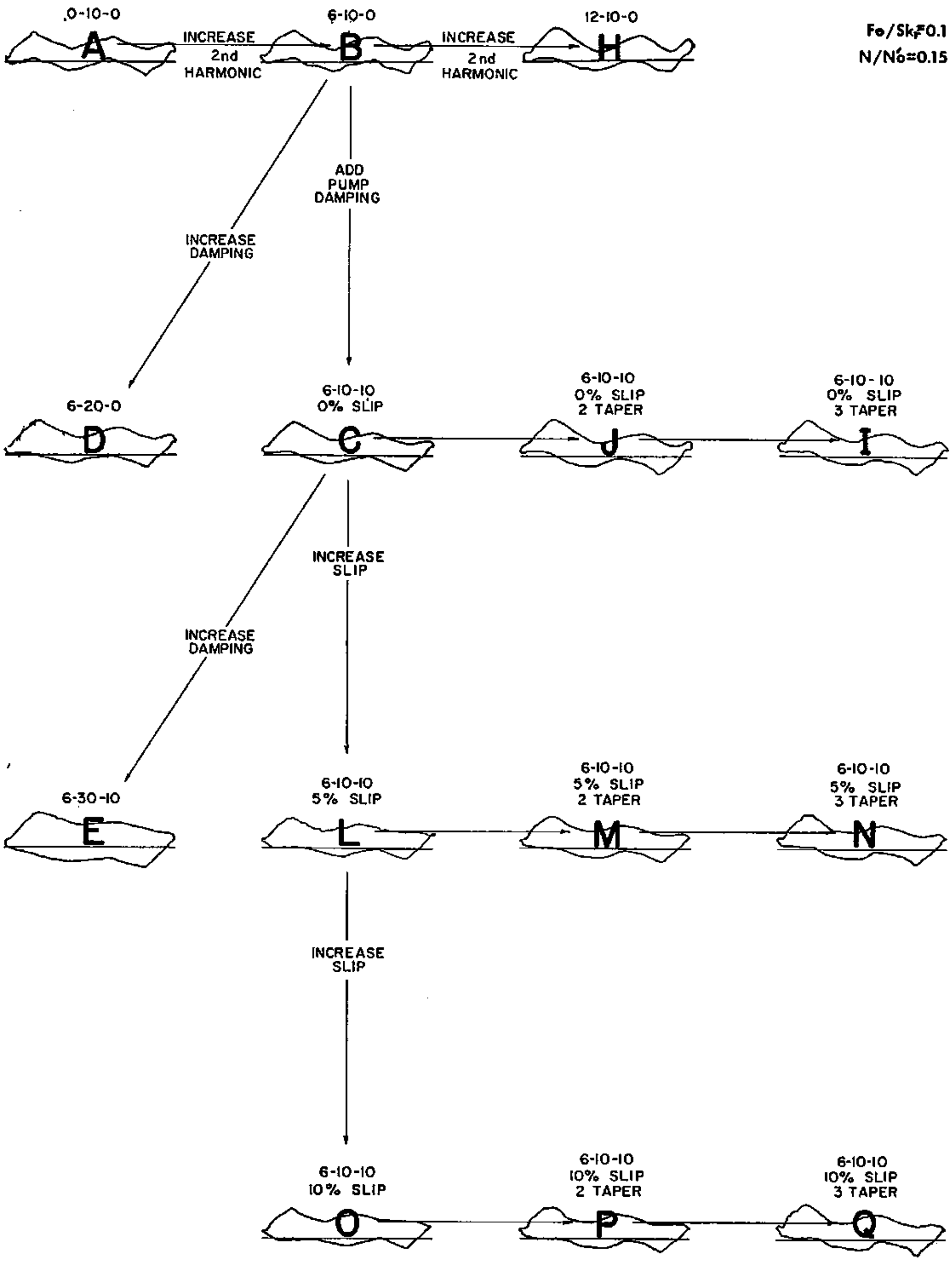
D. Tapered Rod Strings

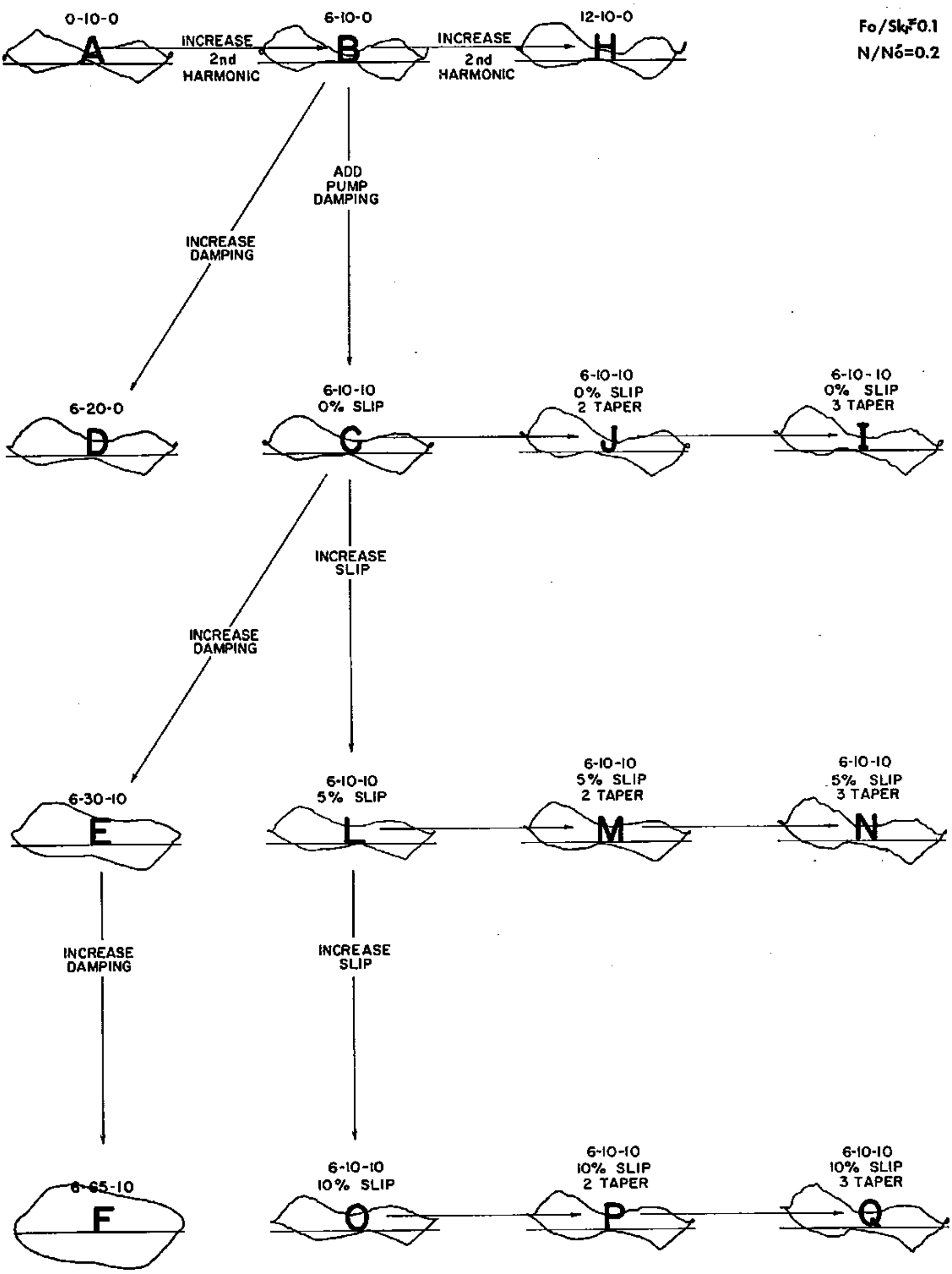
Tests C, J, I; L, M, N; and O, P, Q show the effect of tapered rod strings. Tests C, L, and O were made with straight strings. Tests J, M, and P used a rod string of 50 percent ⅞ inch and 50 percent ¾ inch rods. Test I used a string consisting of 32 percent 1 inch rods, 36 percent ⅞ inch rods and 32 percent ¾ inch rods. These percentages were chosen to show the maximum effect of the tapered strings. Tests N and Q used a string of 28 percent 1 inch rods, 33 percent ⅞ inch, and 39 percent ¾ inch. A polished rod motion containing 6 percent second harmonic and a string damping of 10 percent was used in the three tests.

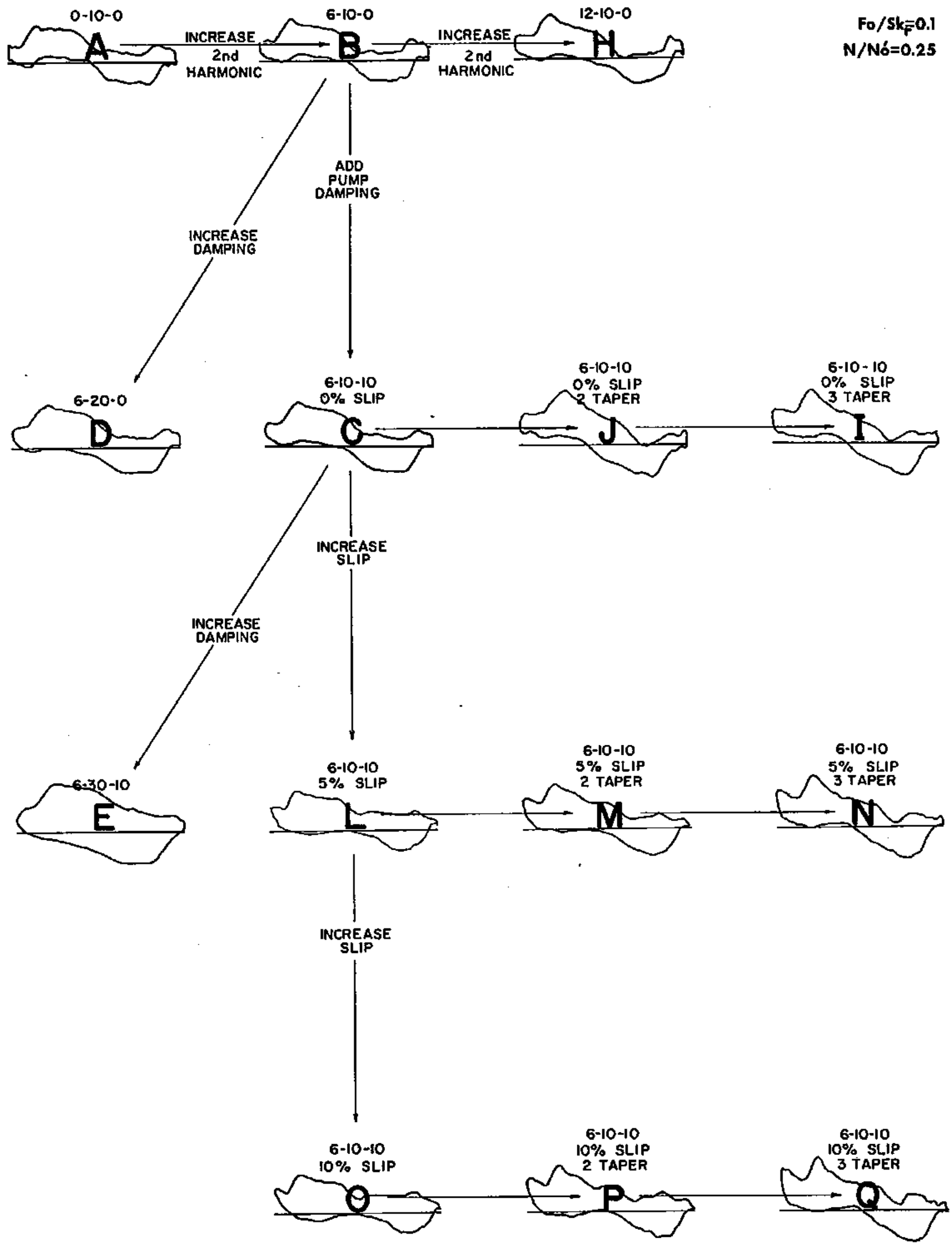
E. Prime Mover Slip

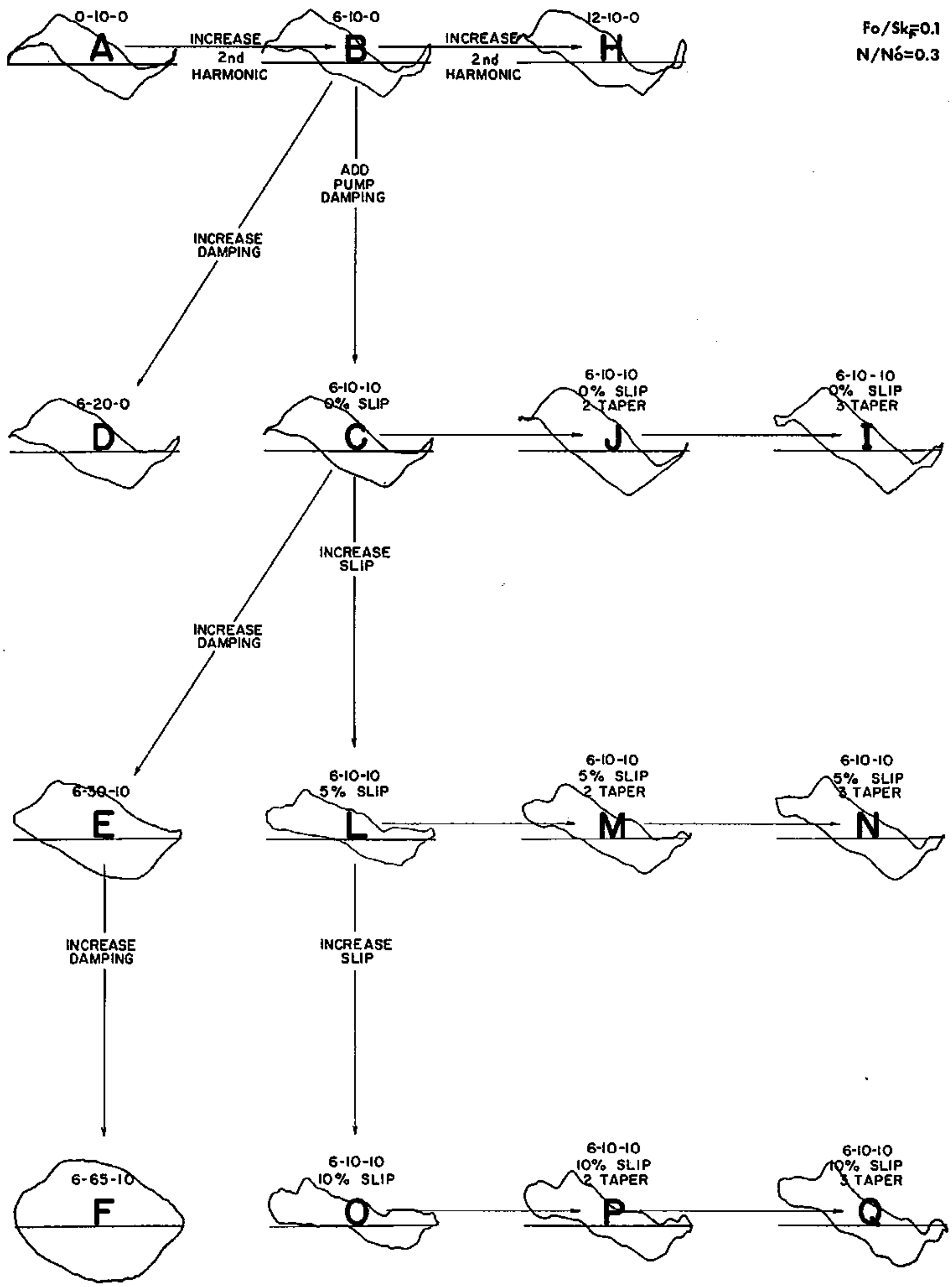
Tests L, M, N, O, P and Q were conducted to show the effect of prime mover slip. Tests L, M, and N employed a pumping unit having 5 percent prime mover slip and Tests O, P and Q used 10 percent slip. Tests C, L, and O are comparable for straight rod strings with 0, 5, and 10 percent slip. Tests J, M and P are comparable for two-way tapered strings and Tests I, N and Q for three-way tapered strings. General character of cards is the same but changes in shape at the ends of the stroke sometimes result, as shown for the test where $Fo/Sk_r = 0.4$, $N/N6 = 0.2$.

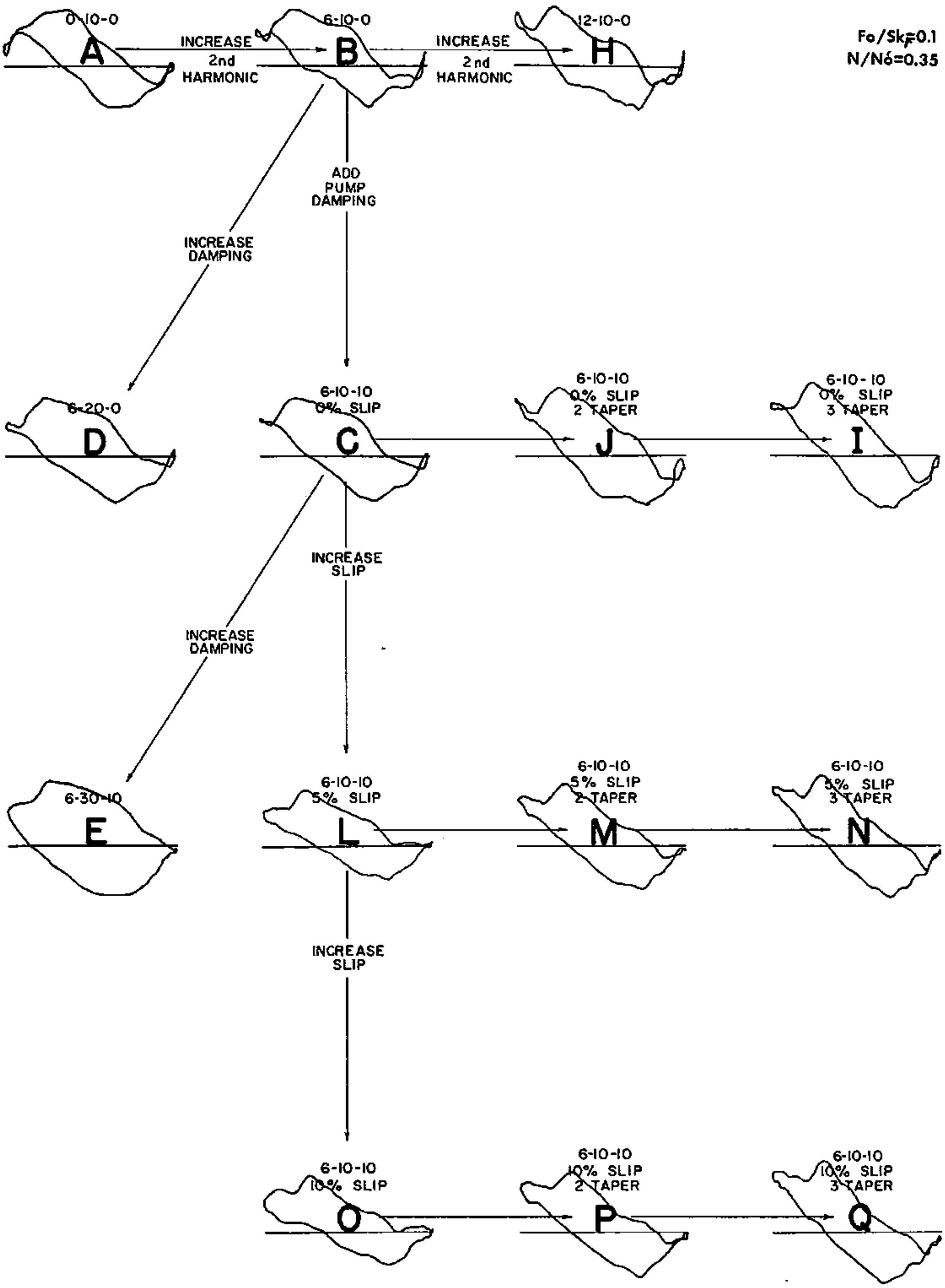

0-10-0
A
INCREASE 2nd HARMONIC
6-10-0
B
INCREASE 2nd HARMONIC
12-10-0
H
Fo/Sk=0.1
N/Nó=0.1
INCREASE DAMPING
ADD PUMP DAMPING
6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE DAMPING
INCREASE SLIP
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE DAMPING
INCREASE SLIP
6-65-10
F
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q

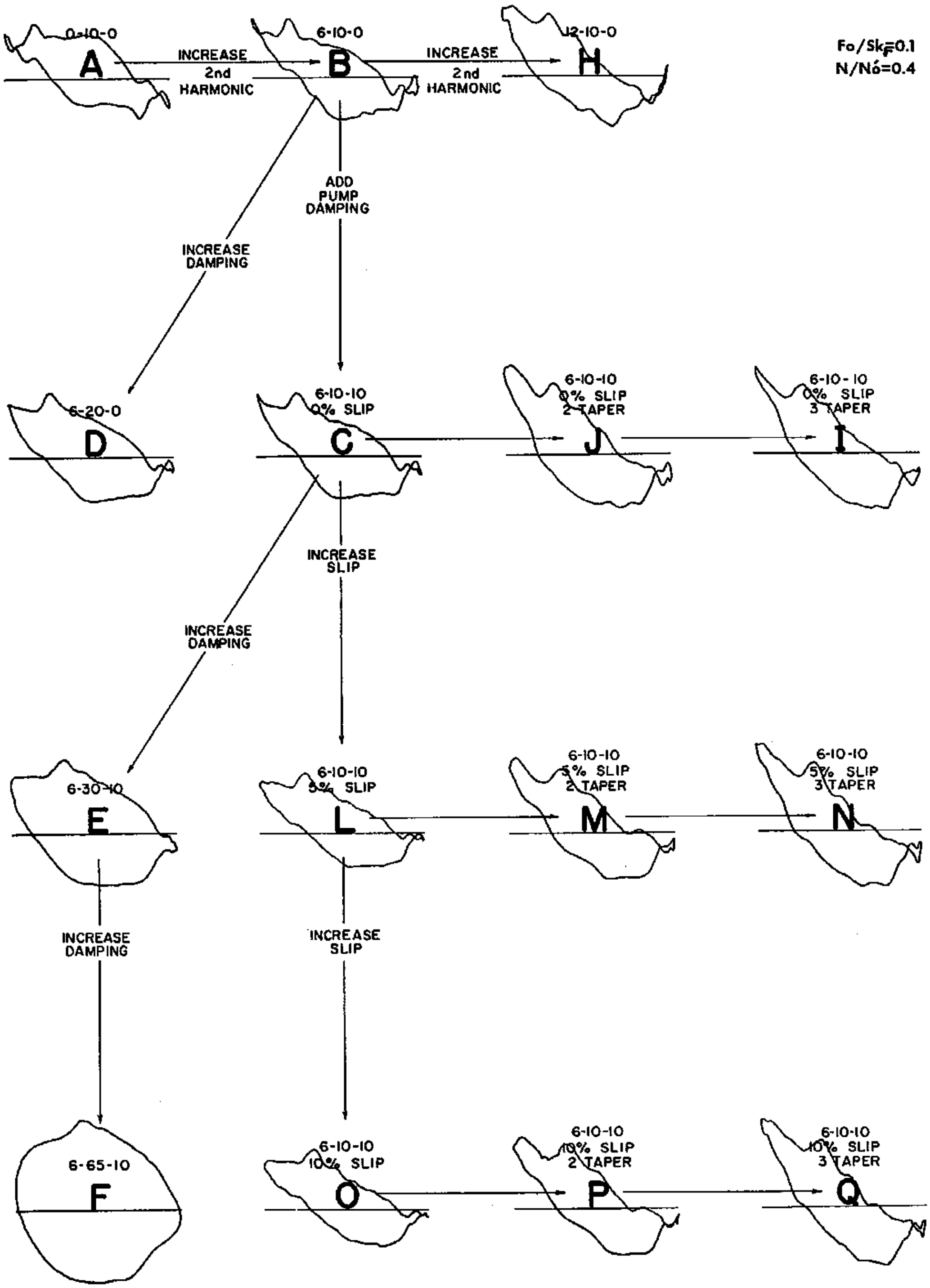

0-10-0
A
INCREASE
2nd
HARMONIC
6-10-0
B
INCREASE
2nd
HARMONIC
12-10-0
H
Fo/Skr=0.1
N/No'=0.15
ADD
PUMP
DAMPING
INCREASE
DAMPING
6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE
SLIP
INCREASE
DAMPING
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE
SLIP
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q

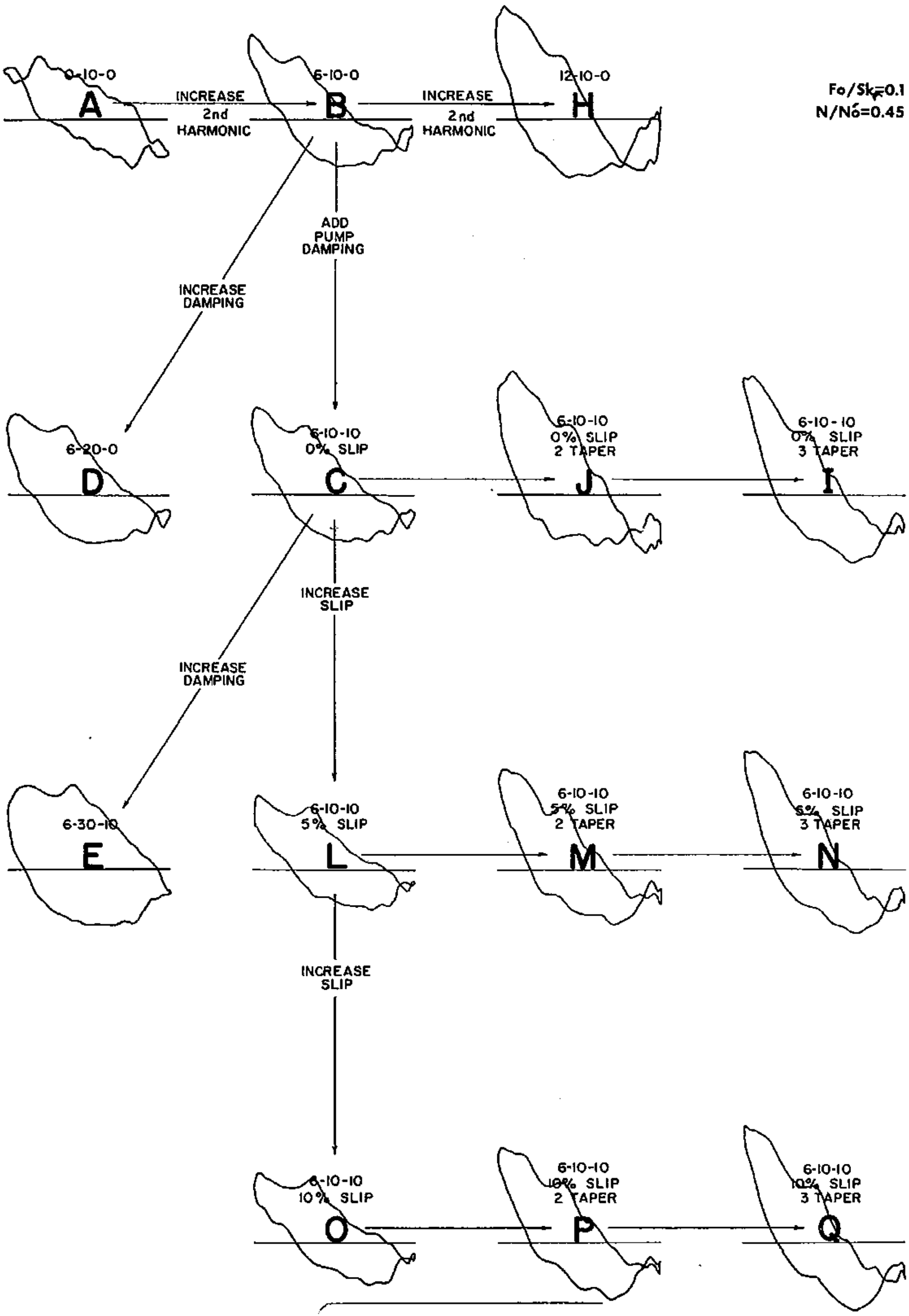

0-10-0
A
INCREASE
2nd
HARMONIC
6-10-0
B
INCREASE
2nd
HARMONIC
12-10-0
H
Fo/Sk=0.1
N/No=0.2
INCREASE
DAMPING
ADD
PUMP
DAMPING
6-20-0
D
6-10-10
0% SLIP
G
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE
DAMPING
INCREASE
SLIP
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE
DAMPING
INCREASE
SLIP
6-65-10
F
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q

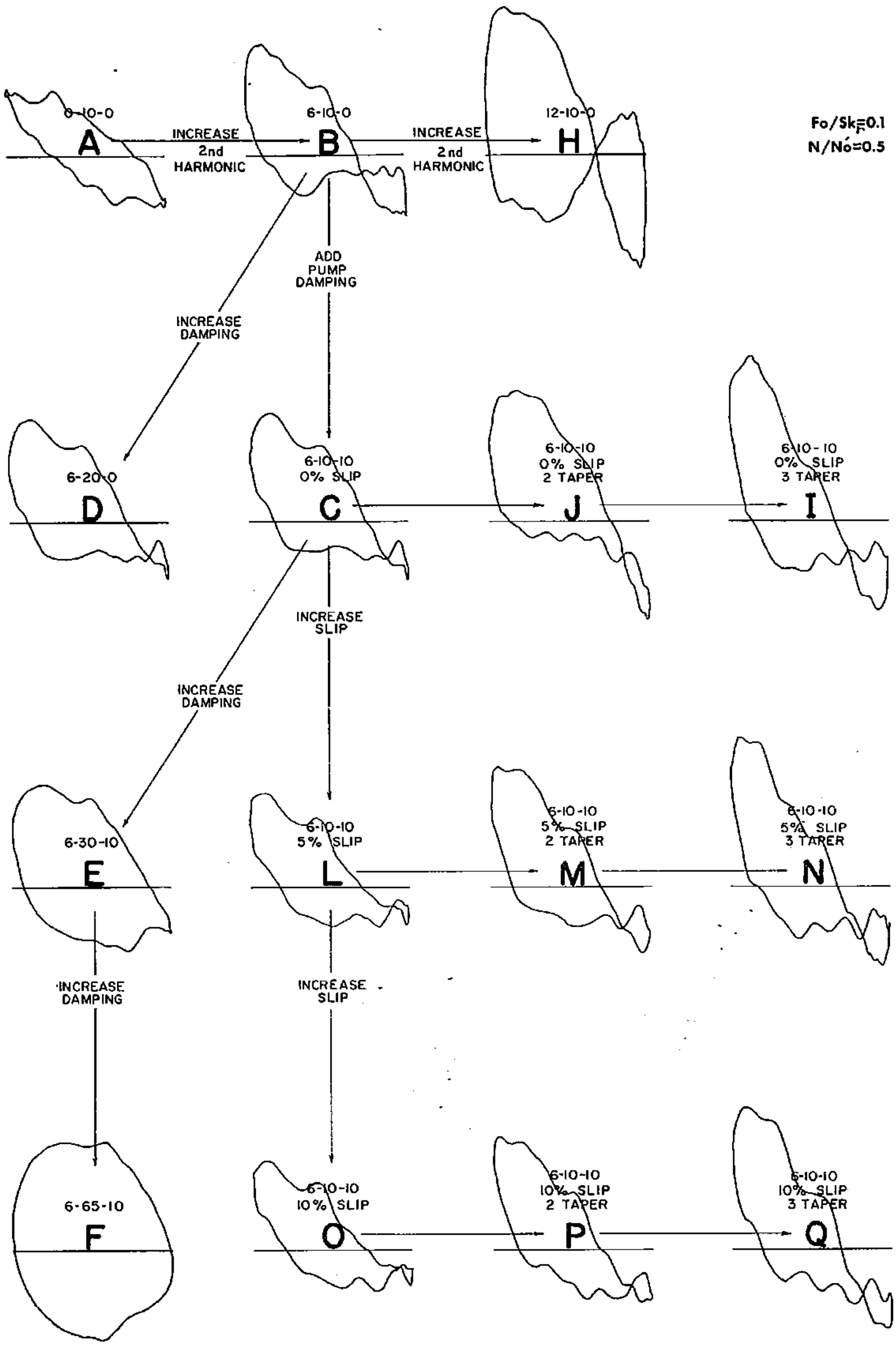

0-10-0
A
INCREASE 2nd HARMONIC
6-10-0
B
INCREASE 2nd HARMONIC
12-10-0
H
Fo/Sk=0.1
N/No'=0.25
ADD PUMP DAMPING
INCREASE DAMPING
6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE SLIP
INCREASE DAMPING
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE SLIP
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q

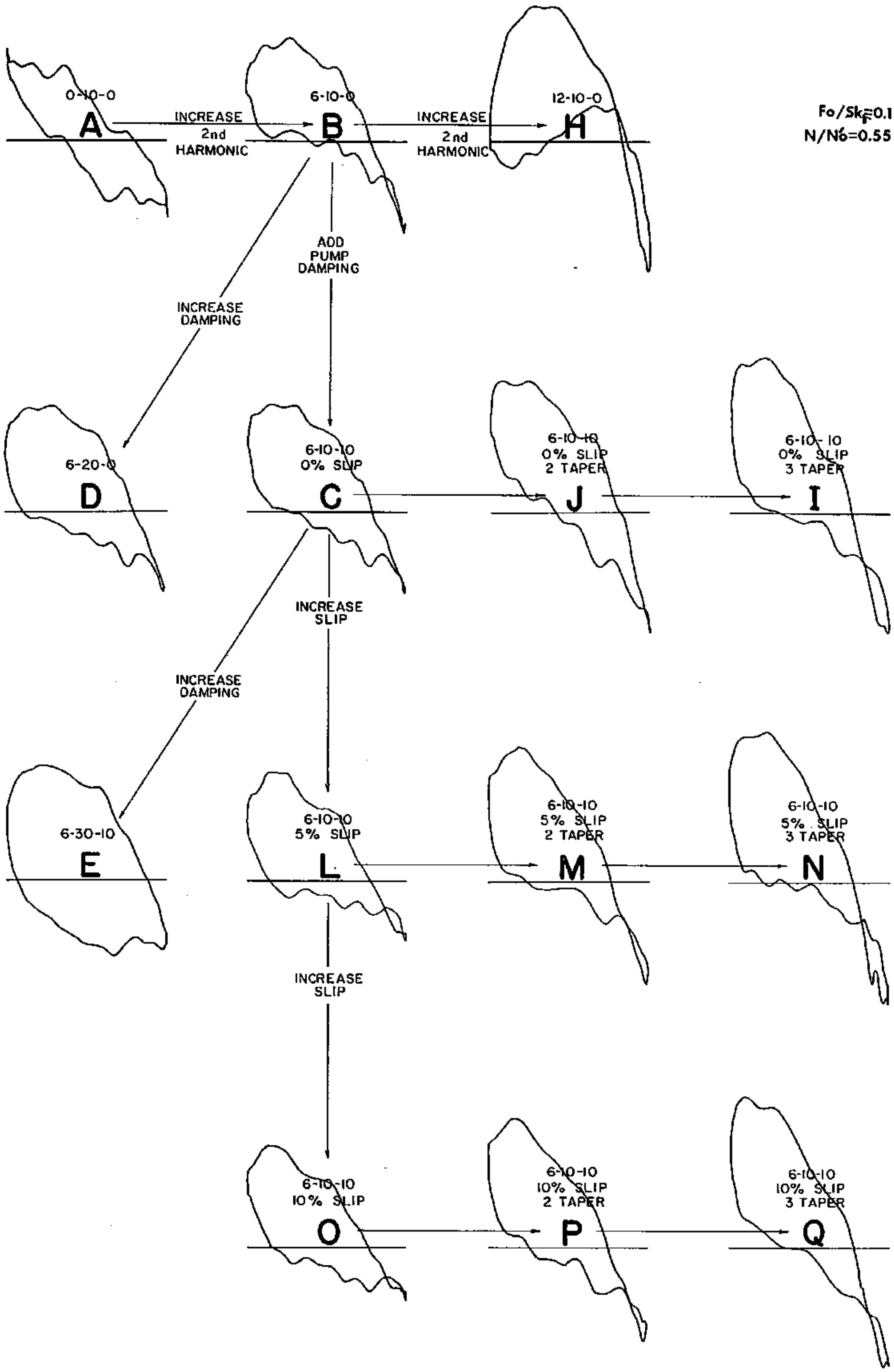

Fo/SkF=0.1
N/No=0.3
0-10-0
A
INCREASE 2nd HARMONIC
6-10-0
B
INCREASE 2nd HARMONIC
12-10-0
H
ADD PUMP DAMPING
INCREASE DAMPING
6-20-0
D
6-10-10 0% SLIP
C
6-10-10 0% SLIP 2 TAPER
J
6-10-10 0% SLIP 3 TAPER
I
INCREASE SLIP
INCREASE DAMPING
6-30-10
E
6-10-10 5% SLIP
L
6-10-10 5% SLIP 2 TAPER
M
6-10-10 5% SLIP 3 TAPER
N
INCREASE DAMPING
INCREASE SLIP
6-65-10
F
6-10-10 10% SLIP
O
6-10-10 10% SLIP 2 TAPER
P
6-10-10 10% SLIP 3 TAPER
Q

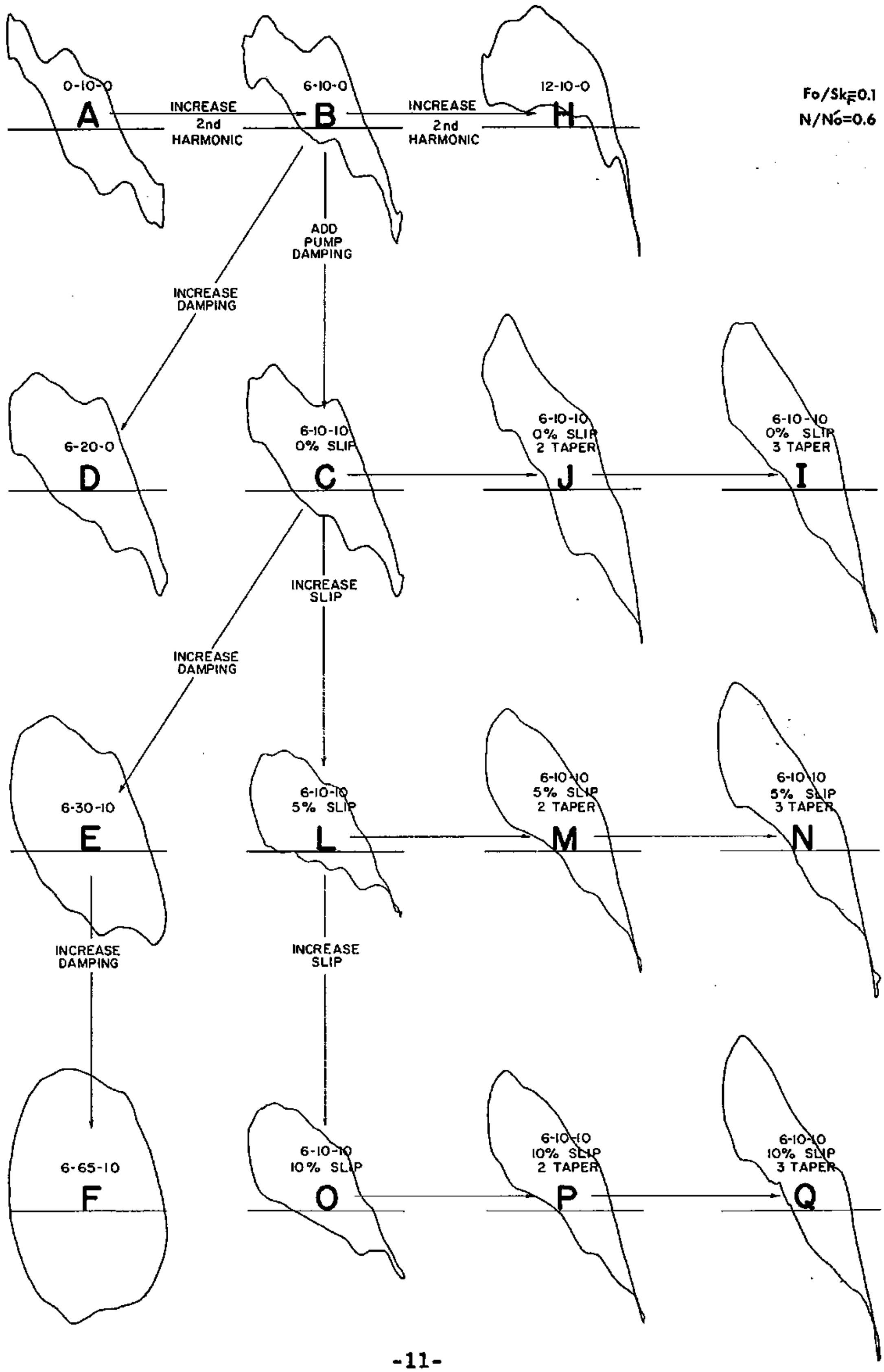

0-10-0
A
INCREASE 2nd HARMONIC
6-10-0
B
INCREASE 2nd HARMONIC
12-10-0
H
Fo/Skr=0.1
N/No=0.35
ADD PUMP DAMPING
INCREASE DAMPING
6-20-0
D
6-10-10 0% SLIP
C
6-10-10 0% SLIP 2 TAPER
J
6-10-10 0% SLIP 3 TAPER
I
INCREASE SLIP
INCREASE DAMPING
6-30-10
E
6-10-10 5% SLIP
L
6-10-10 5% SLIP 2 TAPER
M
6-10-10 5% SLIP 3 TAPER
N
INCREASE SLIP
6-10-10 10% SLIP
O
6-10-10 10% SLIP 2 TAPER
P
6-10-10 10% SLIP 3 TAPER
Q

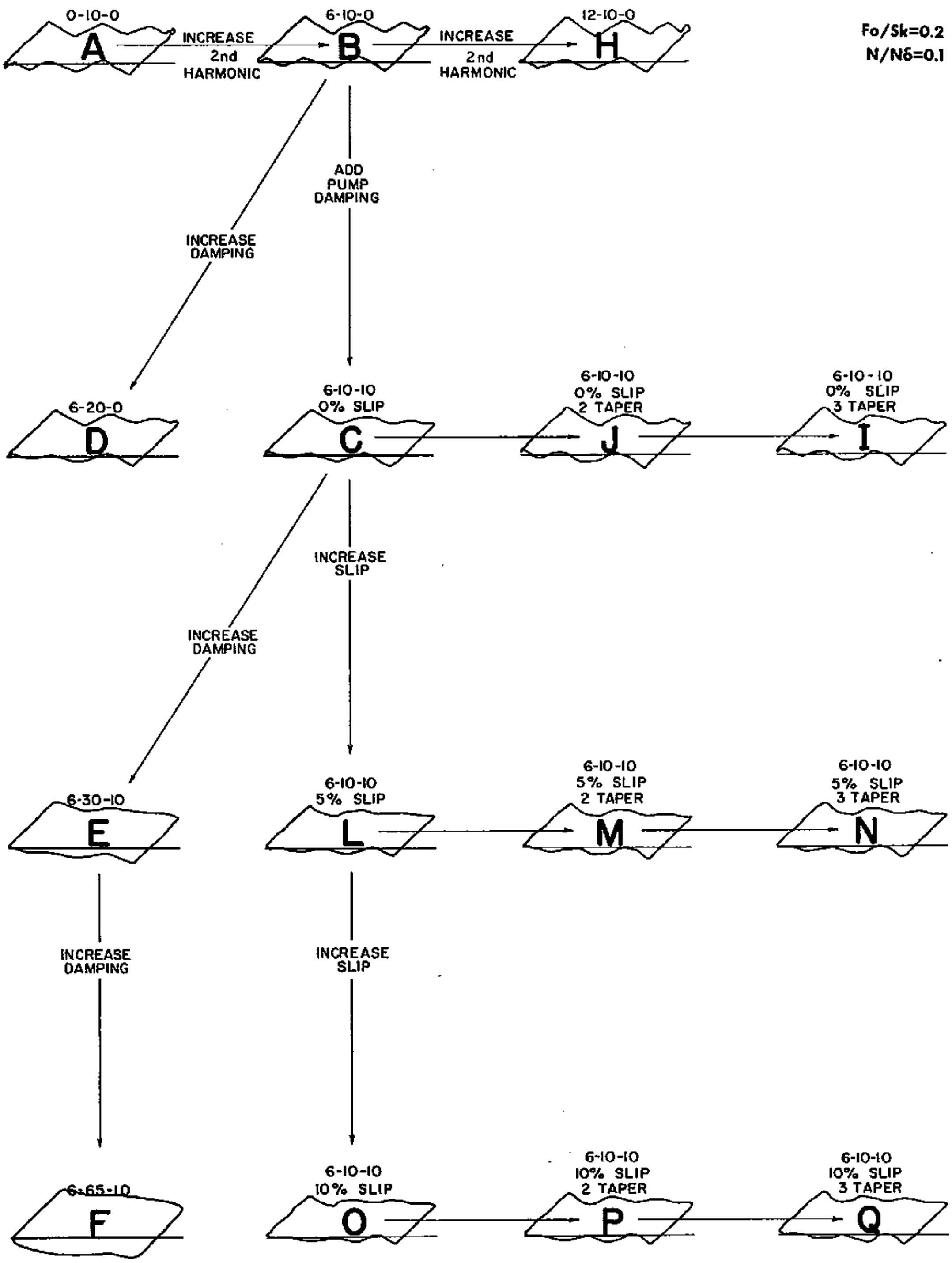

Fo/Sk=0.1
N/No=0.4
0-10-0
A
INCREASE 2nd HARMONIC
6-10-0
B
INCREASE 2nd HARMONIC
12-10-0
H
ADD PUMP DAMPING
INCREASE DAMPING
6-20-0
D
6-10-10 0% SLIP
C
6-10-10 0% SLIP 2 TAPER
J
6-10-10 0% SLIP 3 TAPER
I
INCREASE SLIP
INCREASE DAMPING
6-30-10
E
6-10-10 5% SLIP
L
6-10-10 5% SLIP 2 TAPER
M
6-10-10 5% SLIP 3 TAPER
N
INCREASE DAMPING
INCREASE SLIP
6-65-10
F
6-10-10 10% SLIP
O
6-10-10 10% SLIP 2 TAPER
P
6-10-10 10% SLIP 3 TAPER
Q

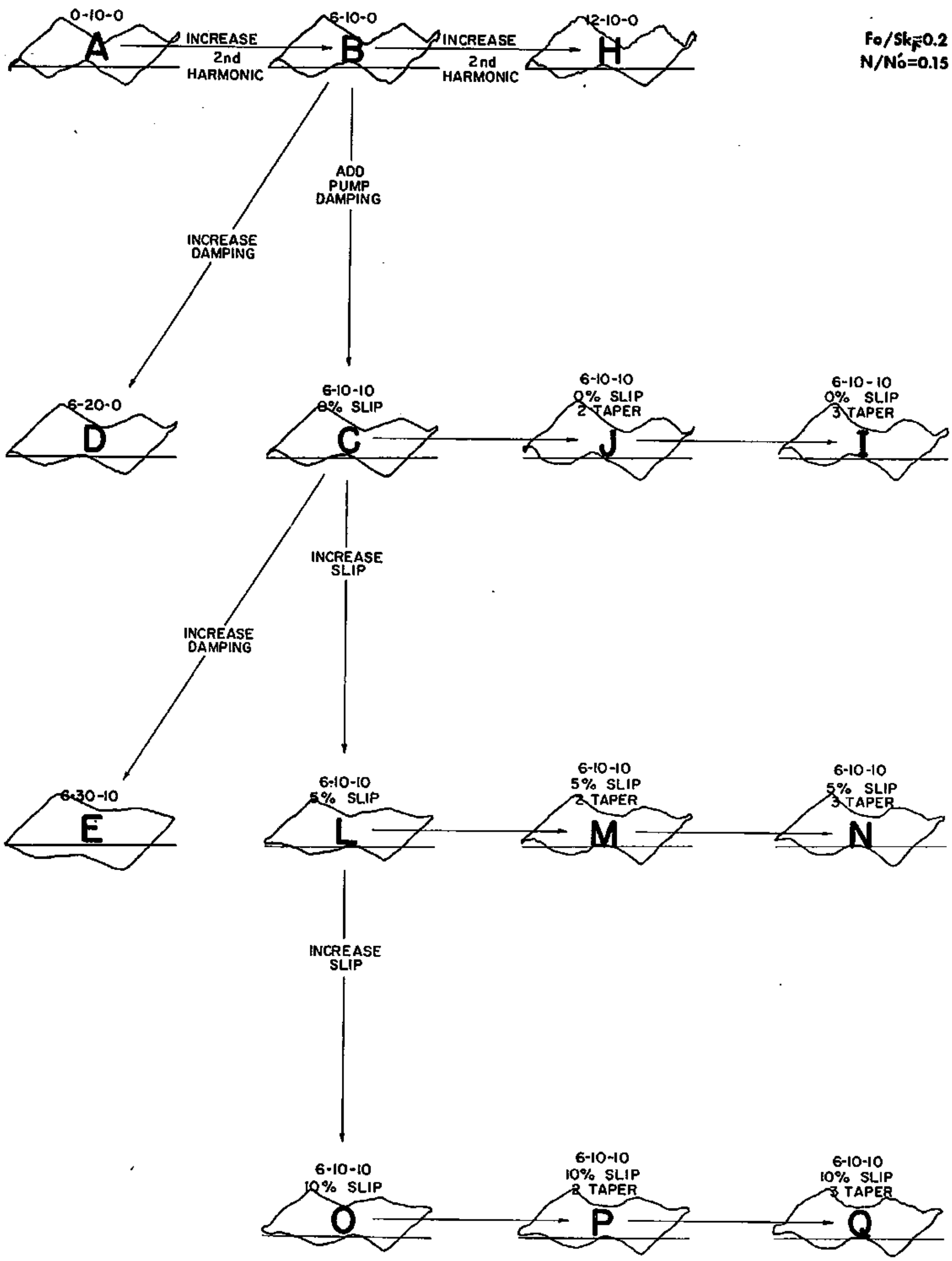

0-10-0
A
INCREASE
2nd
HARMONIC
6-10-0
B
INCREASE
2nd
HARMONIC
12-10-0
H
Fo/Sk=0.1
N/No=0.45
ADD
PUMP
DAMPING
INCREASE
DAMPING
6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE
SLIP
INCREASE
DAMPING
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE
SLIP
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q

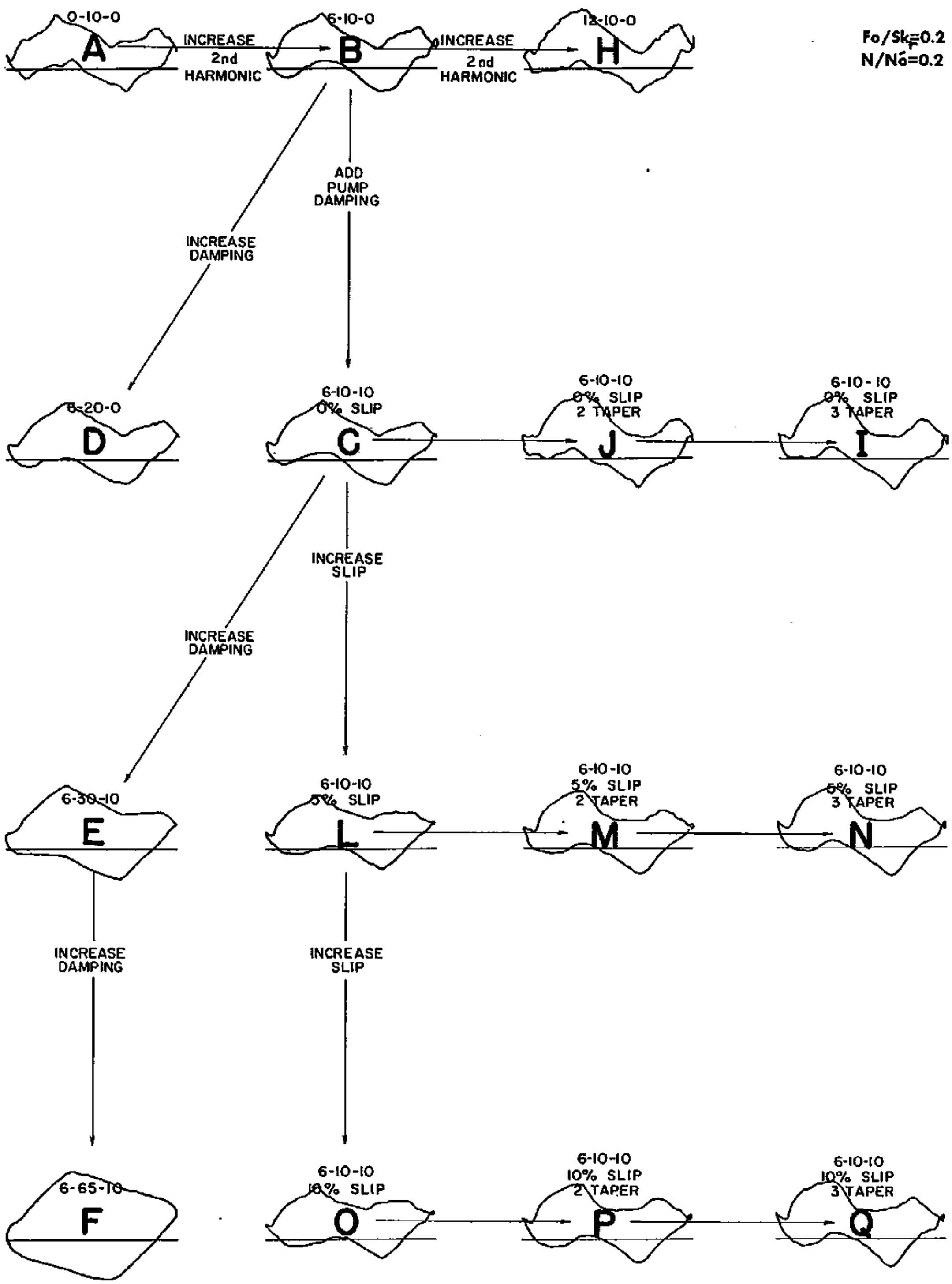

0-10-0
A
INCREASE 2nd HARMONIC
6-10-0
B
INCREASE 2nd HARMONIC
12-10-0
H
Fo/Sk=0.1
N/No=0.5
ADD PUMP DAMPING
INCREASE DAMPING
6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE SLIP
INCREASE DAMPING
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE DAMPING
INCREASE SLIP
6-65-10
F
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q


0-10-0
A
INCREASE
2nd
HARMONIC
6-10-0
B
INCREASE
2nd
HARMONIC
12-10-0
H
Fo/Sk=0.1
N/N'o=0.55
ADD
PUMP
DAMPING
INCREASE
DAMPING
6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE
SLIP
INCREASE
DAMPING
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE
SLIP
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q

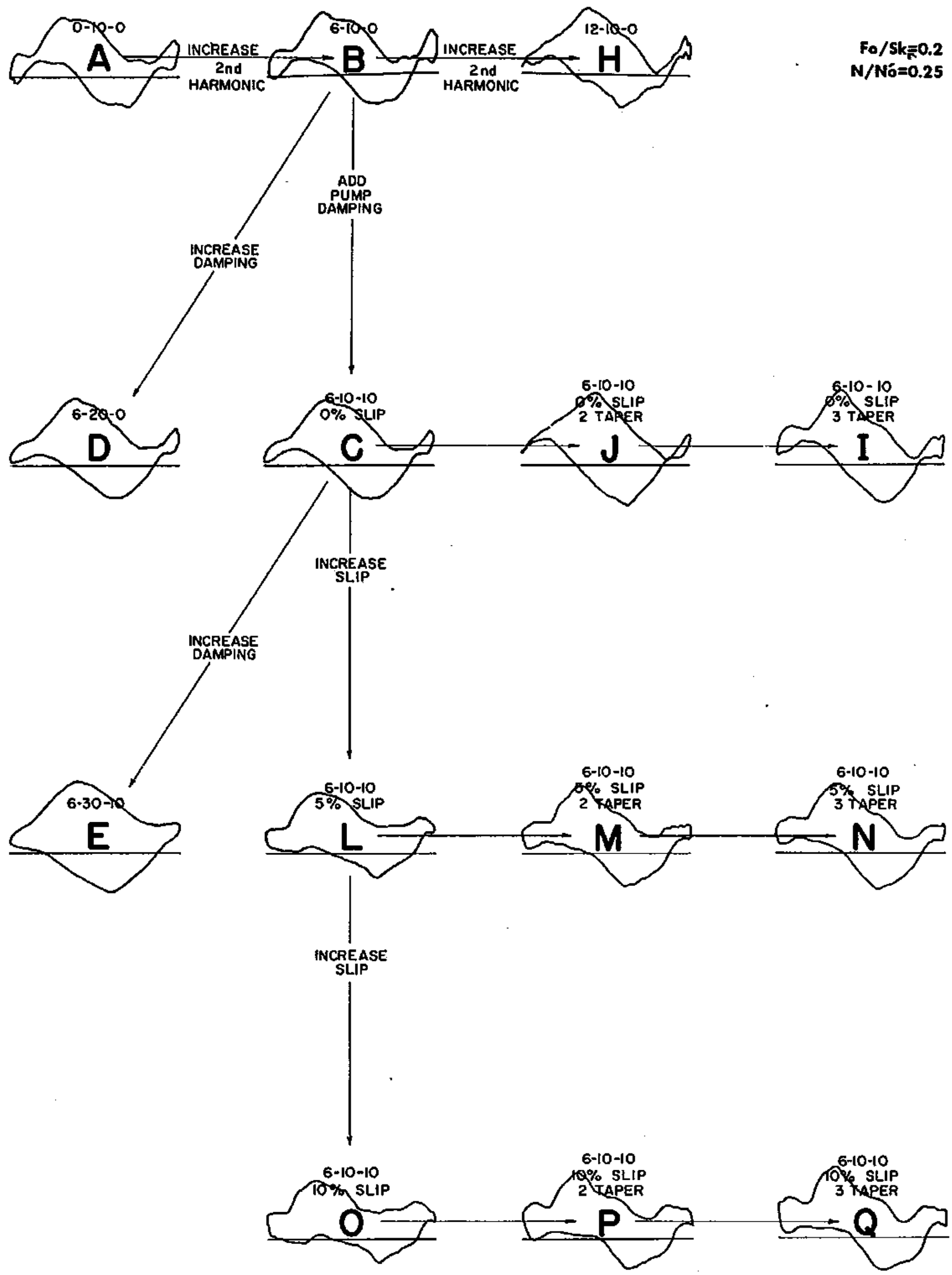

Fo/Sk=0.1
N/N'o=0.6
0-10-0
A
INCREASE
2nd
HARMONIC
6-10-0
B
INCREASE
2nd
HARMONIC
12-10-0
H
ADD
PUMP
DAMPING
INCREASE
DAMPING
6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE
SLIP
INCREASE
DAMPING
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE
DAMPING
INCREASE
SLIP
6-65-10
F
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q


0-10-0
A
INCREASE 2nd HARMONIC
6-10-0
B
INCREASE 2nd HARMONIC
12-10-0
H
Fo/Sk=0.2
N/Nδ=0.1
ADD PUMP DAMPING
INCREASE DAMPING
6-20-0
D
6-10-10 0% SLIP
C
6-10-10 0% SLIP 2 TAPER
J
6-10-10 0% SLIP 3 TAPER
I
INCREASE SLIP
INCREASE DAMPING
6-30-10
E
6-10-10 5% SLIP
L
6-10-10 5% SLIP 2 TAPER
M
6-10-10 5% SLIP 3 TAPER
N
INCREASE DAMPING
INCREASE SLIP
6-65-10
F
6-10-10 10% SLIP
O
6-10-10 10% SLIP 2 TAPER
P
6-10-10 10% SLIP 3 TAPER
Q


0-10-0
A
INCREASE
2nd
HARMONIC
6-10-0
B
INCREASE
2nd
HARMONIC
12-10-0
H
Fo/Skr=0.2
N/No'=0.15
ADD
PUMP
DAMPING
INCREASE
DAMPING
6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
INCREASE
SLIP
INCREASE
DAMPING
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE
SLIP
6-10-10
10% SLIP
O
6-10-10
10% SLIP
2 TAPER
P
6-10-10
10% SLIP
3 TAPER
Q



0-10-0
A
INCREASE 2nd HARMONIC
6-10-0
B
INCREASE 2nd HARMONIC
12-10-0
H
Fo/Sk=0.2
N/No=0.2
ADD PUMP DAMPING
INCREASE DAMPING
6-20-0
D
6-10-10 0% SLIP
C
6-10-10 0% SLIP 2 TAPER
J
6-10-10 0% SLIP 3 TAPER
I
INCREASE SLIP
INCREASE DAMPING
6-30-10
E
6-10-10 5% SLIP
L
6-10-10 5% SLIP 2 TAPER
M
6-10-10 5% SLIP 3 TAPER
N
INCREASE DAMPING
INCREASE SLIP
6-65-10
F
6-10-10 10% SLIP
O
6-10-10 10% SLIP 2 TAPER
P
6-10-10 10% SLIP 3 TAPER
Q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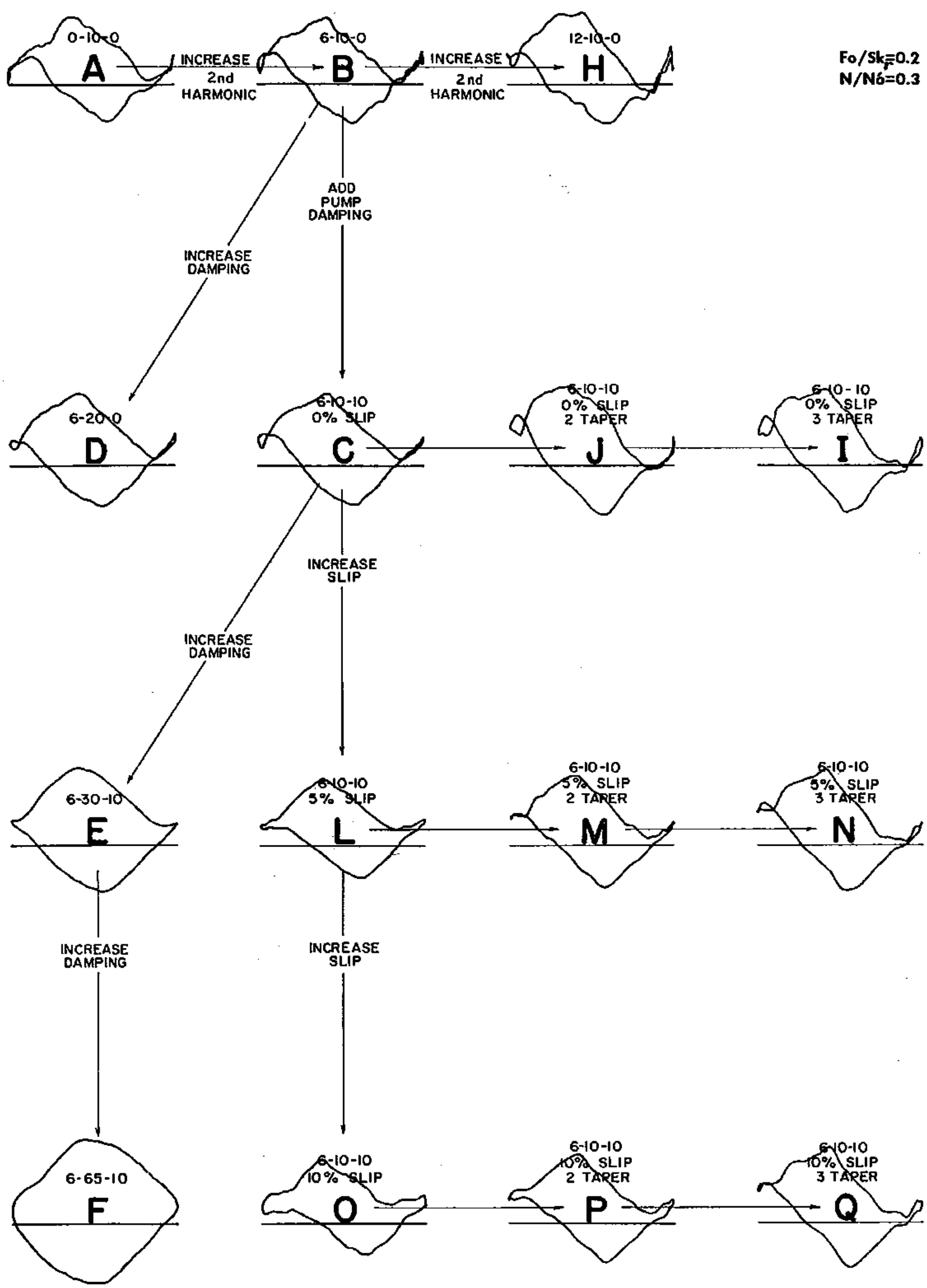
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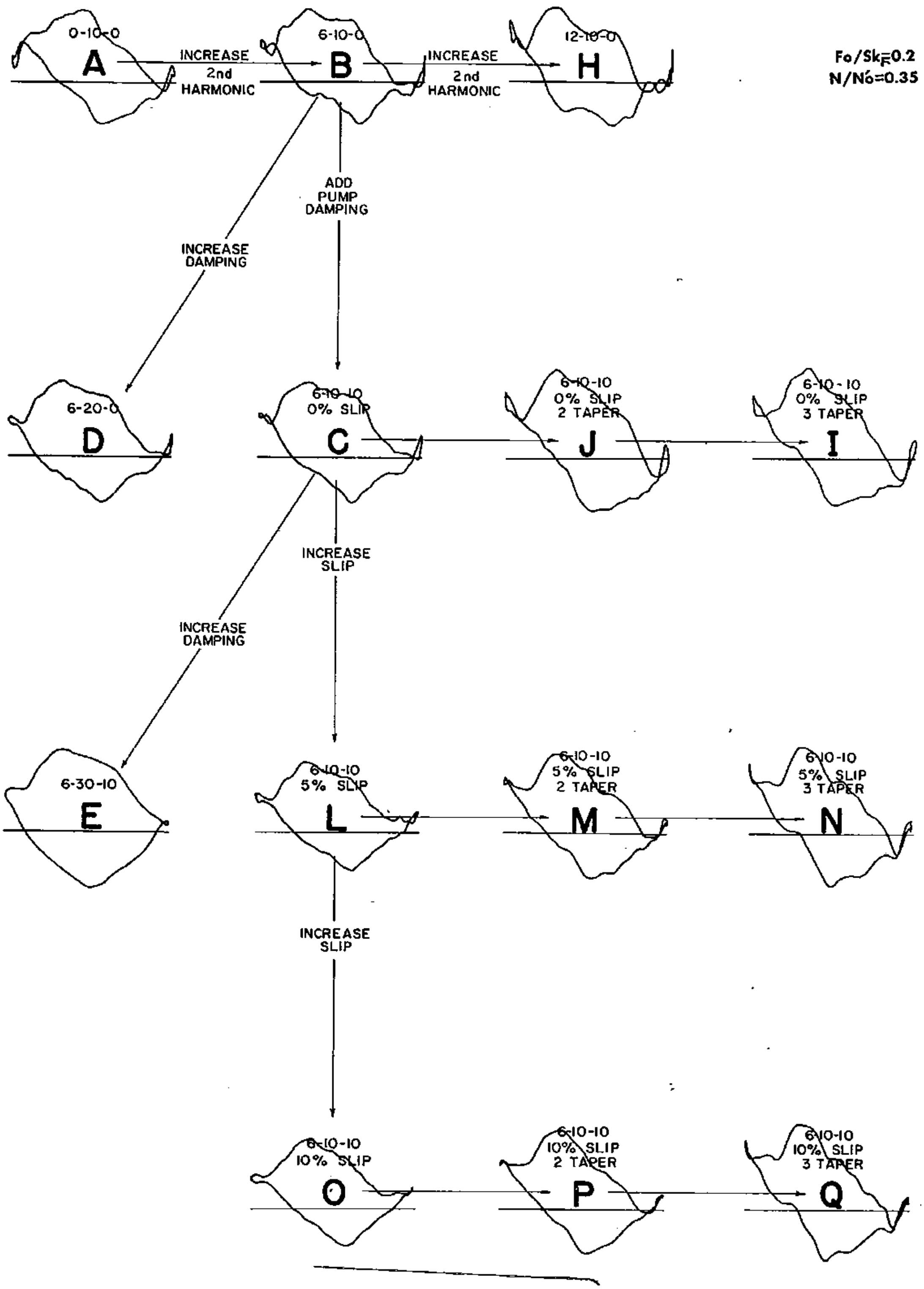
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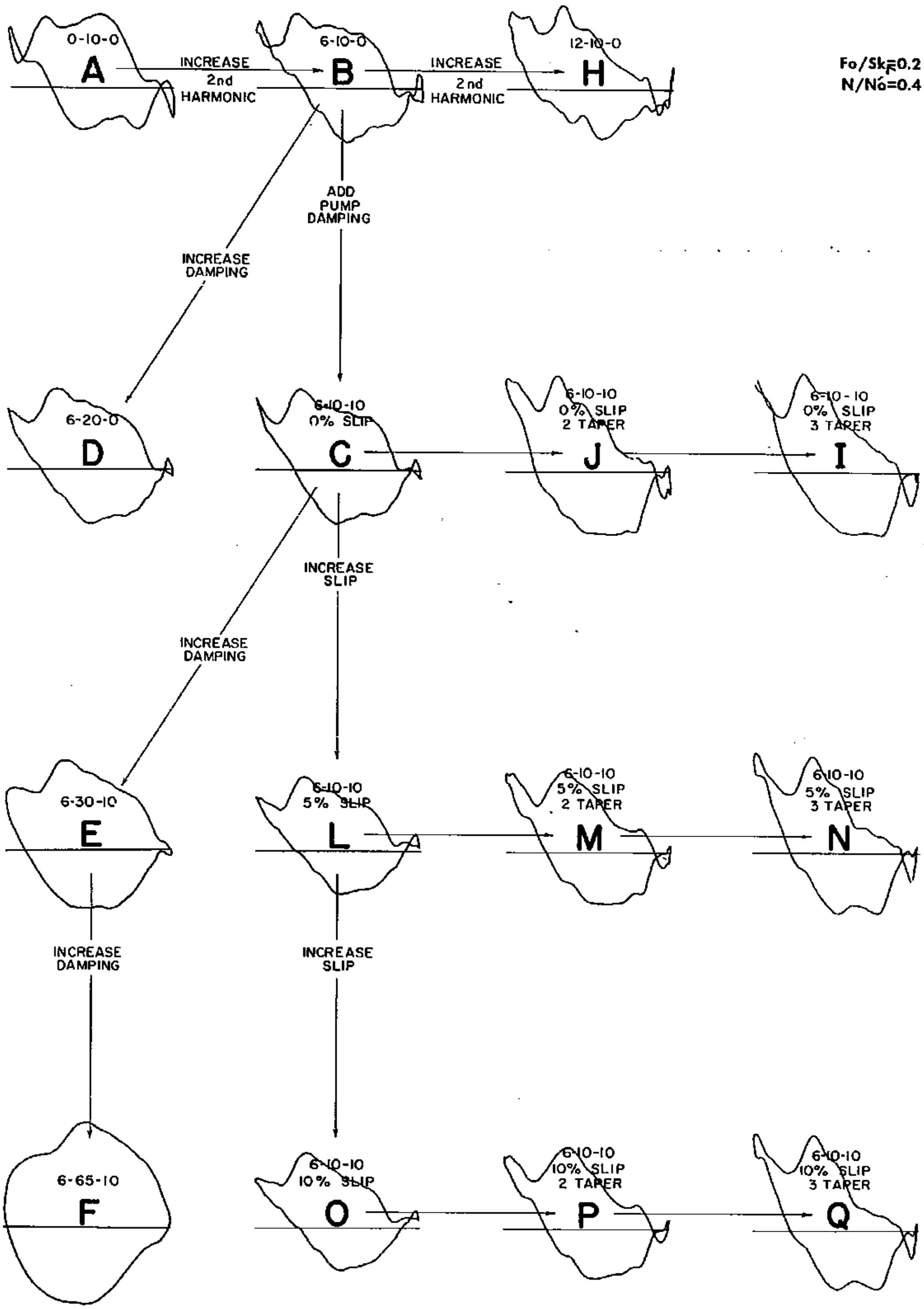
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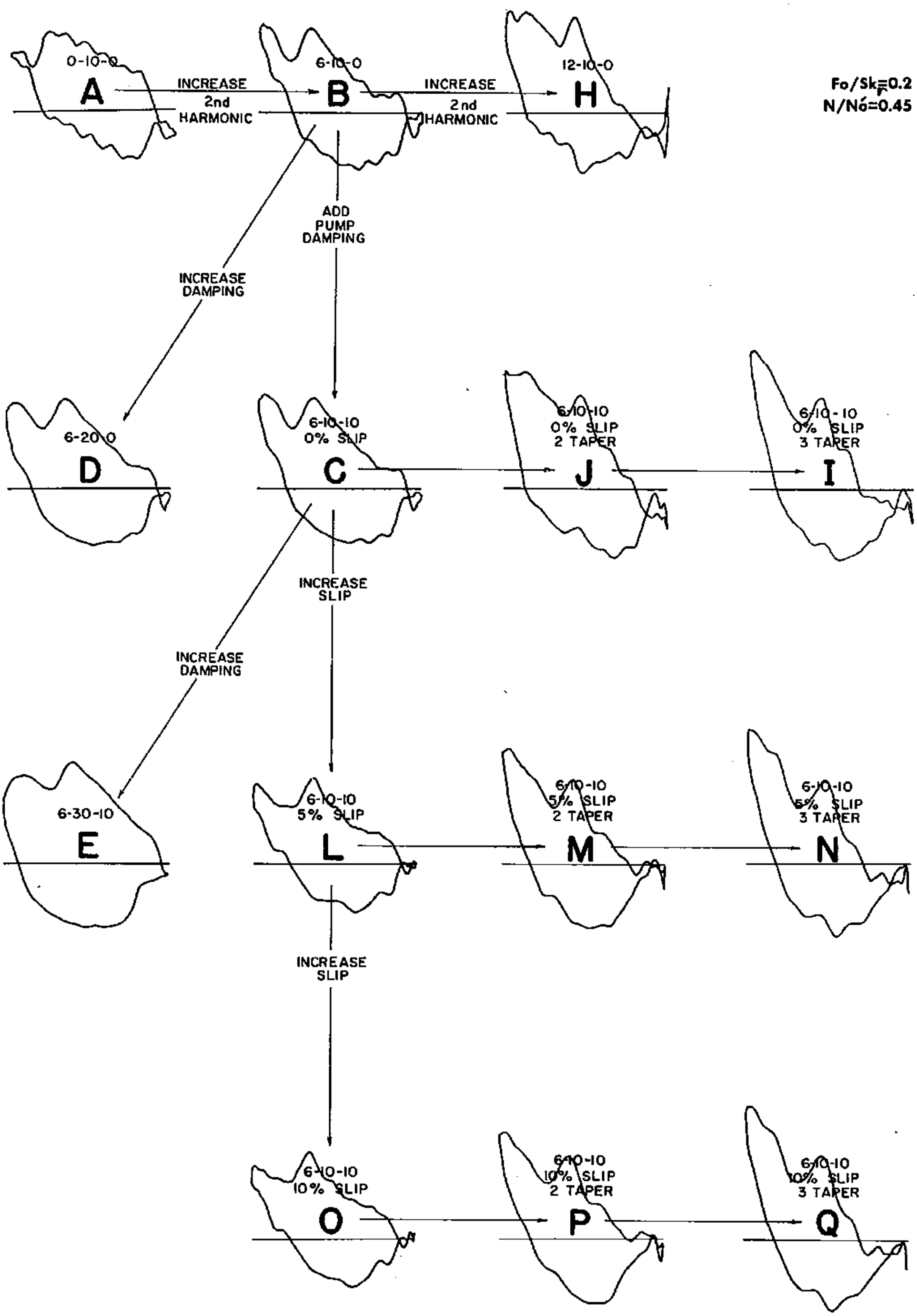
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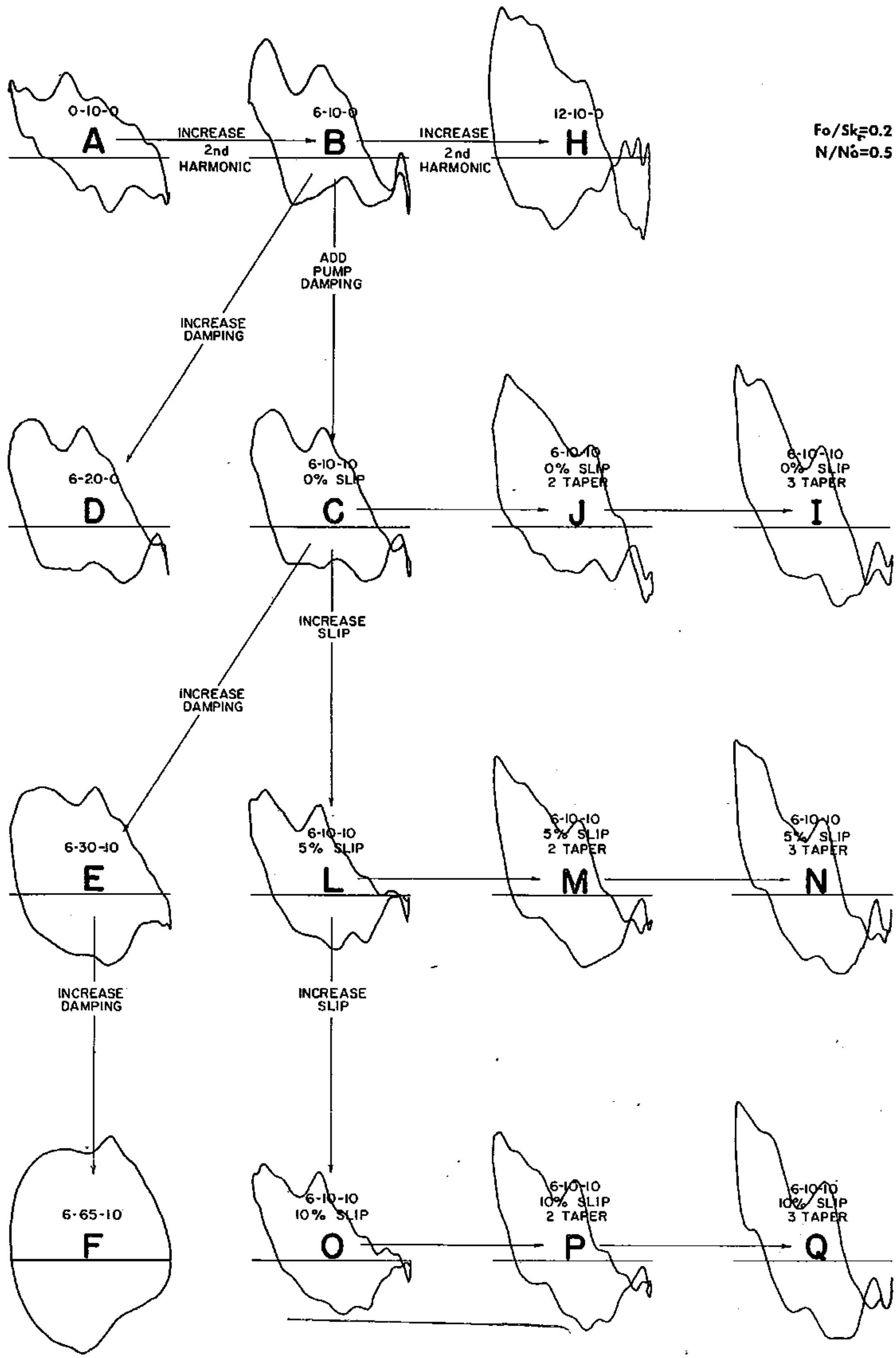
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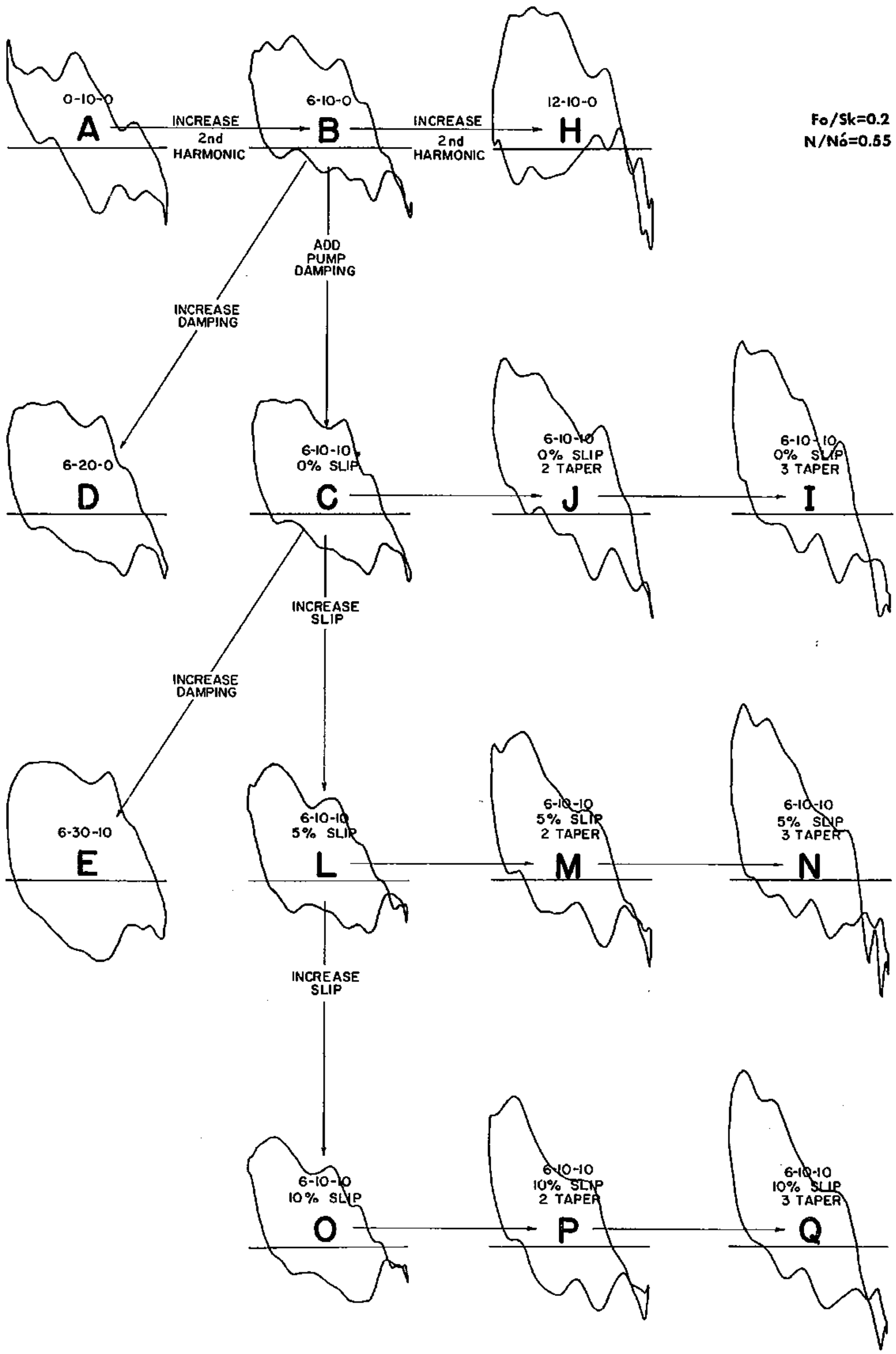
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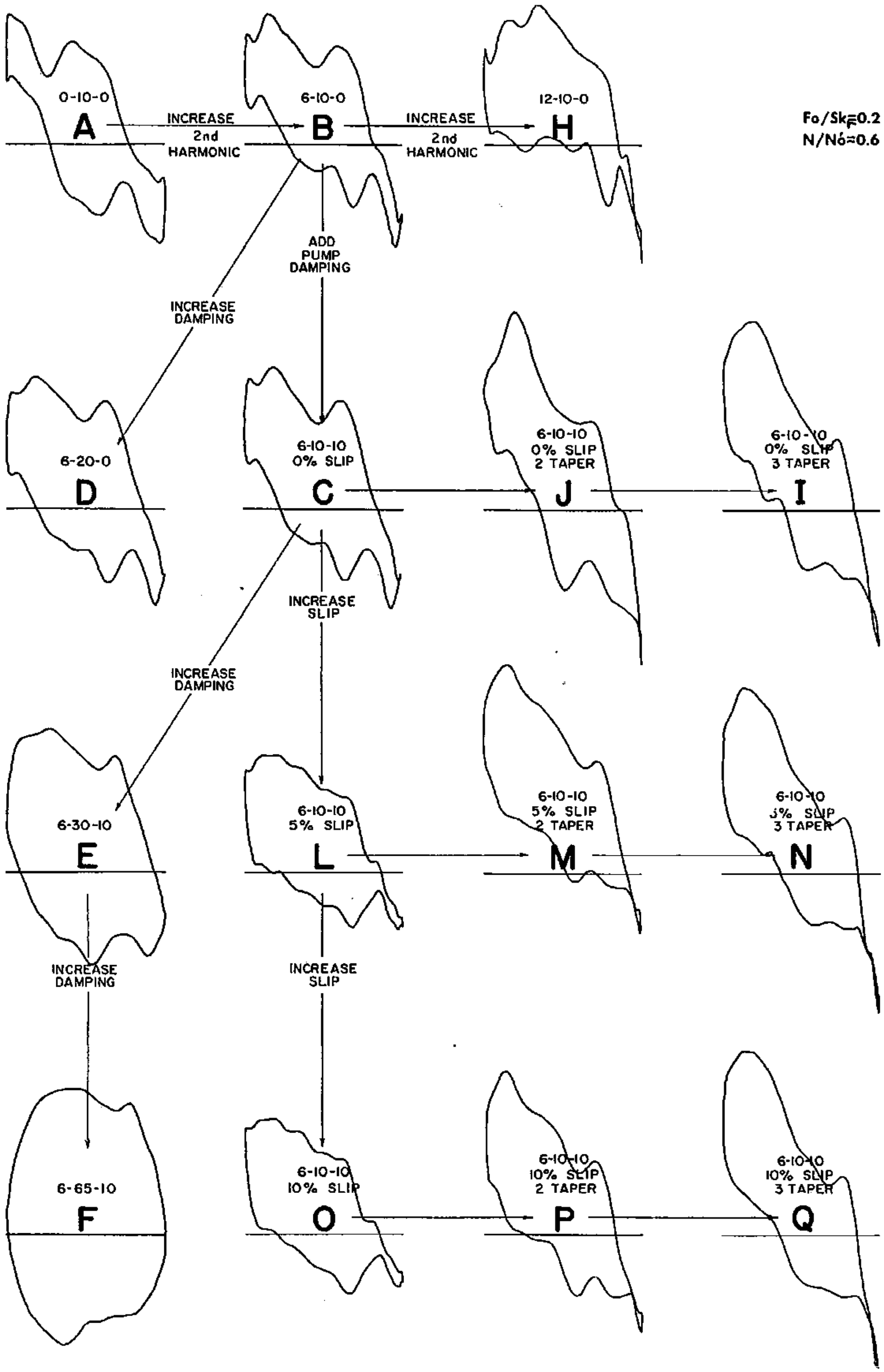
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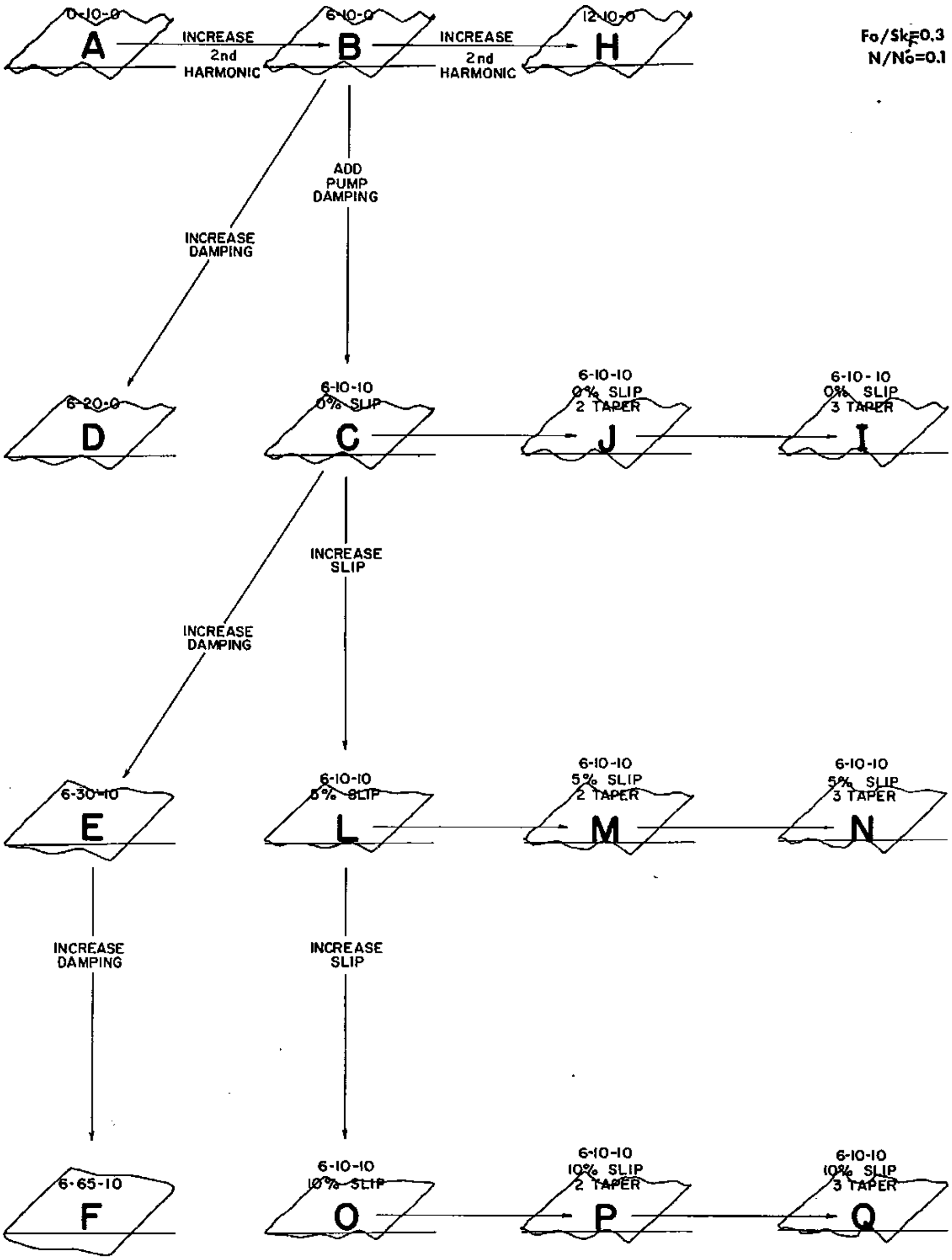
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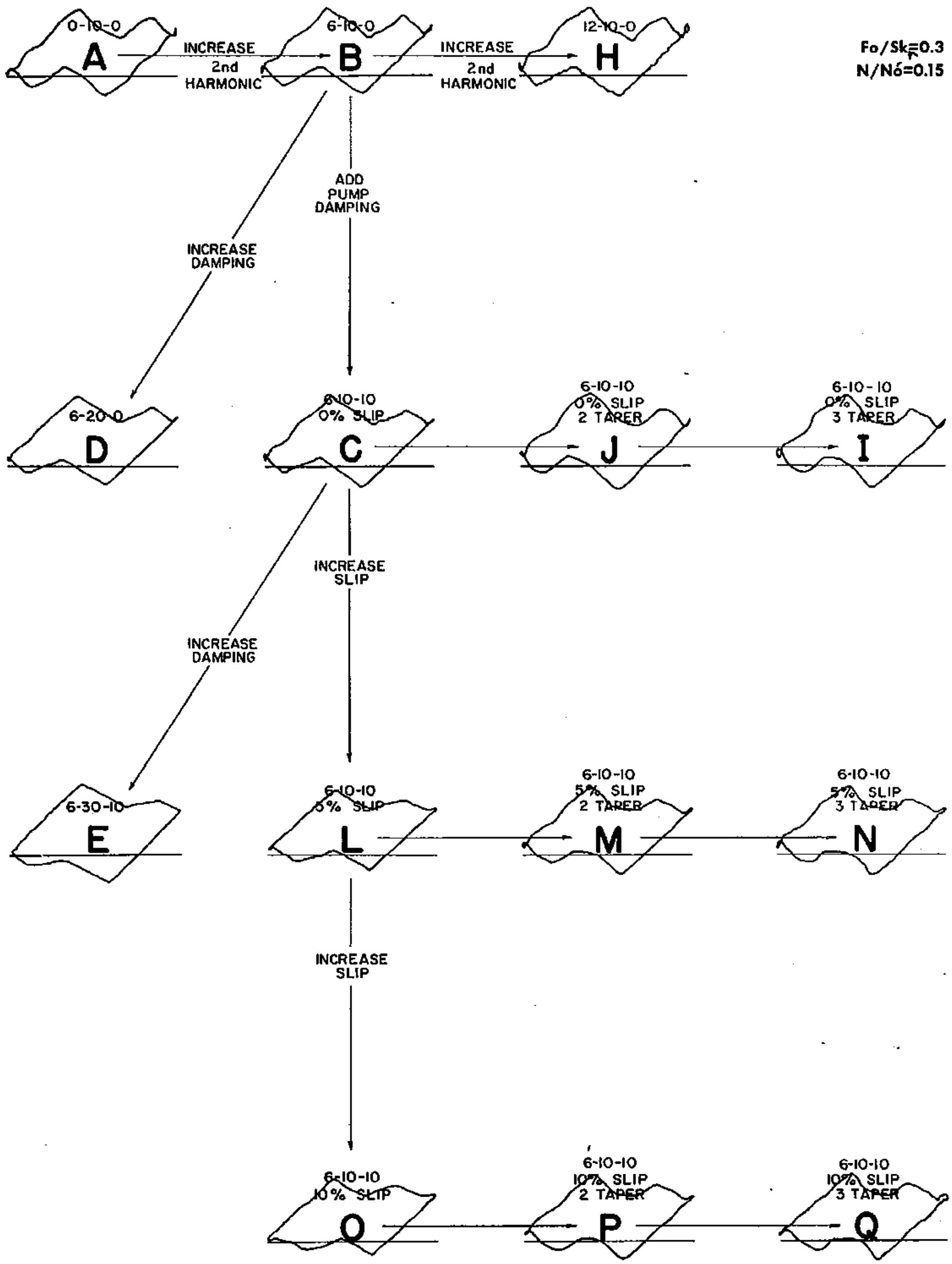
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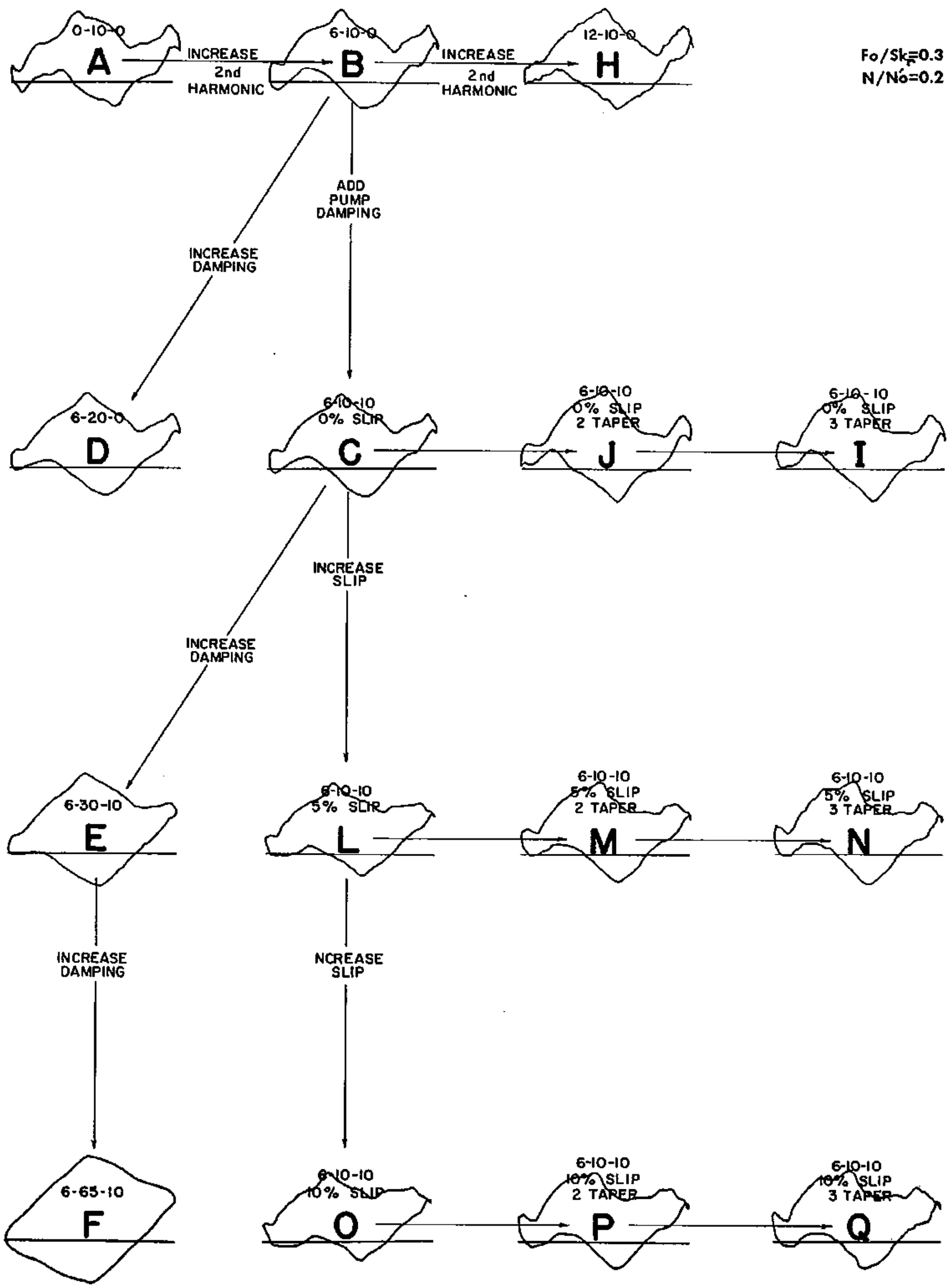
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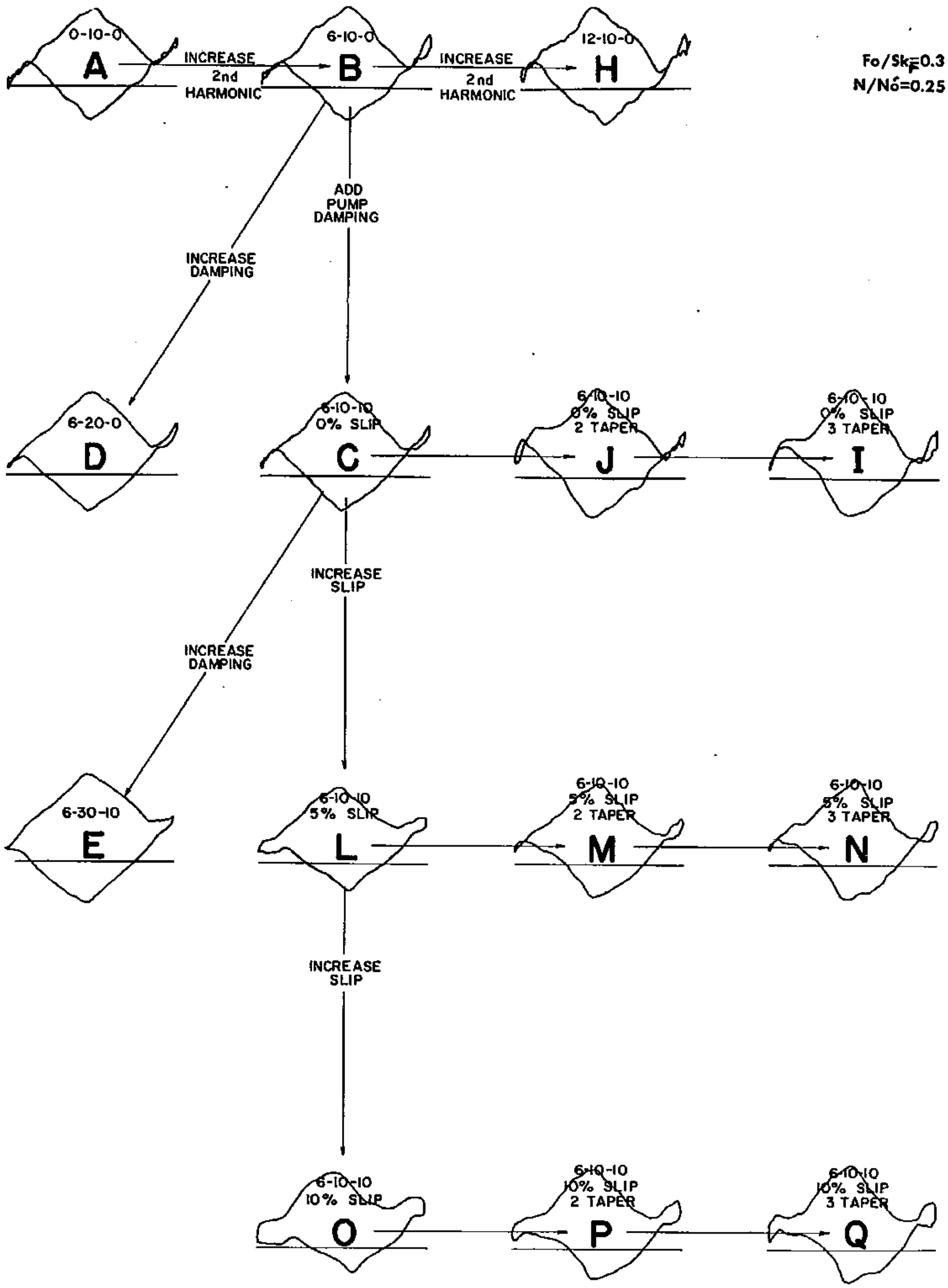

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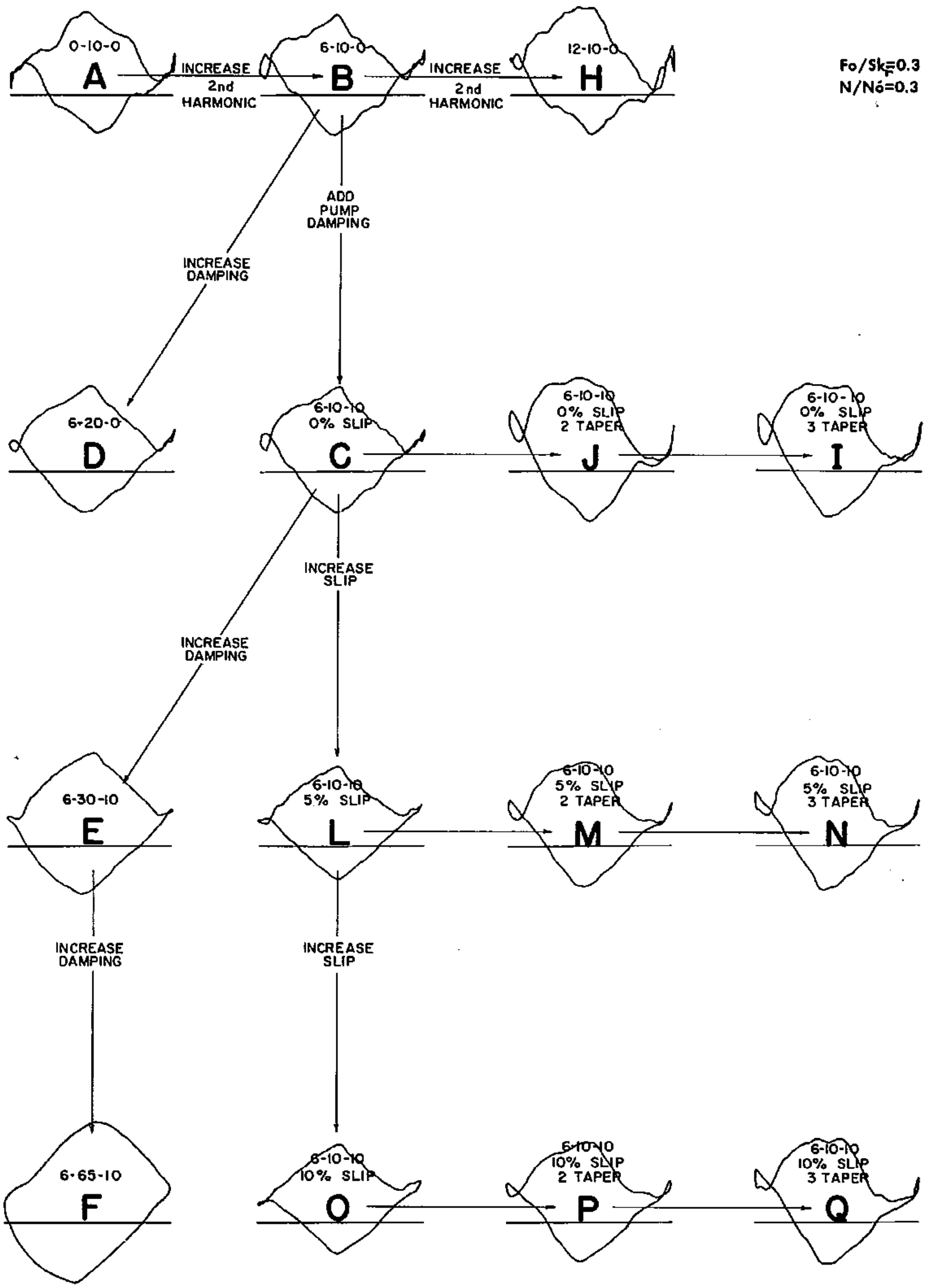
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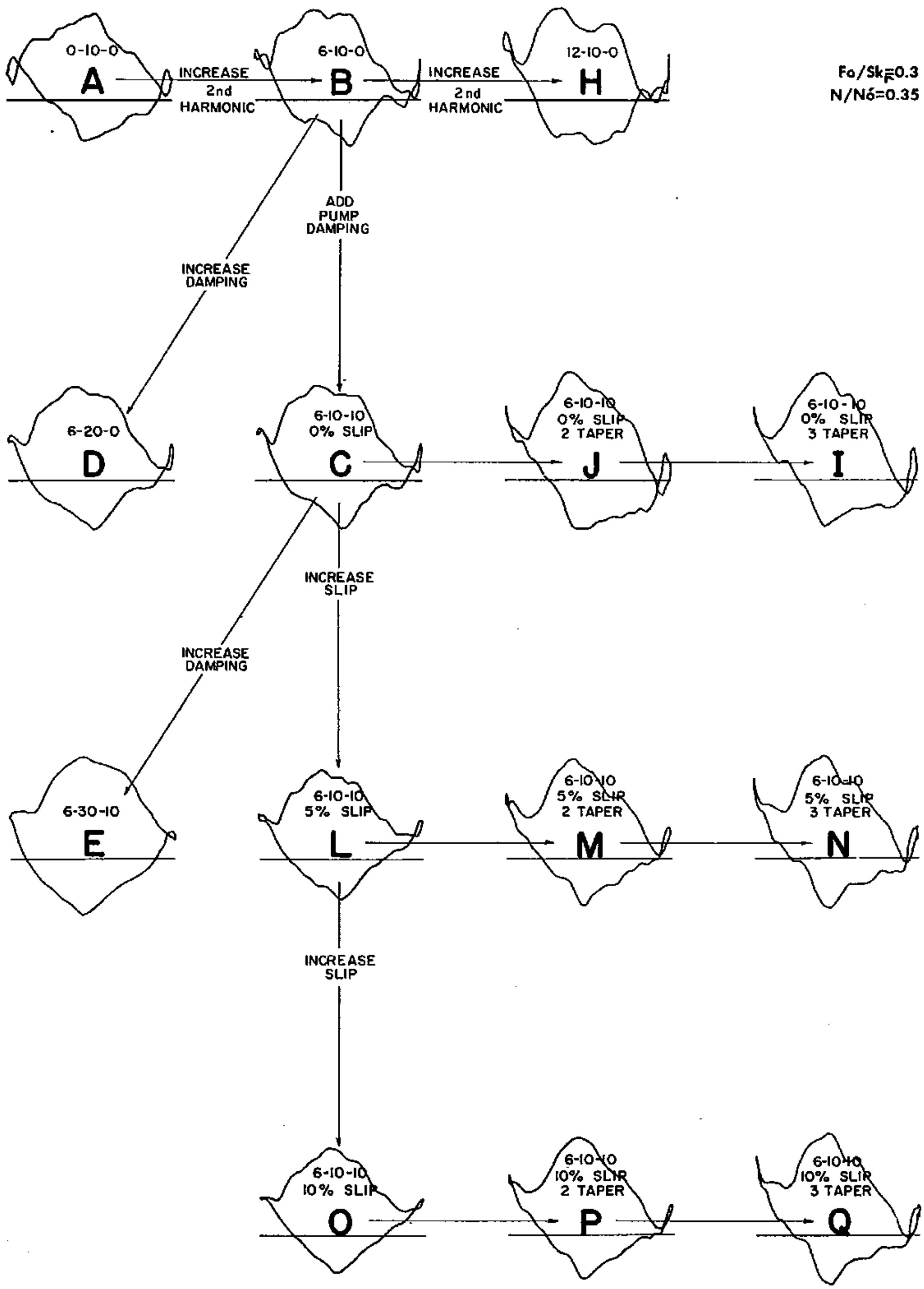
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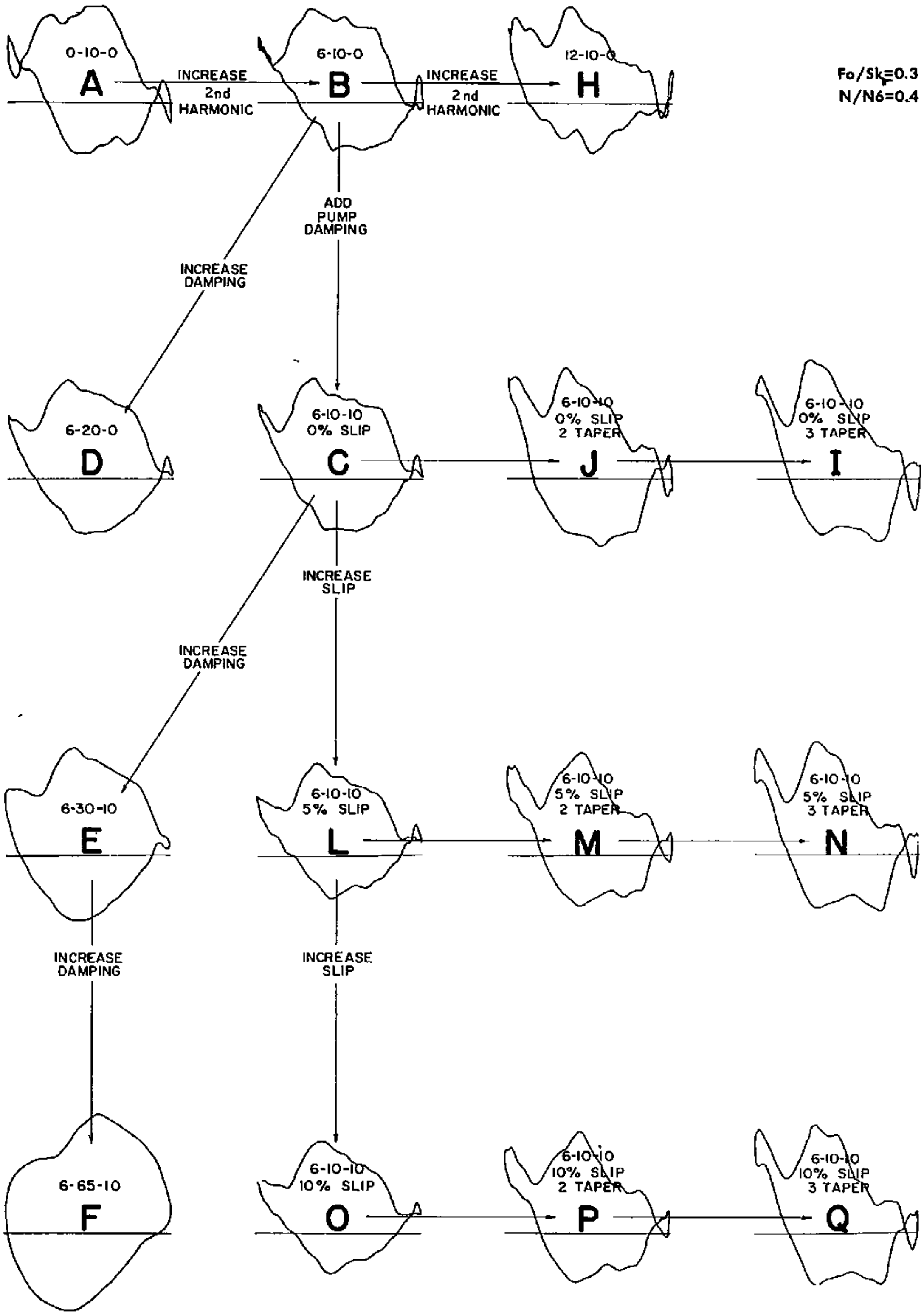
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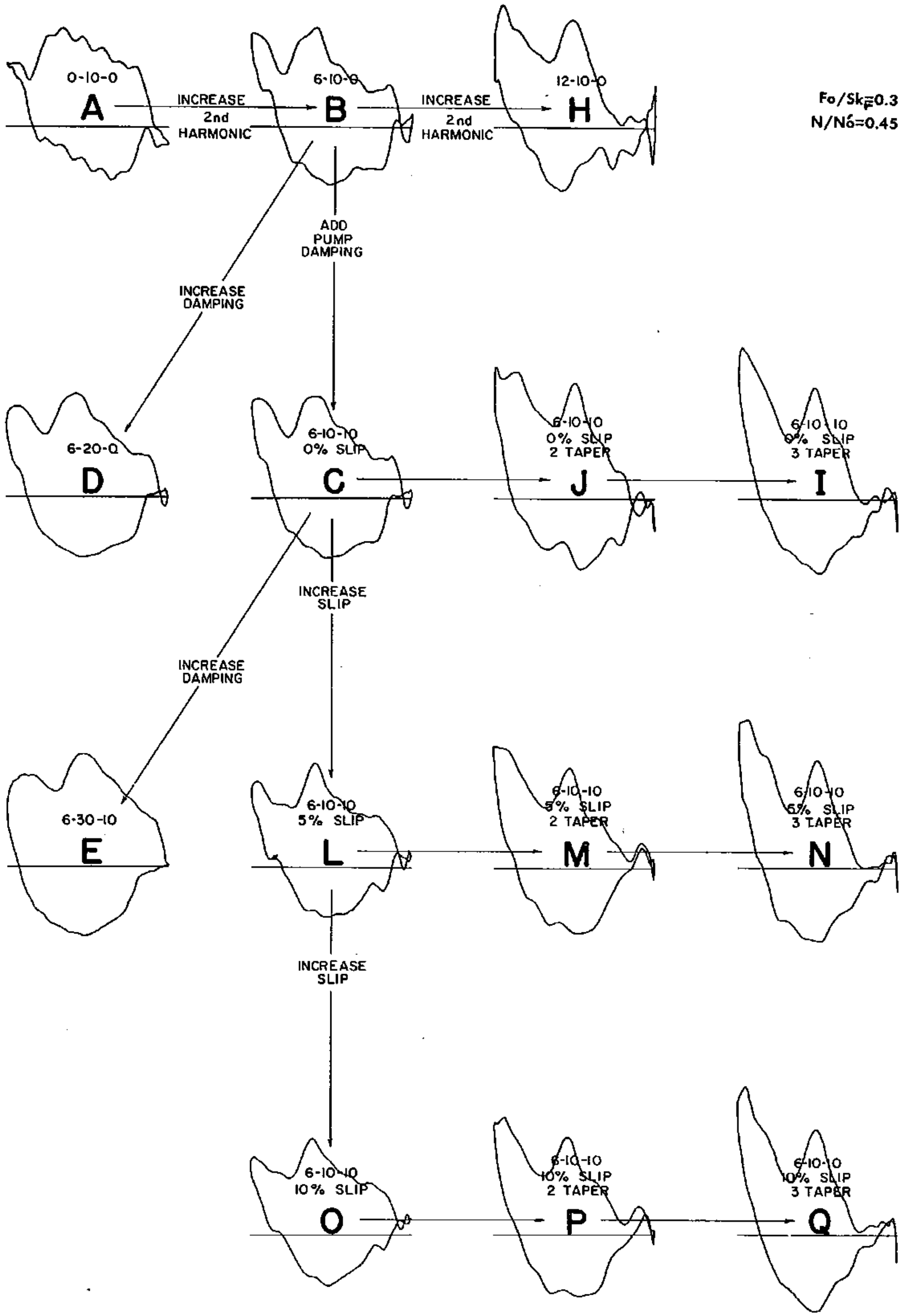
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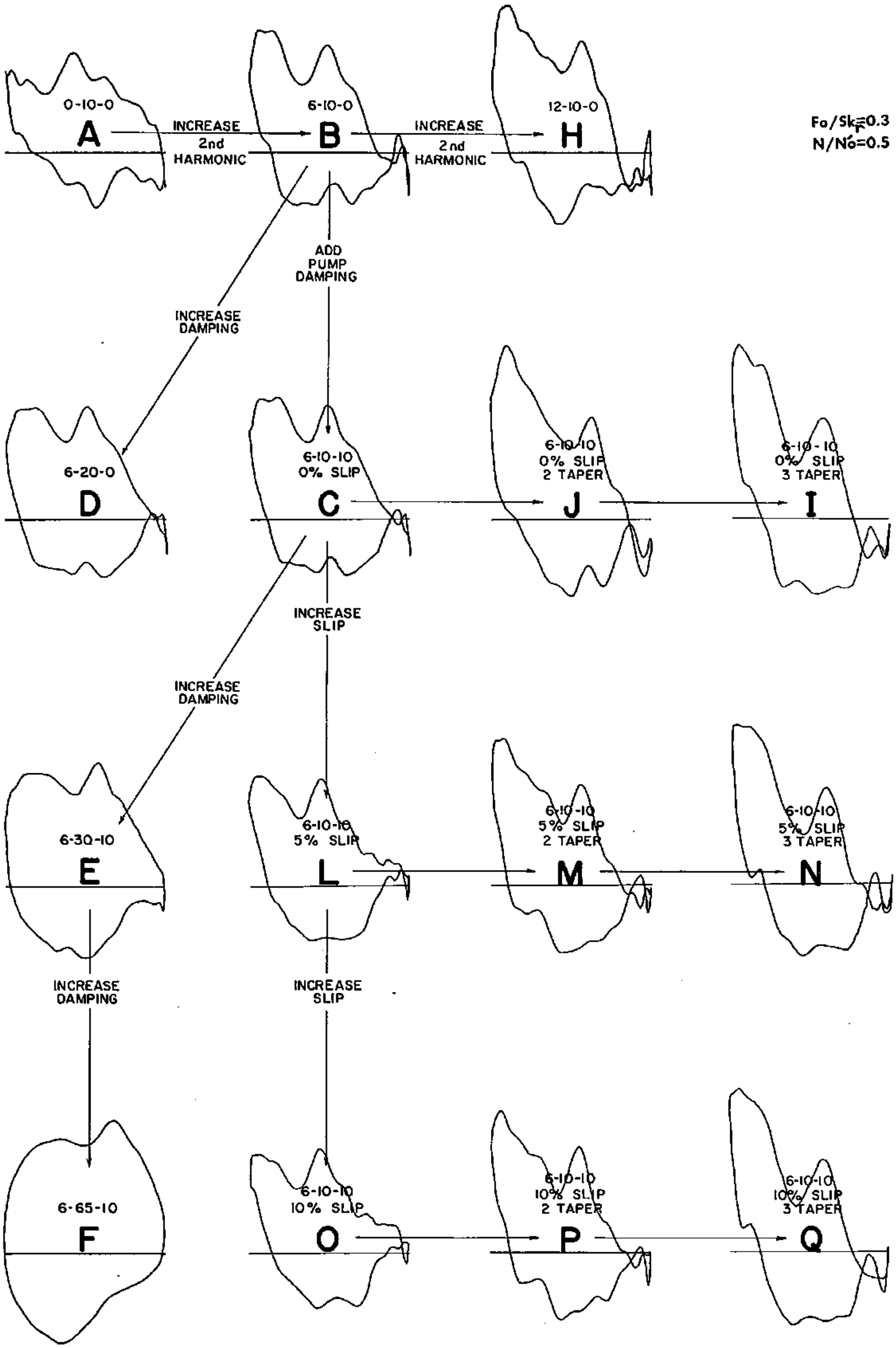
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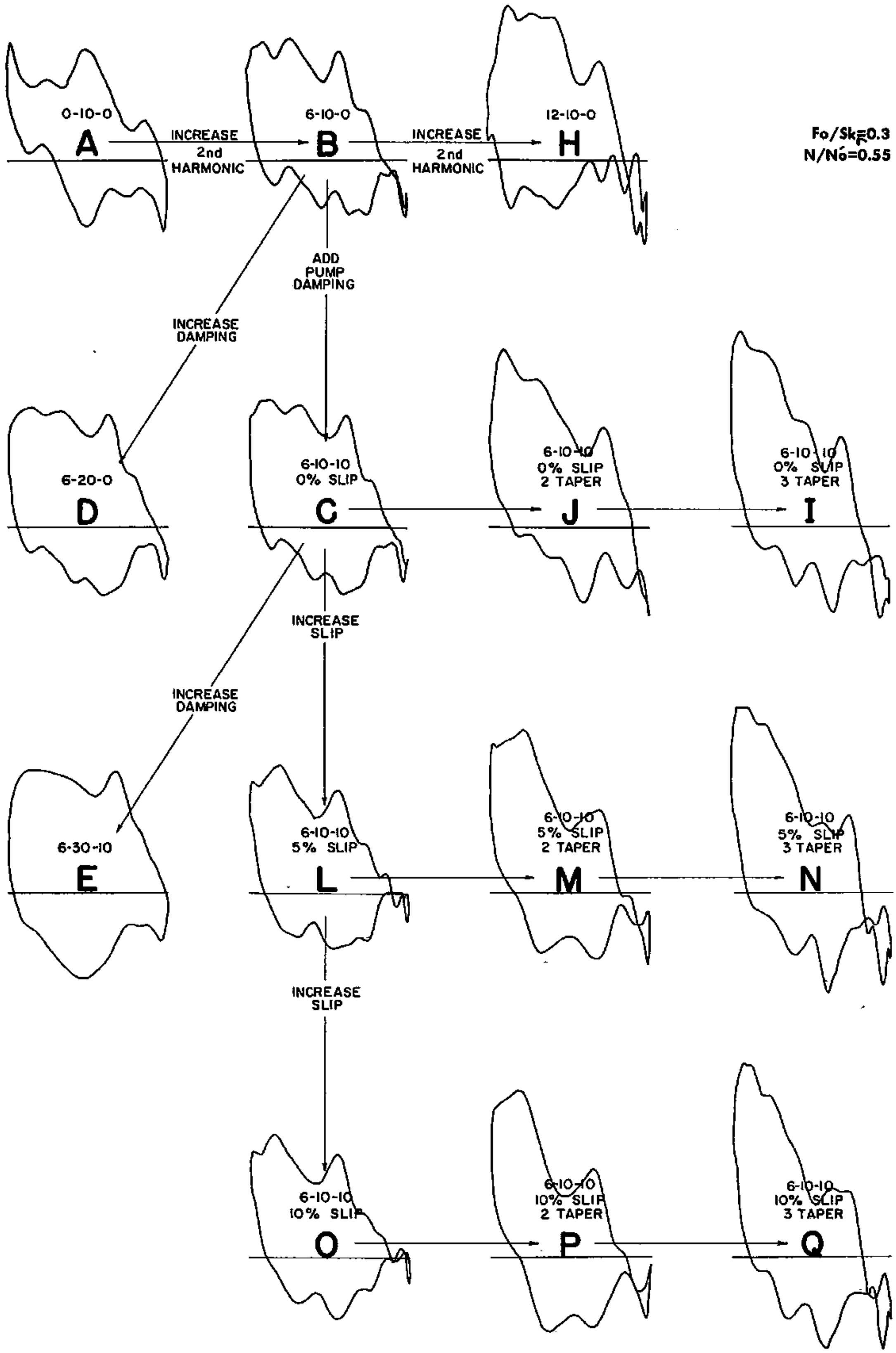
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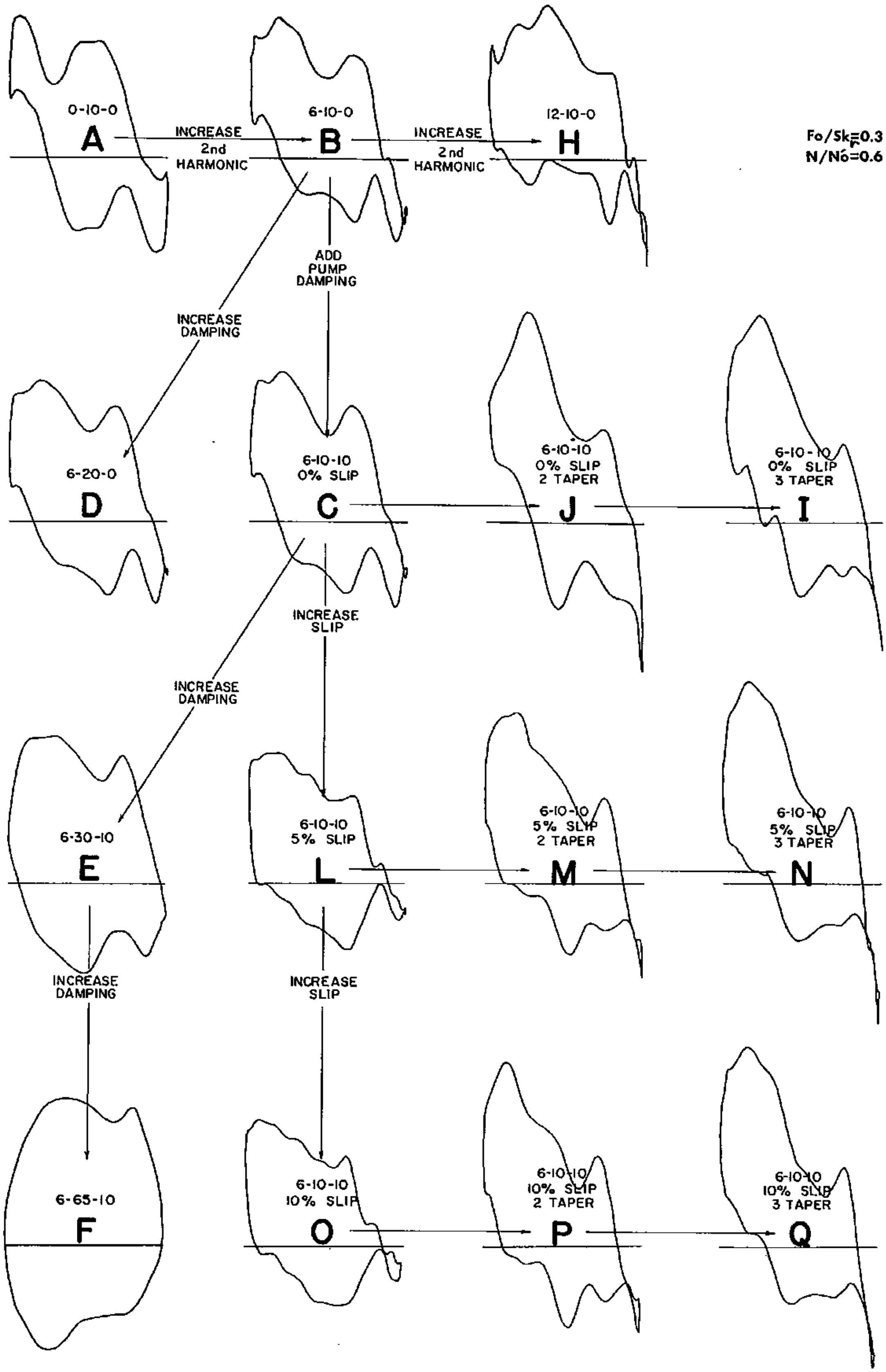
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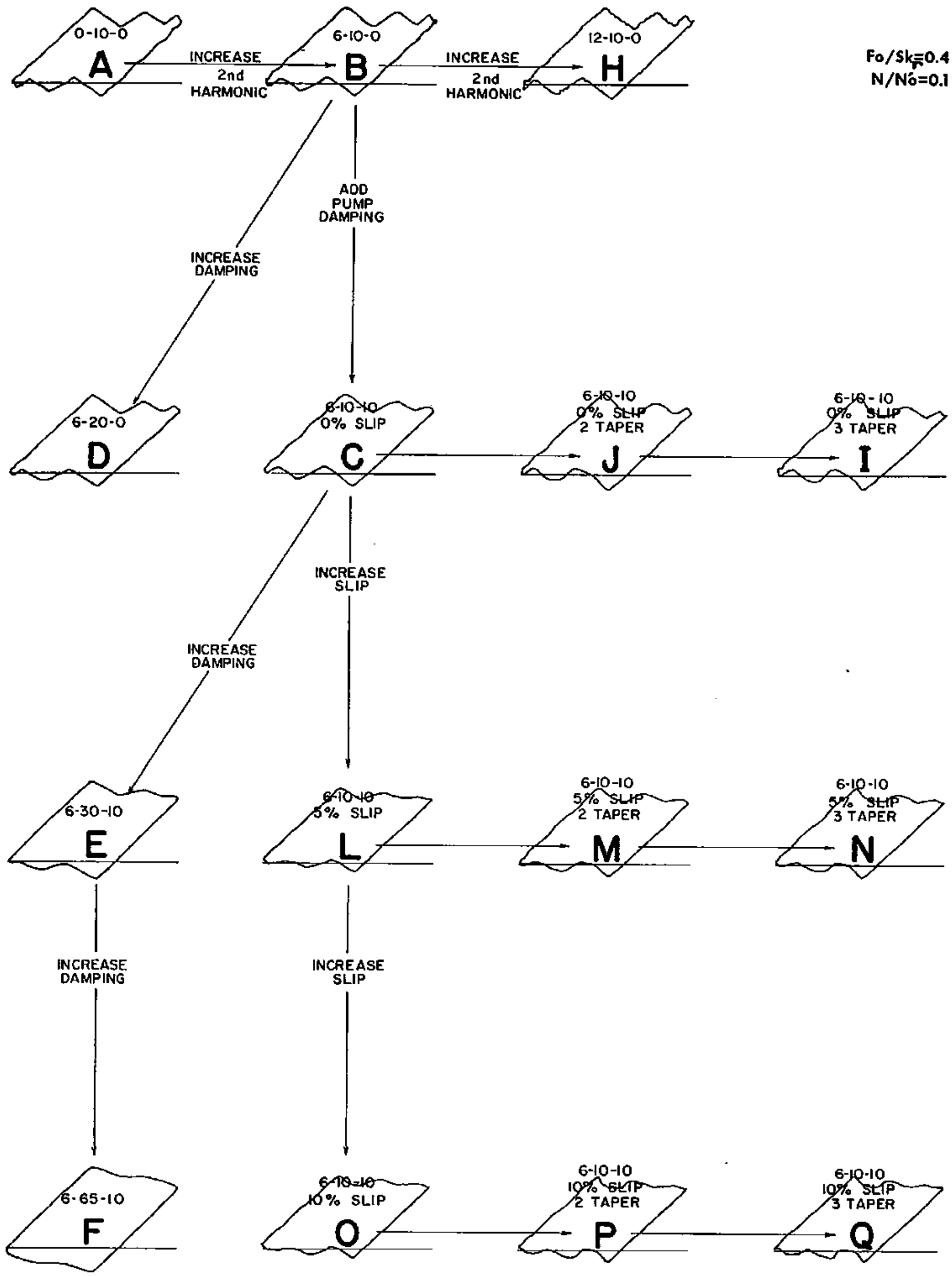
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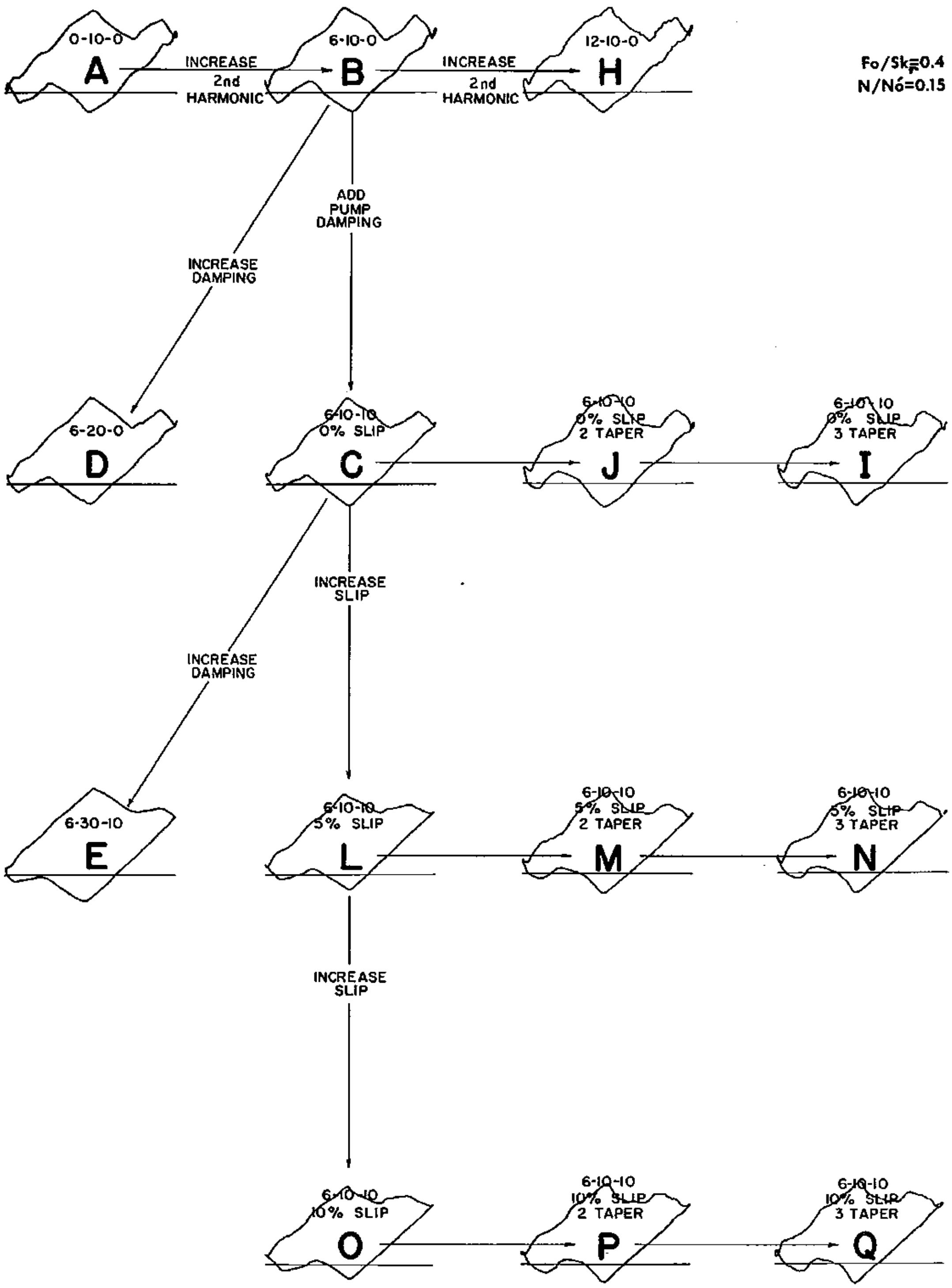

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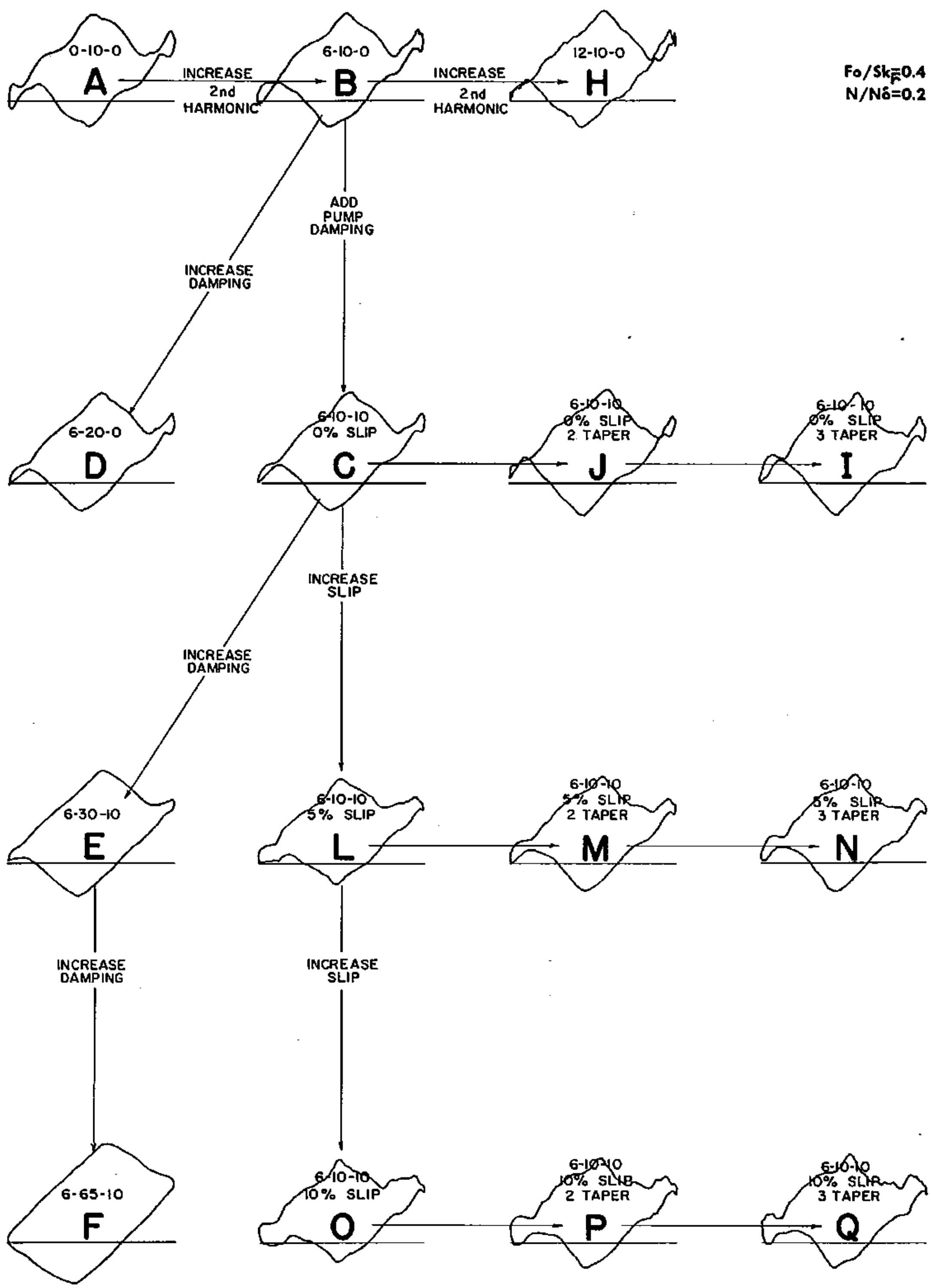
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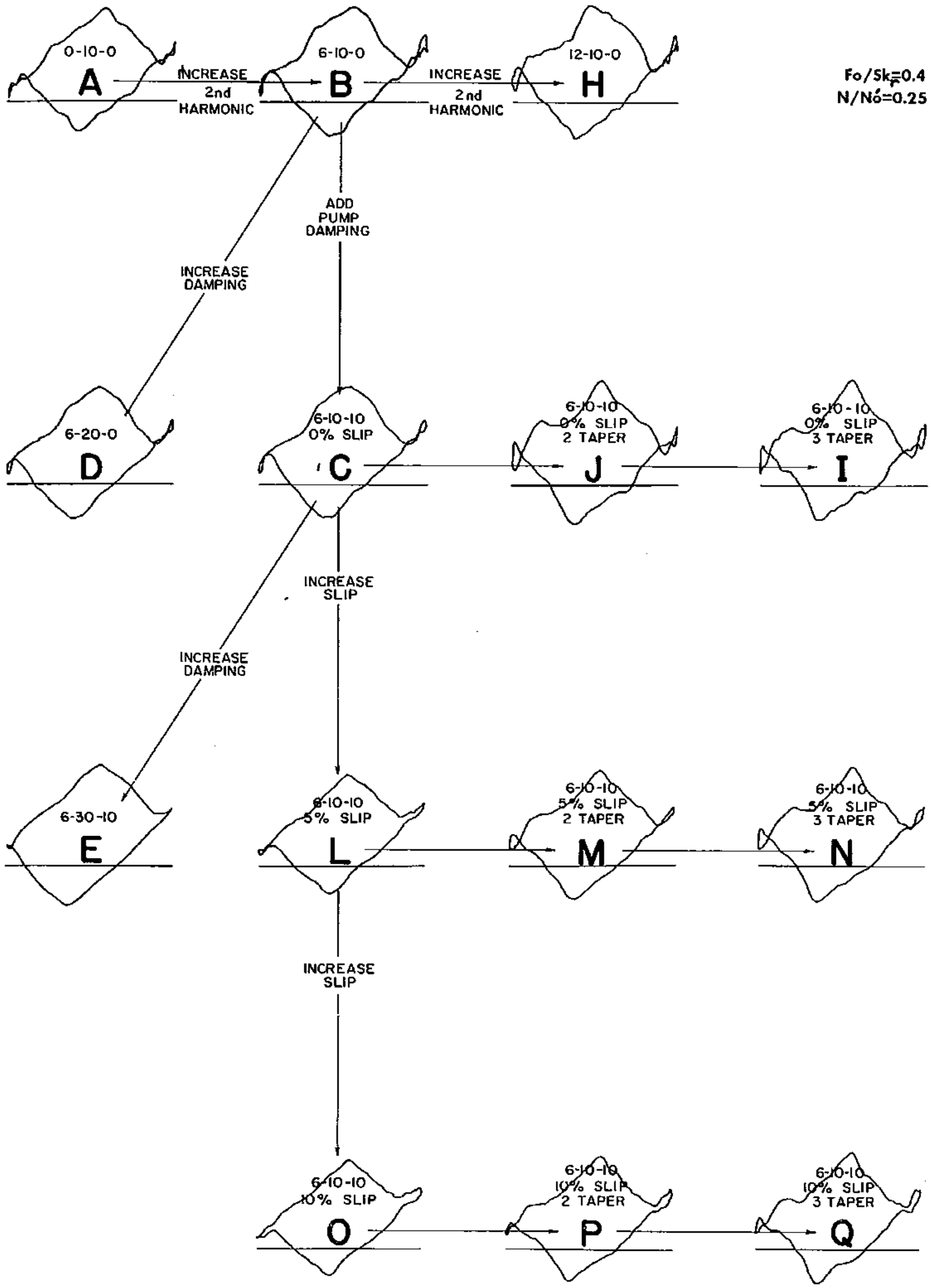
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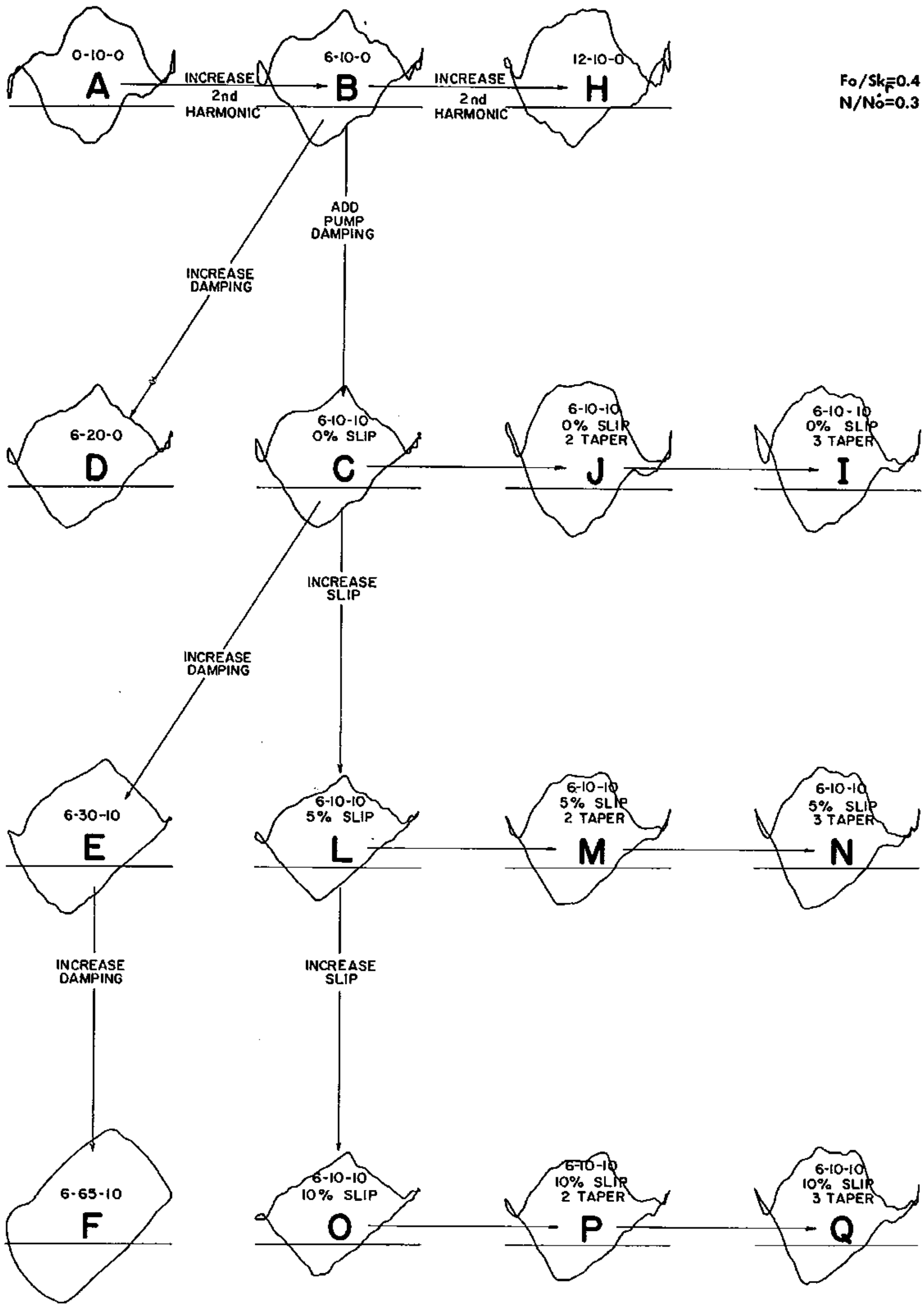
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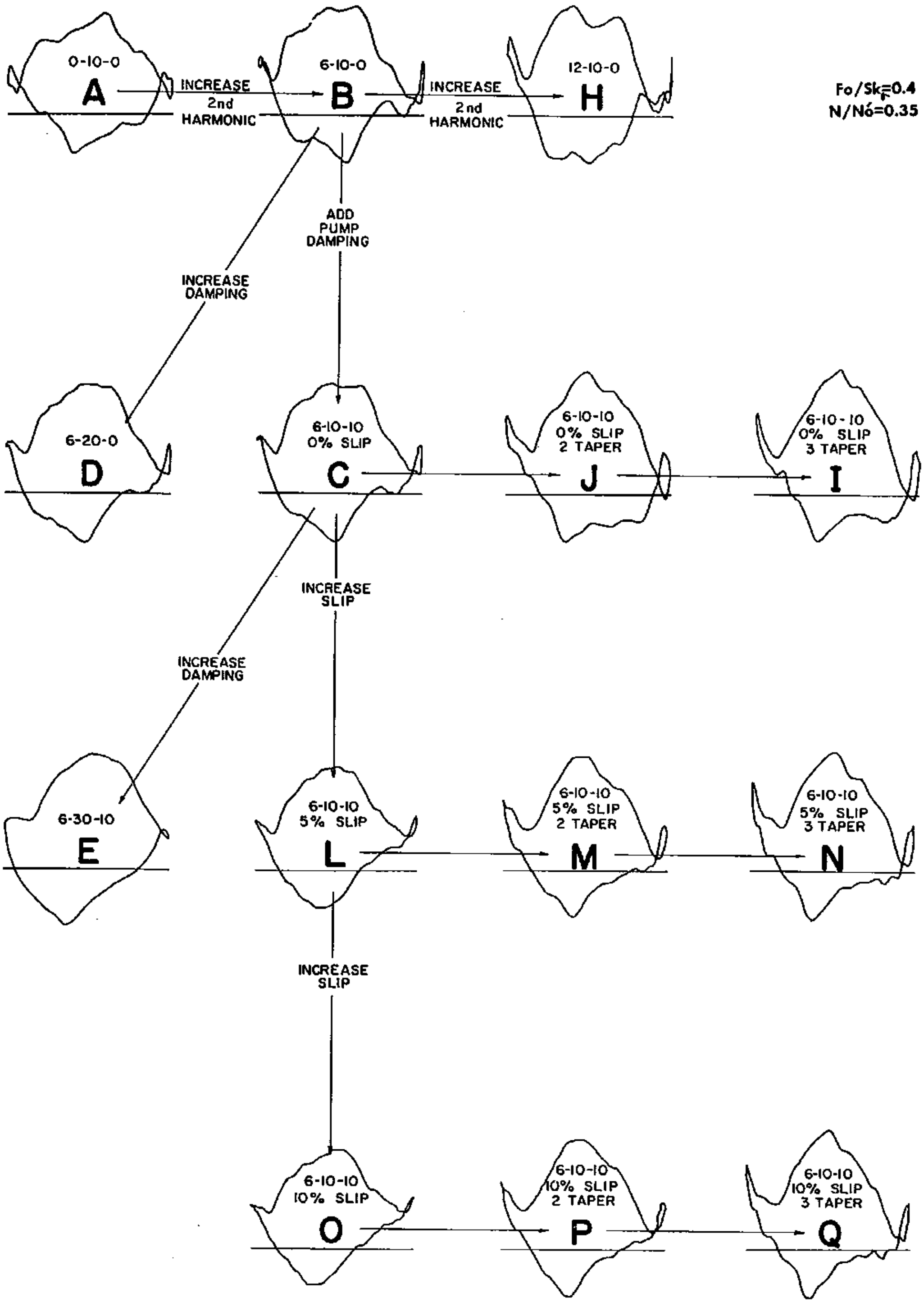
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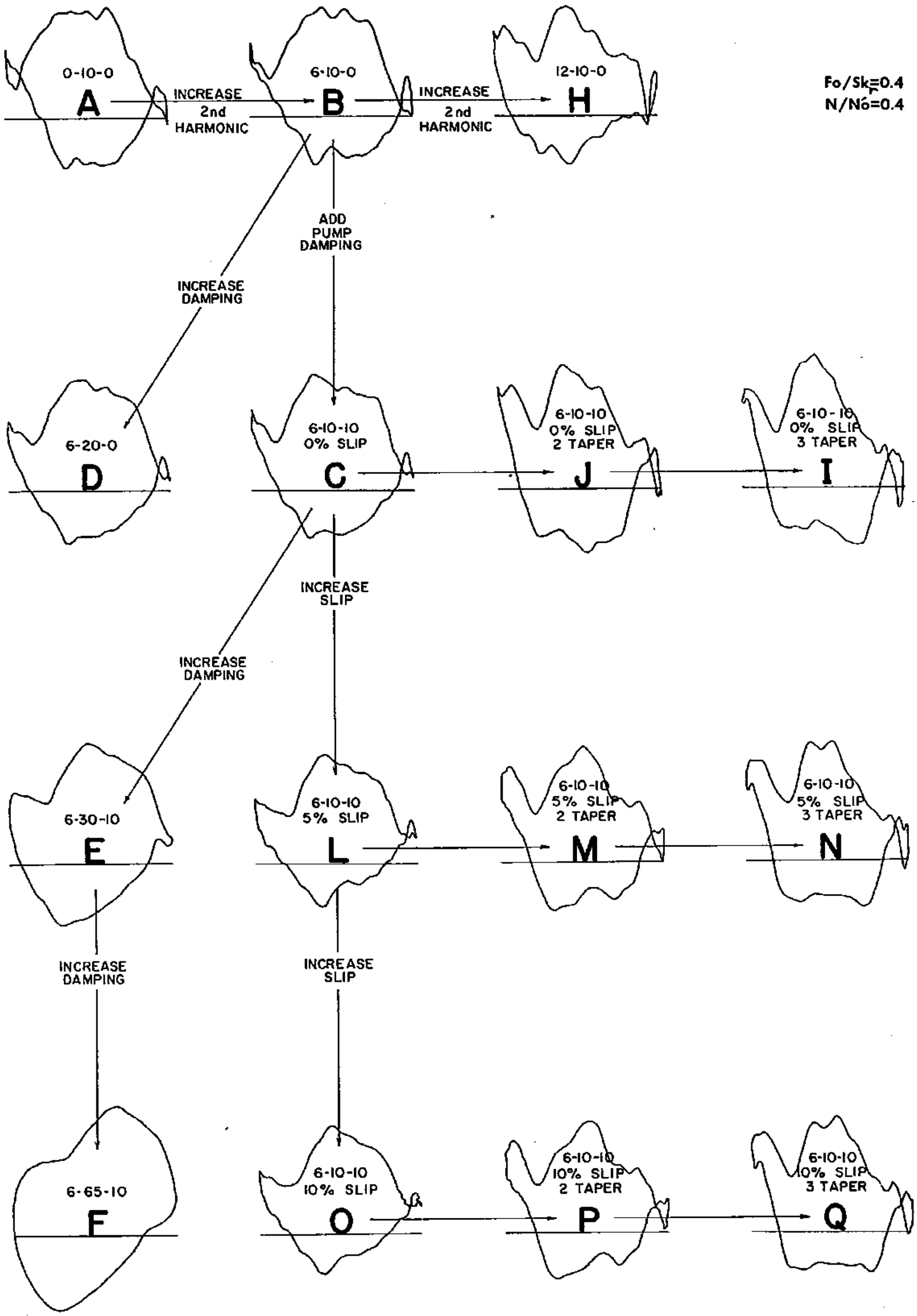
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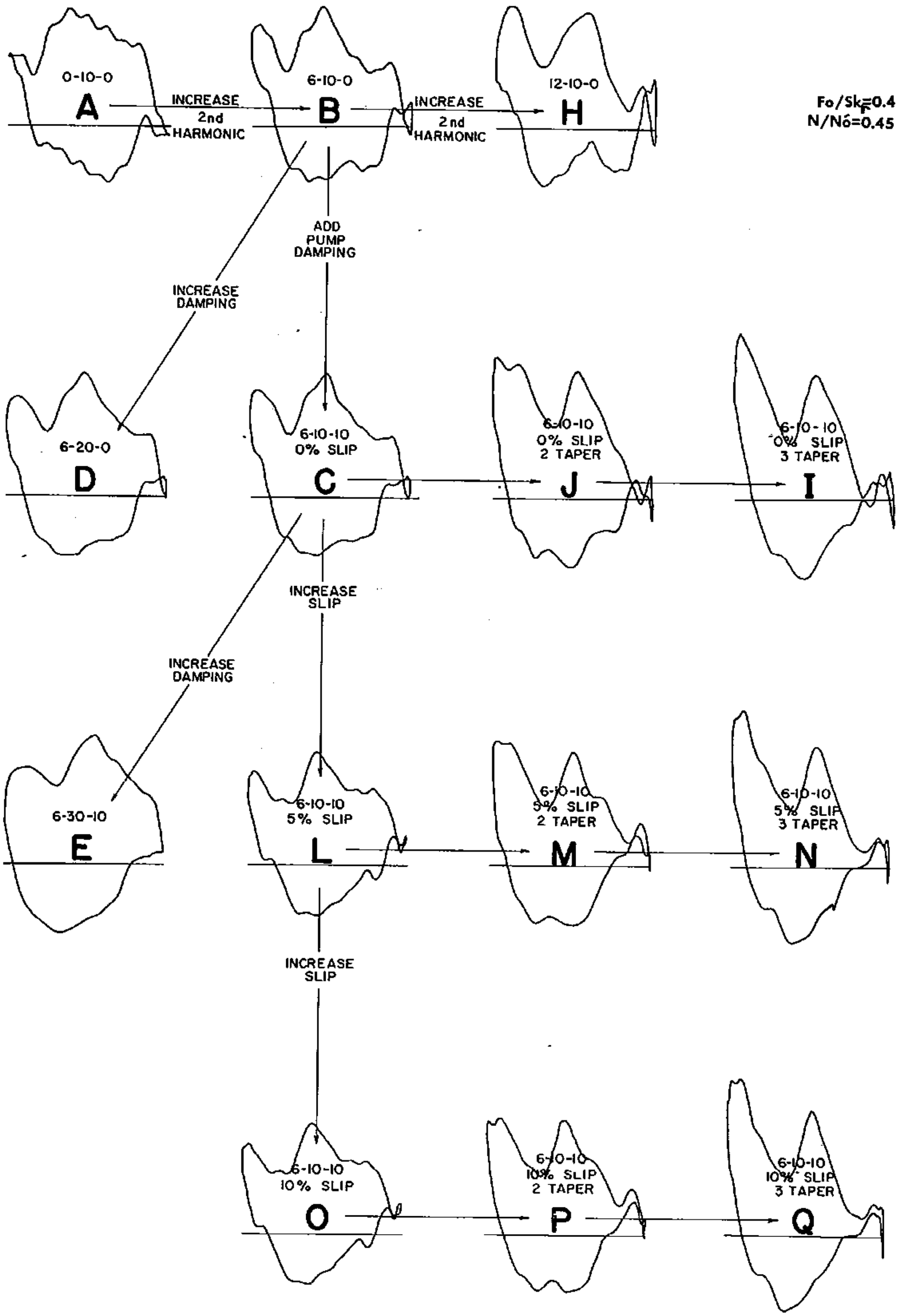
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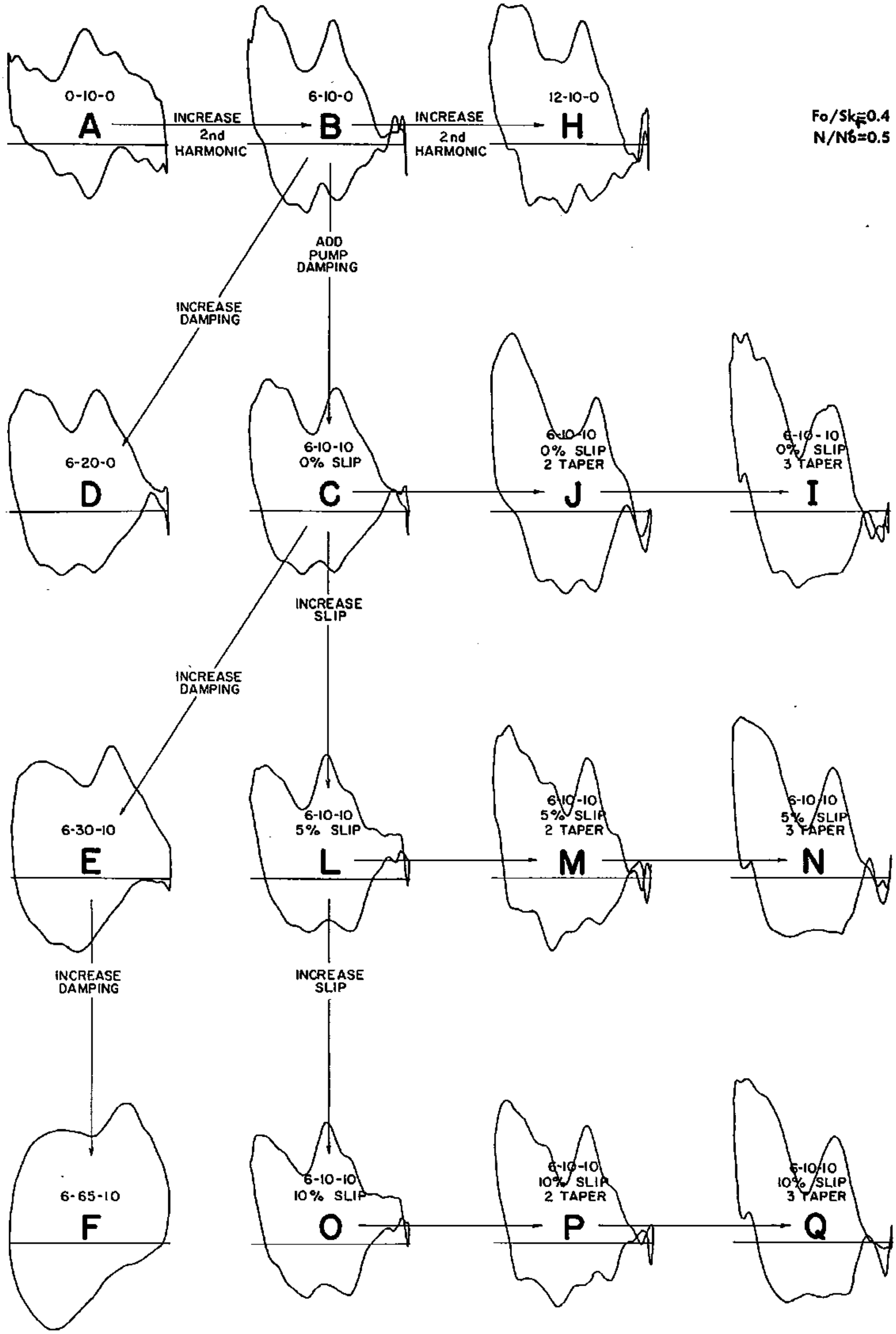
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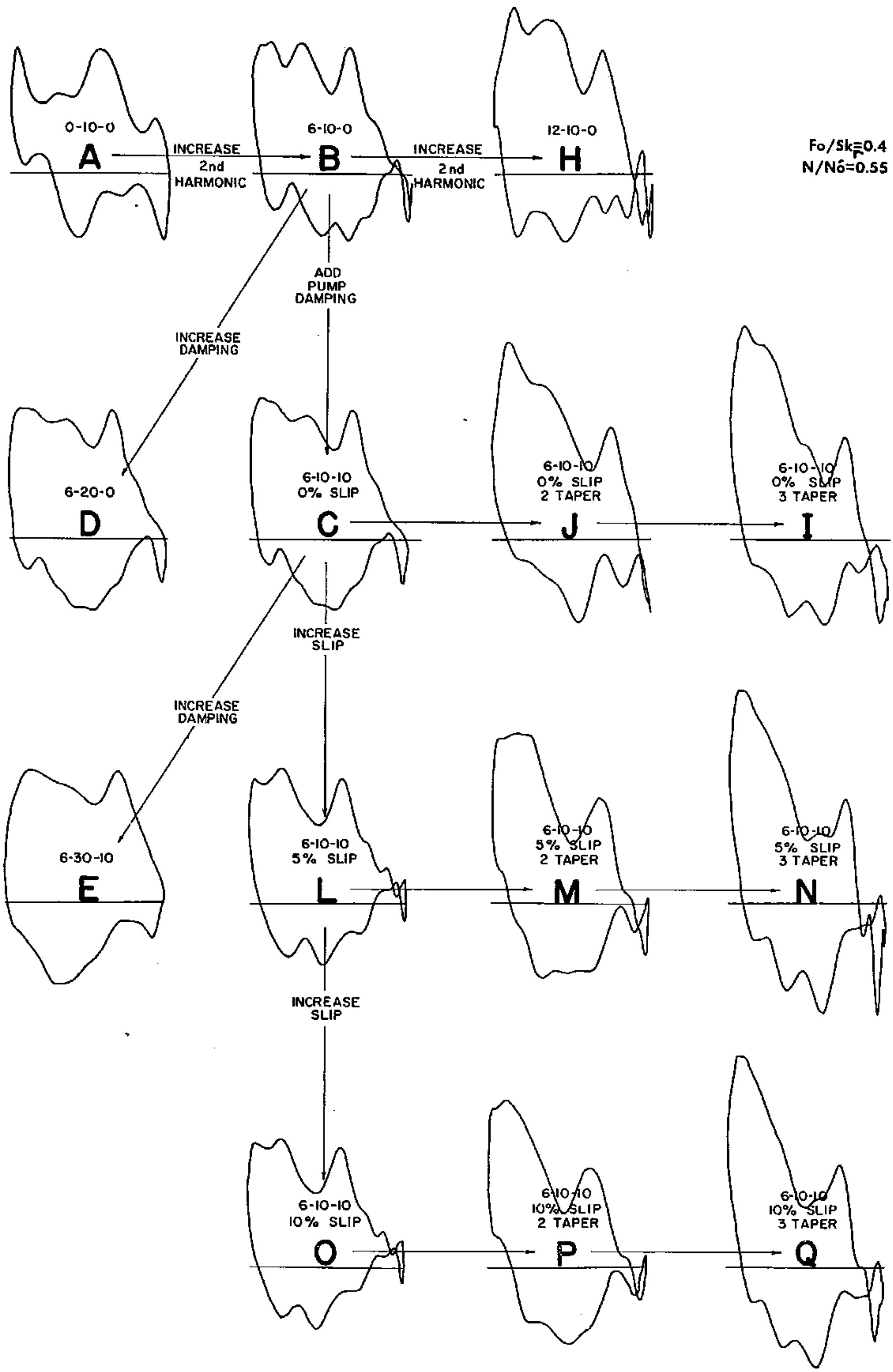
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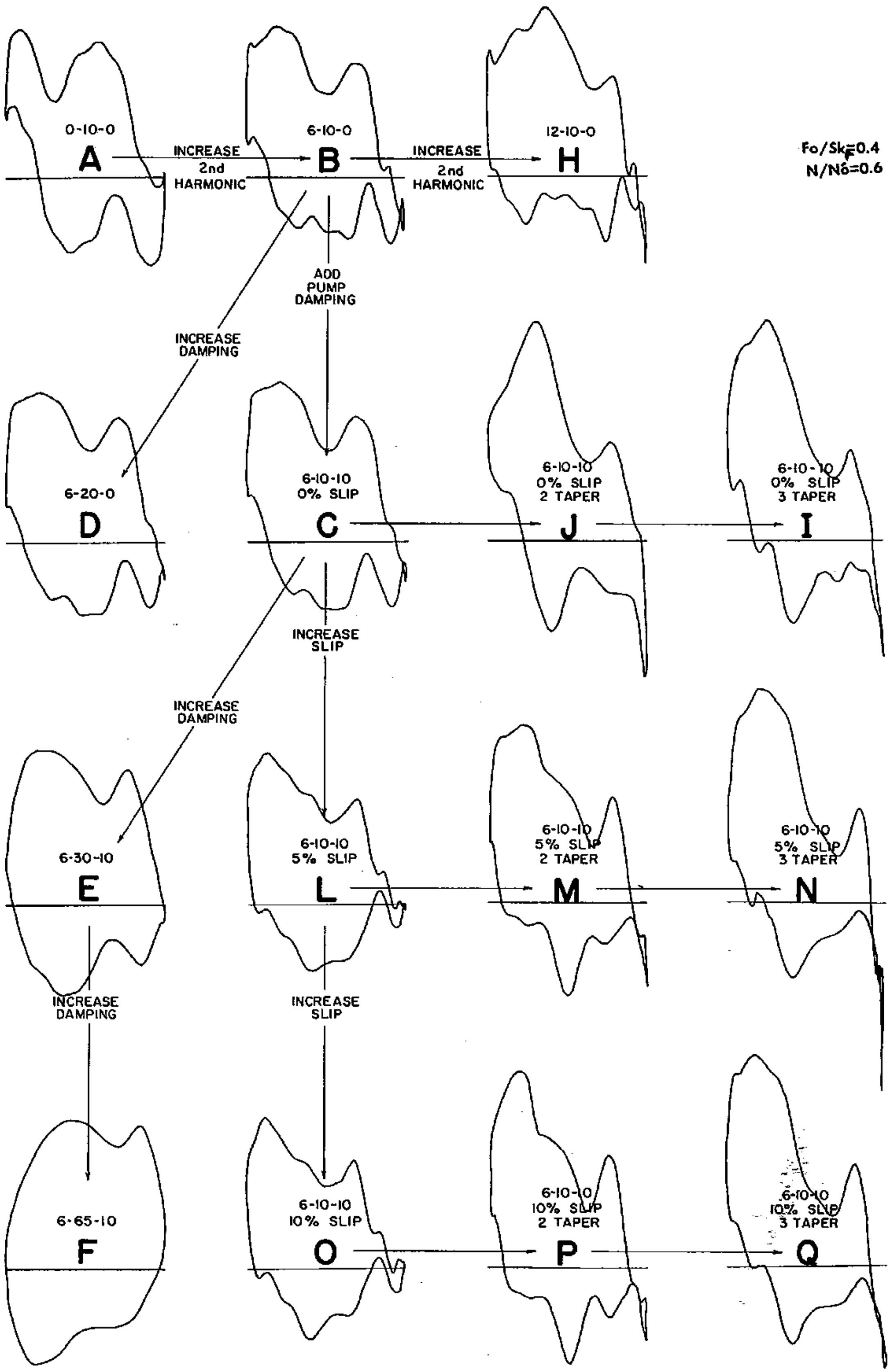
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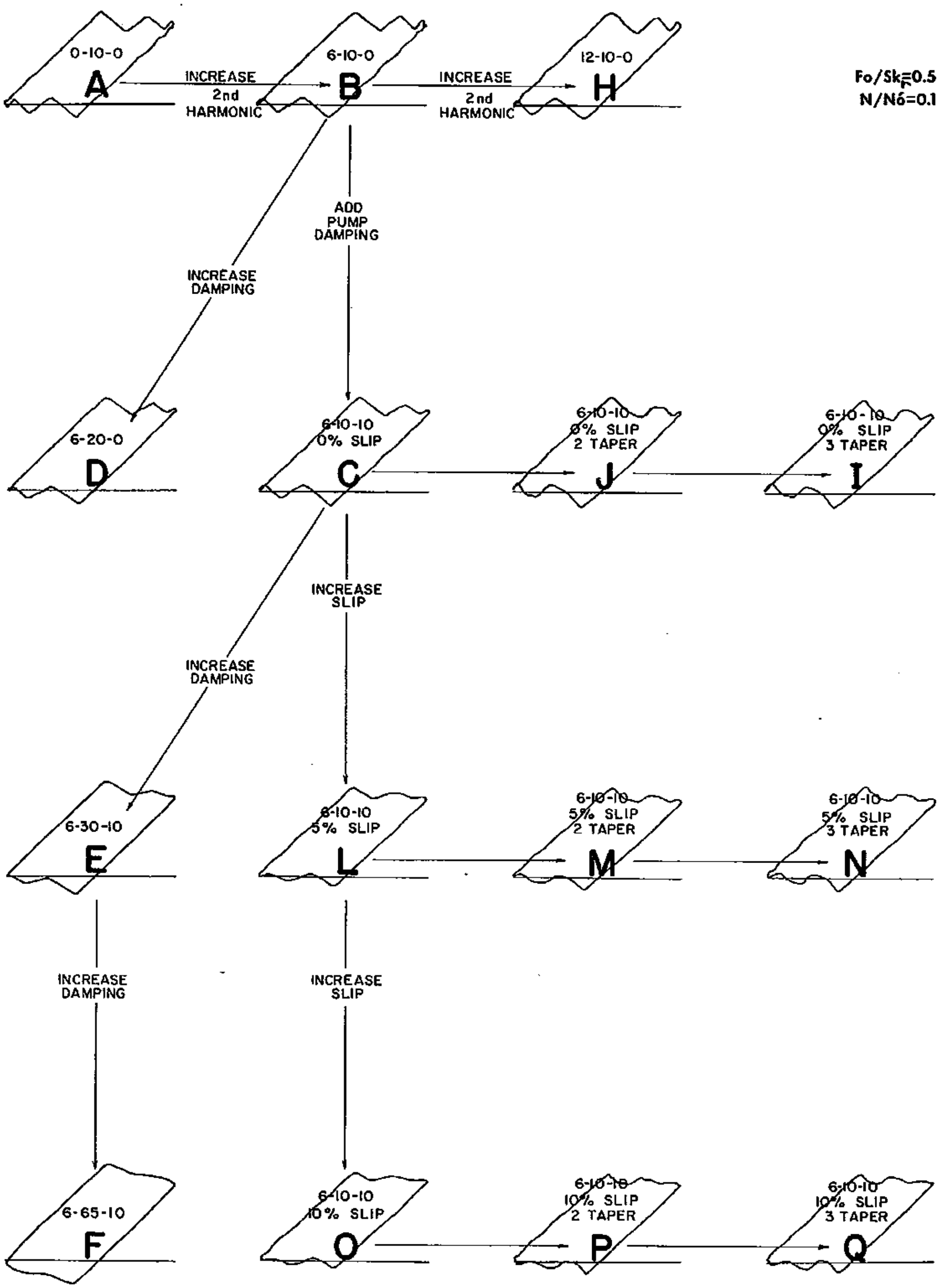

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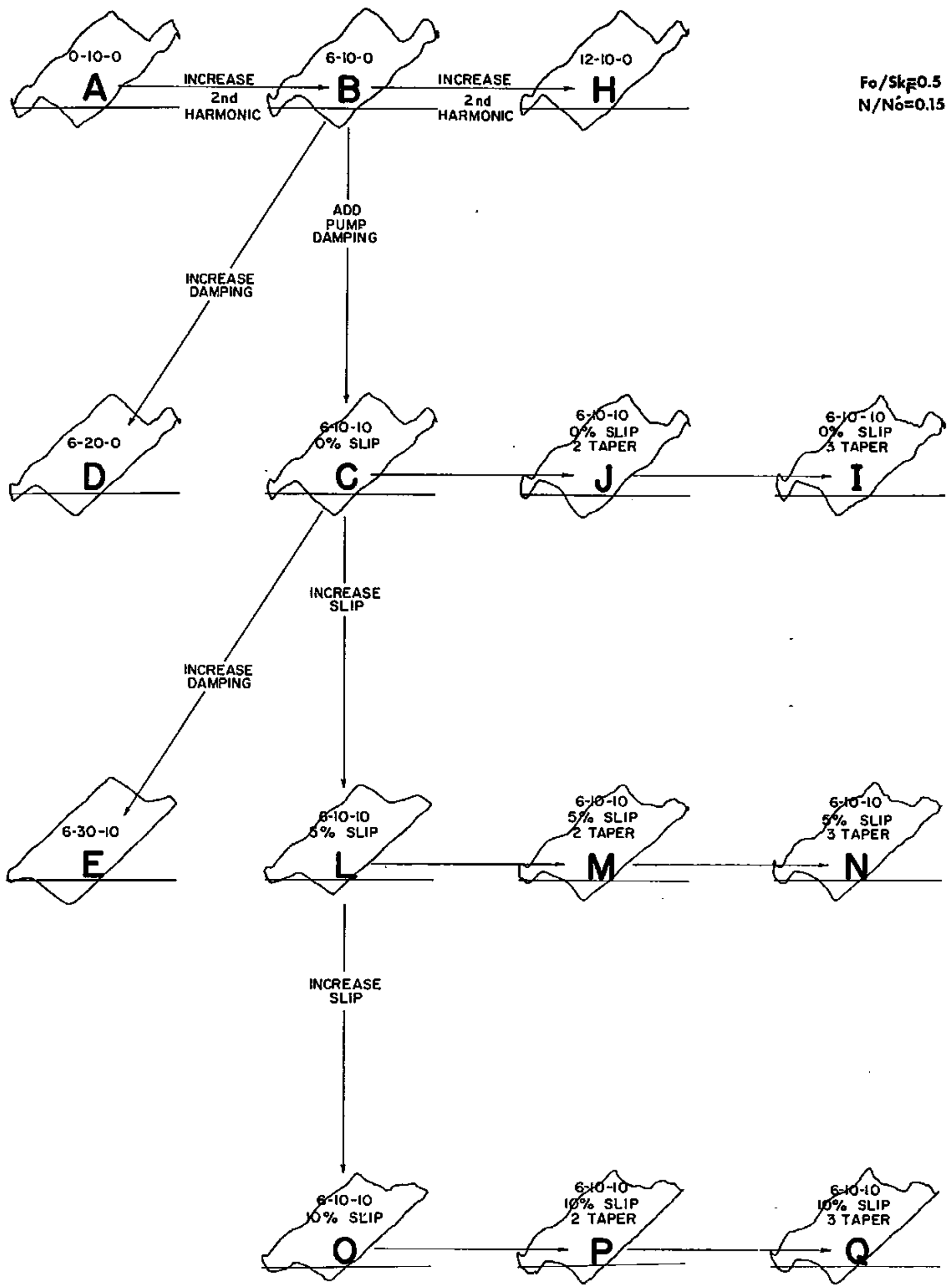
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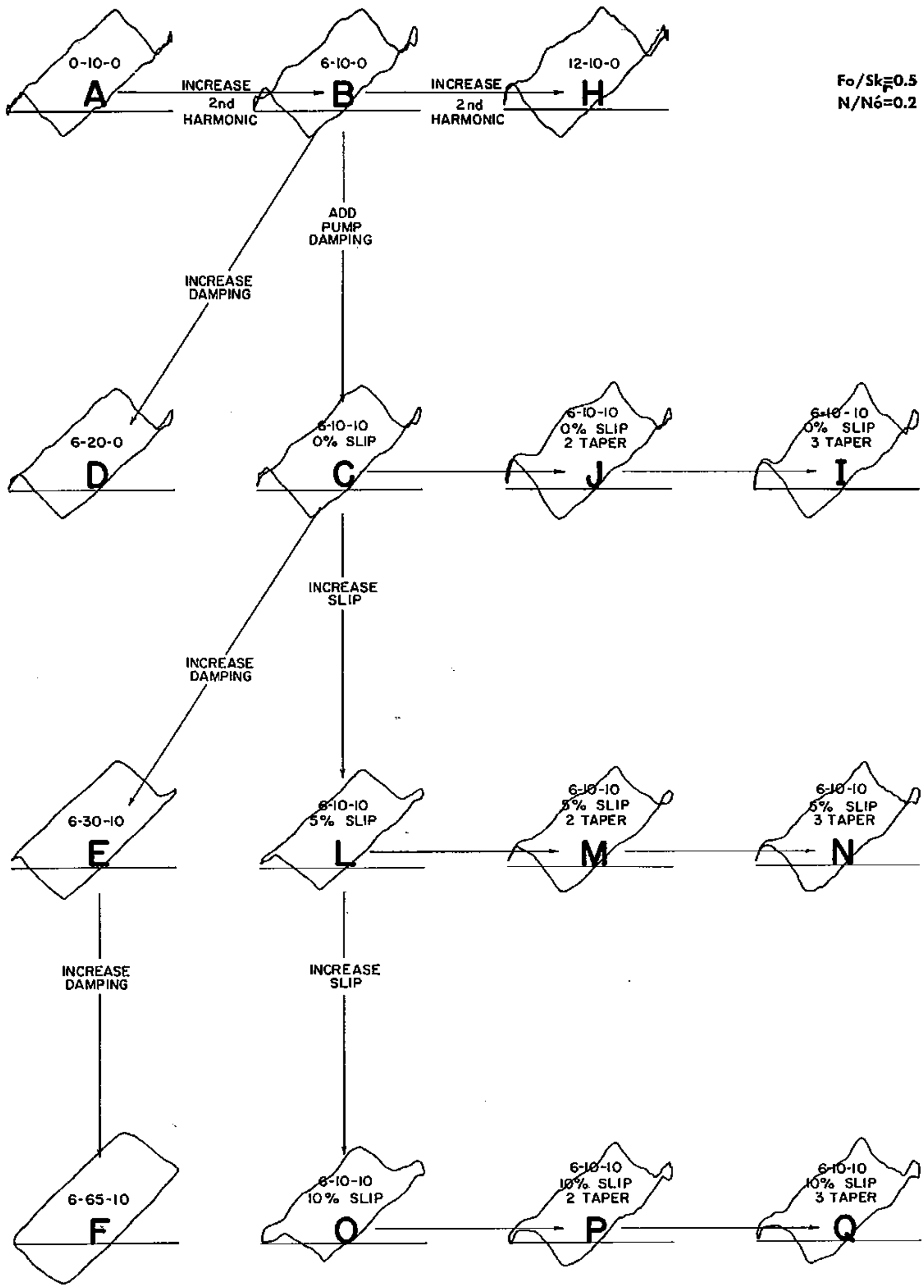
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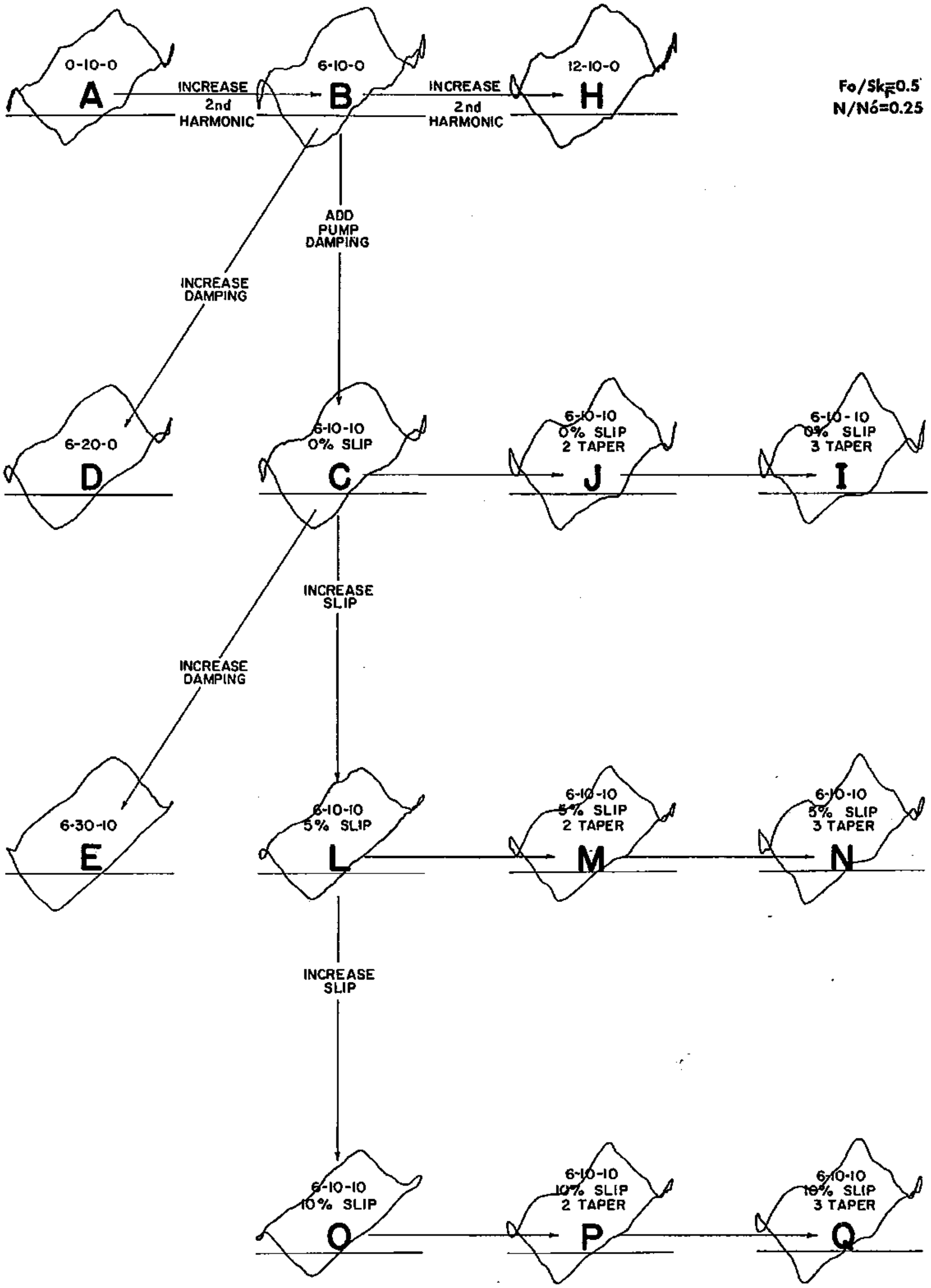
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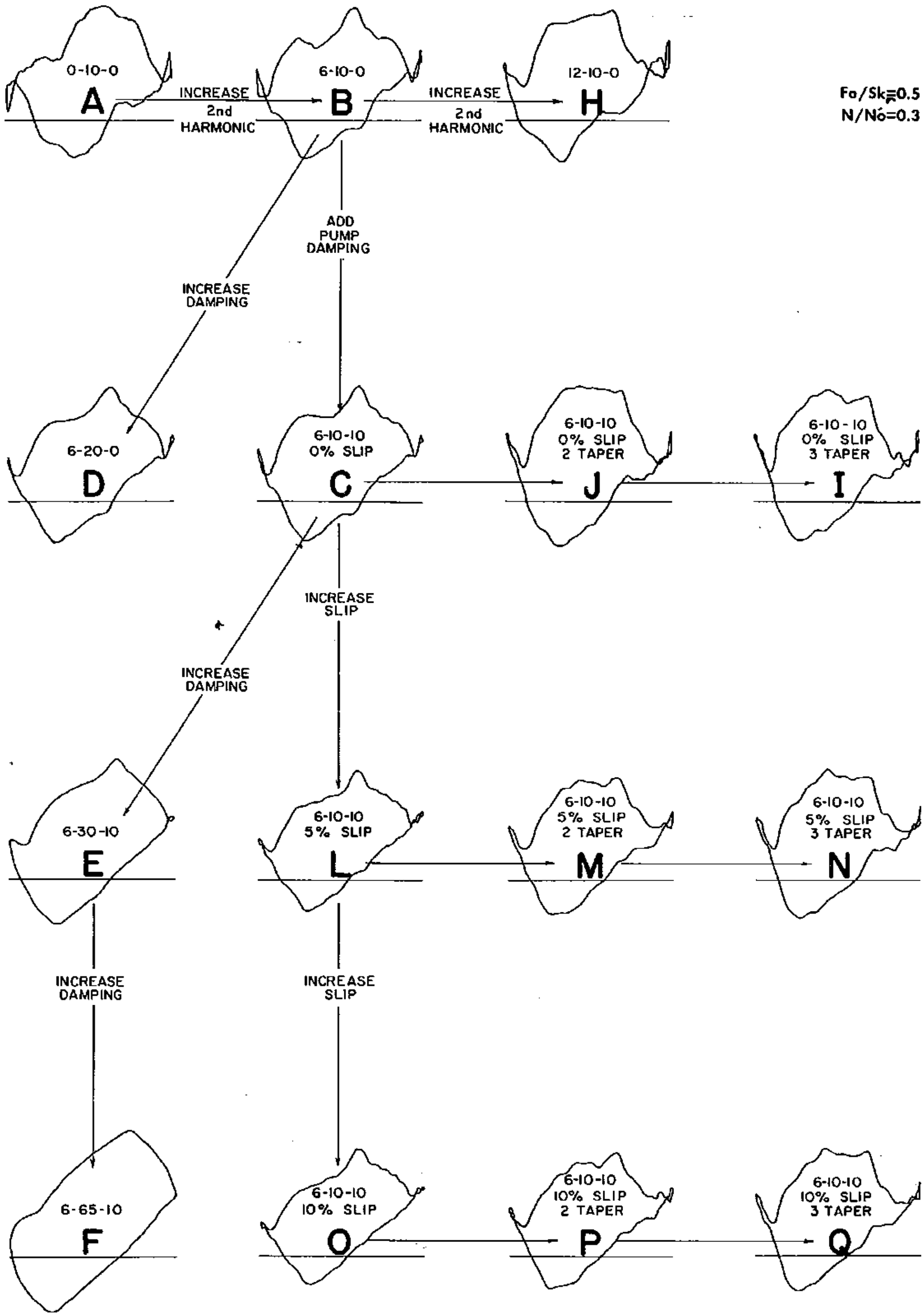
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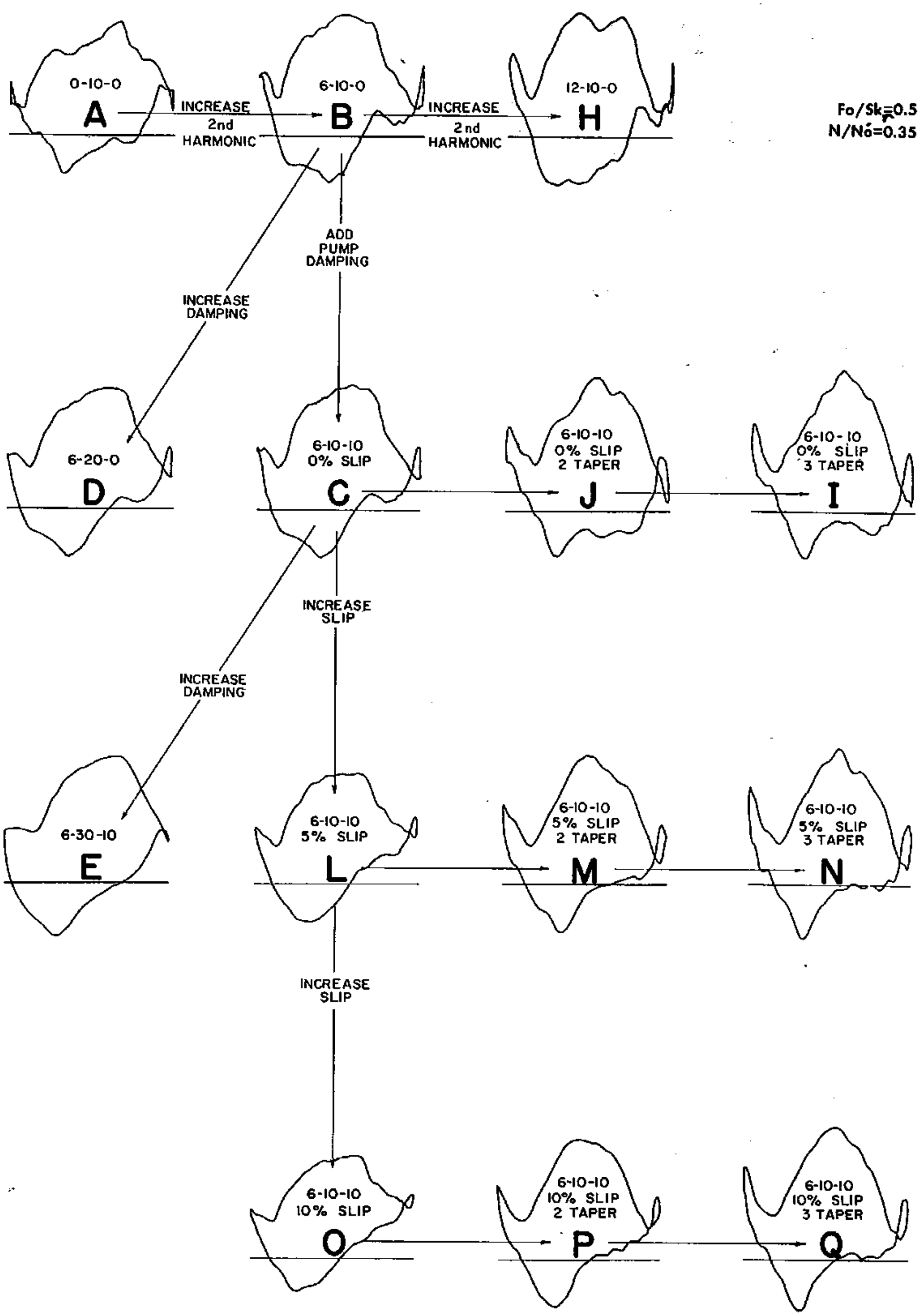
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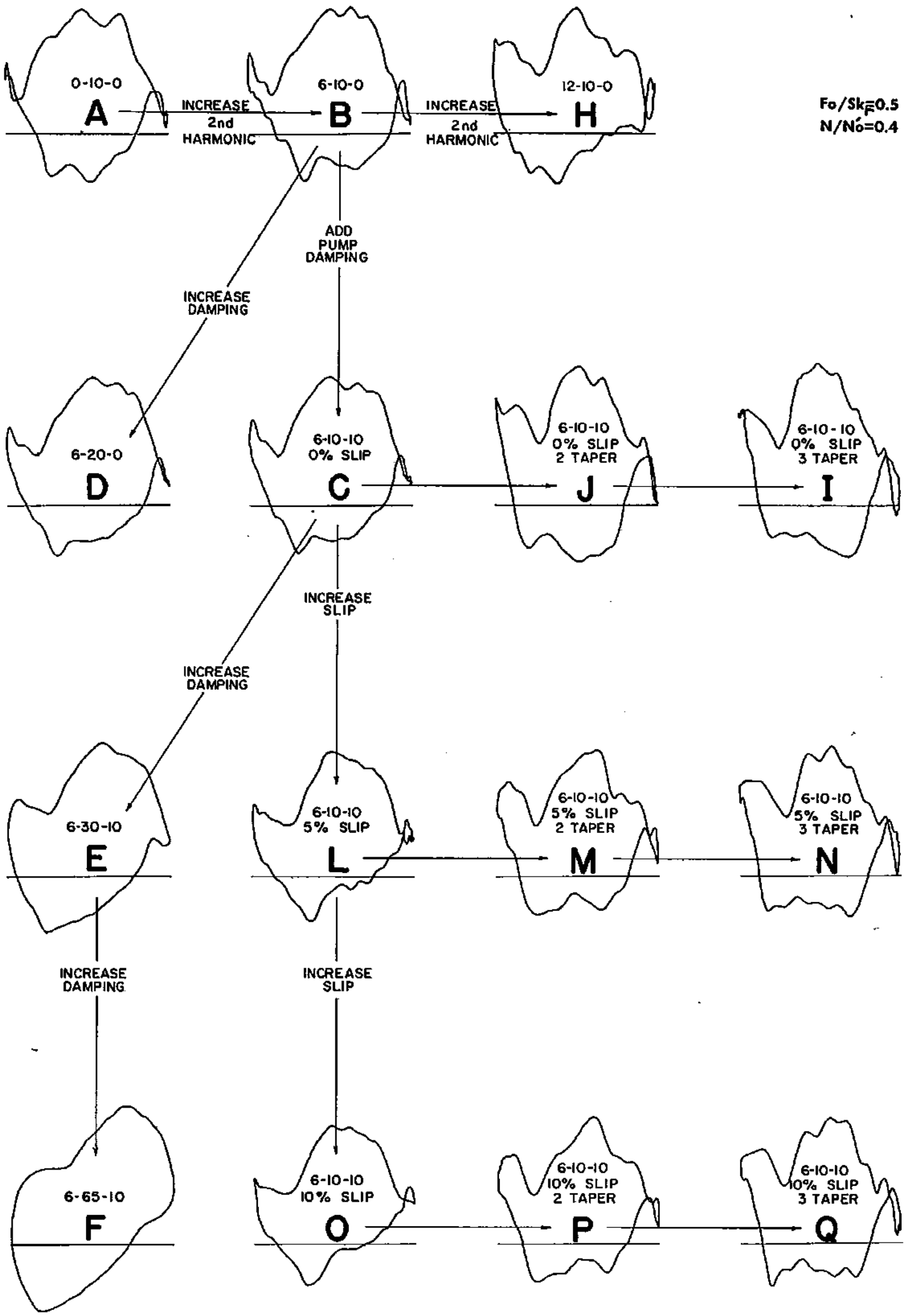
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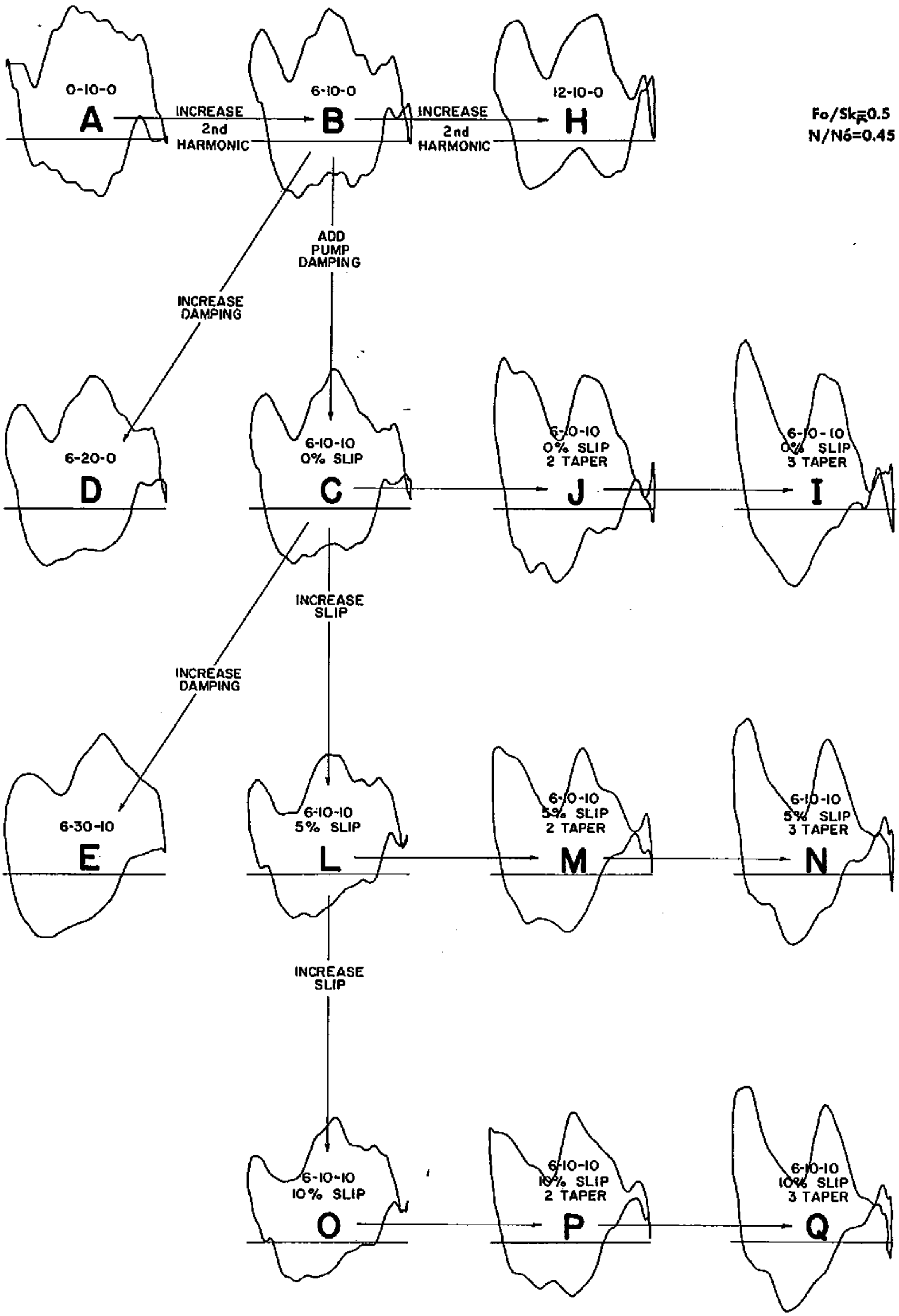
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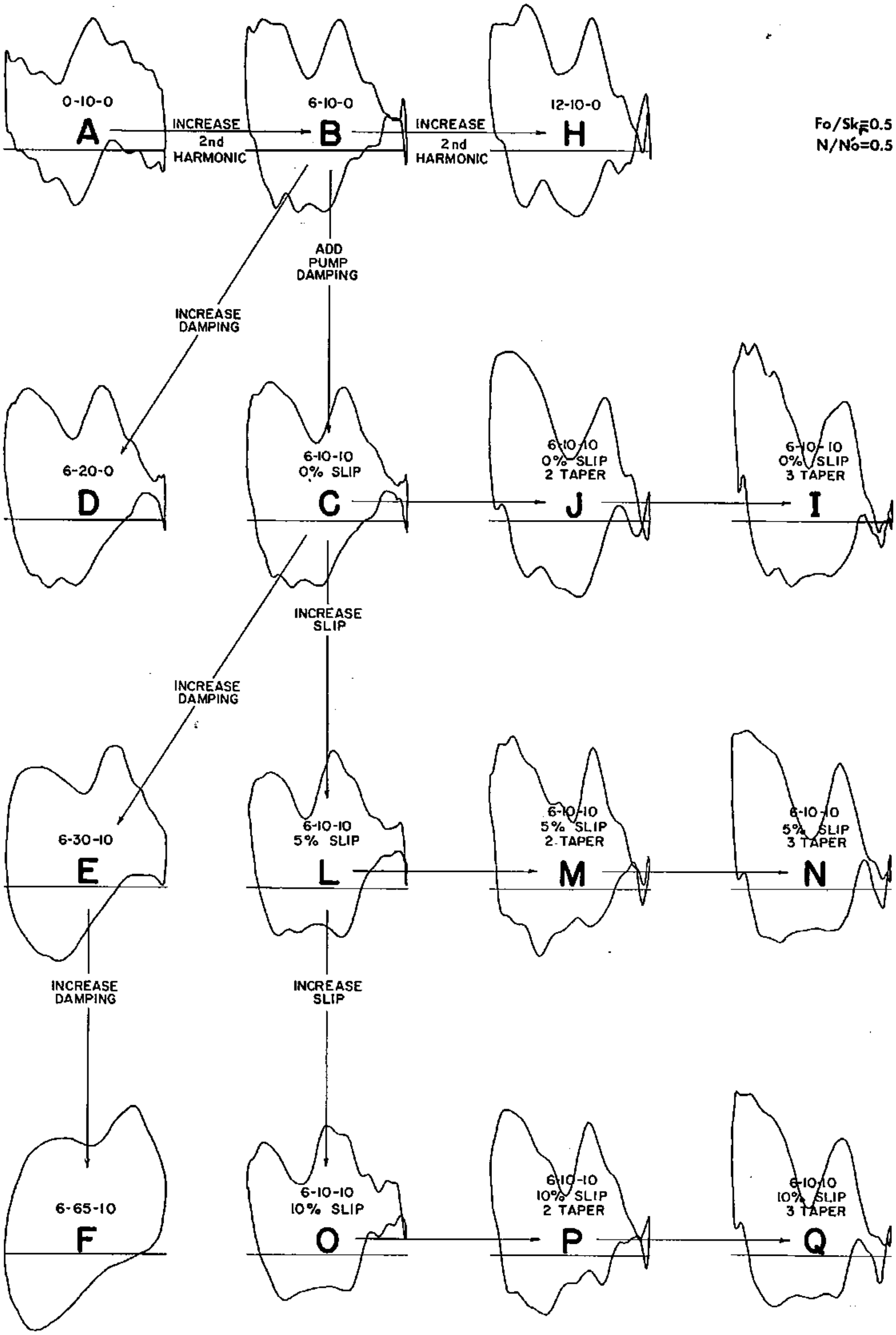
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D
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C
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0% SLIP
2 TAPER
J
6-10-10
0% SLIP
3 TAPER
I
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SLIP
INCREASE
DAMPING
6-30-10
E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
6-10-10
5% SLIP
3 TAPER
N
INCREASE
DAMPING
INCREASE
SLIP
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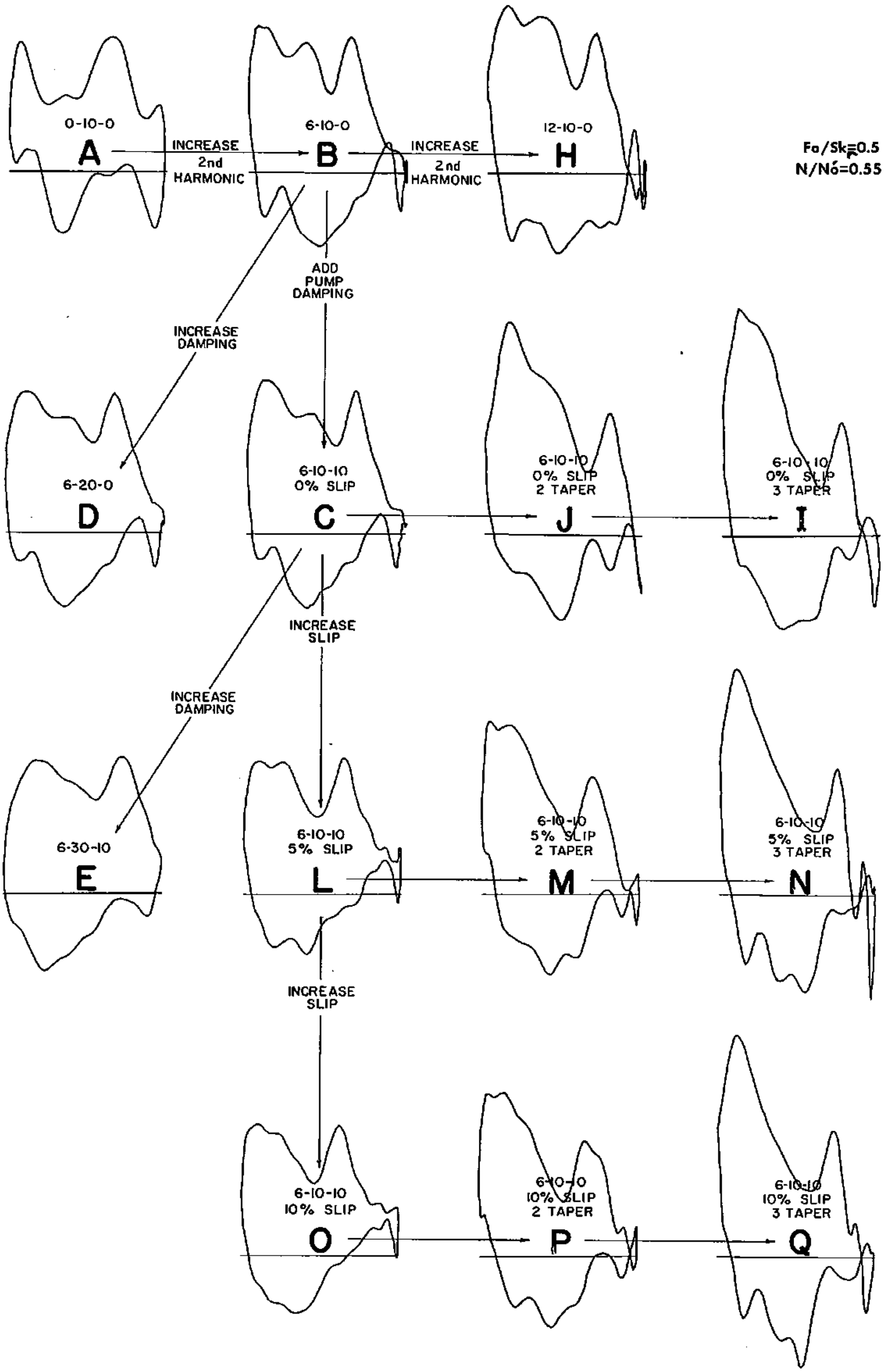
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C
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0% SLIP
2 TAPER
J
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0% SLIP
3 TAPER
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SLIP
INCREASE
DAMPING
6-30-10
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2 TAPER
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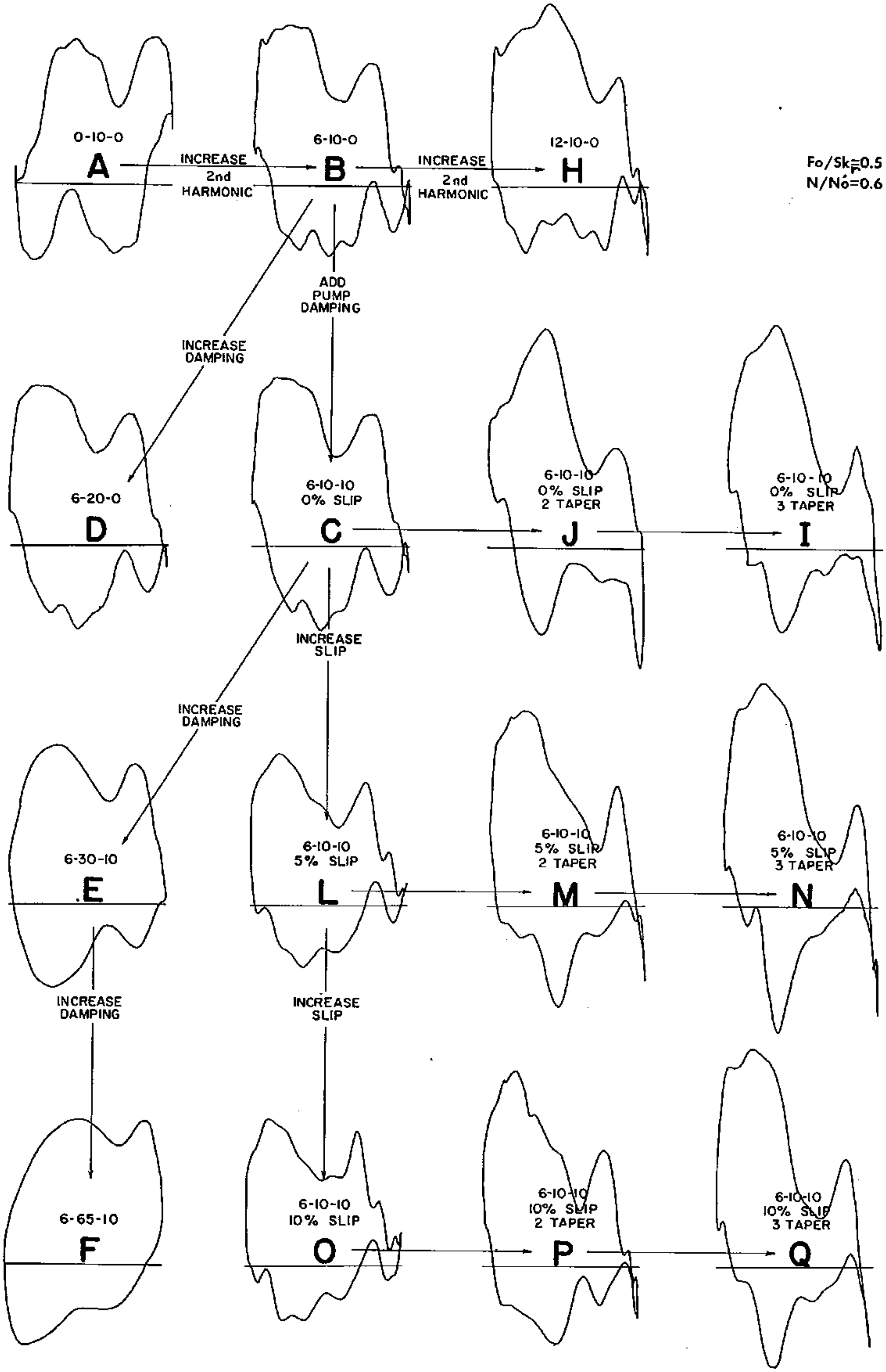

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6-20-0
D
6-10-10
0% SLIP
C
6-10-10
0% SLIP
2 TAPER
J
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0% SLIP
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INCREASE DAMPING
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E
6-10-10
5% SLIP
L
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5% SLIP
2 TAPER
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3 TAPER
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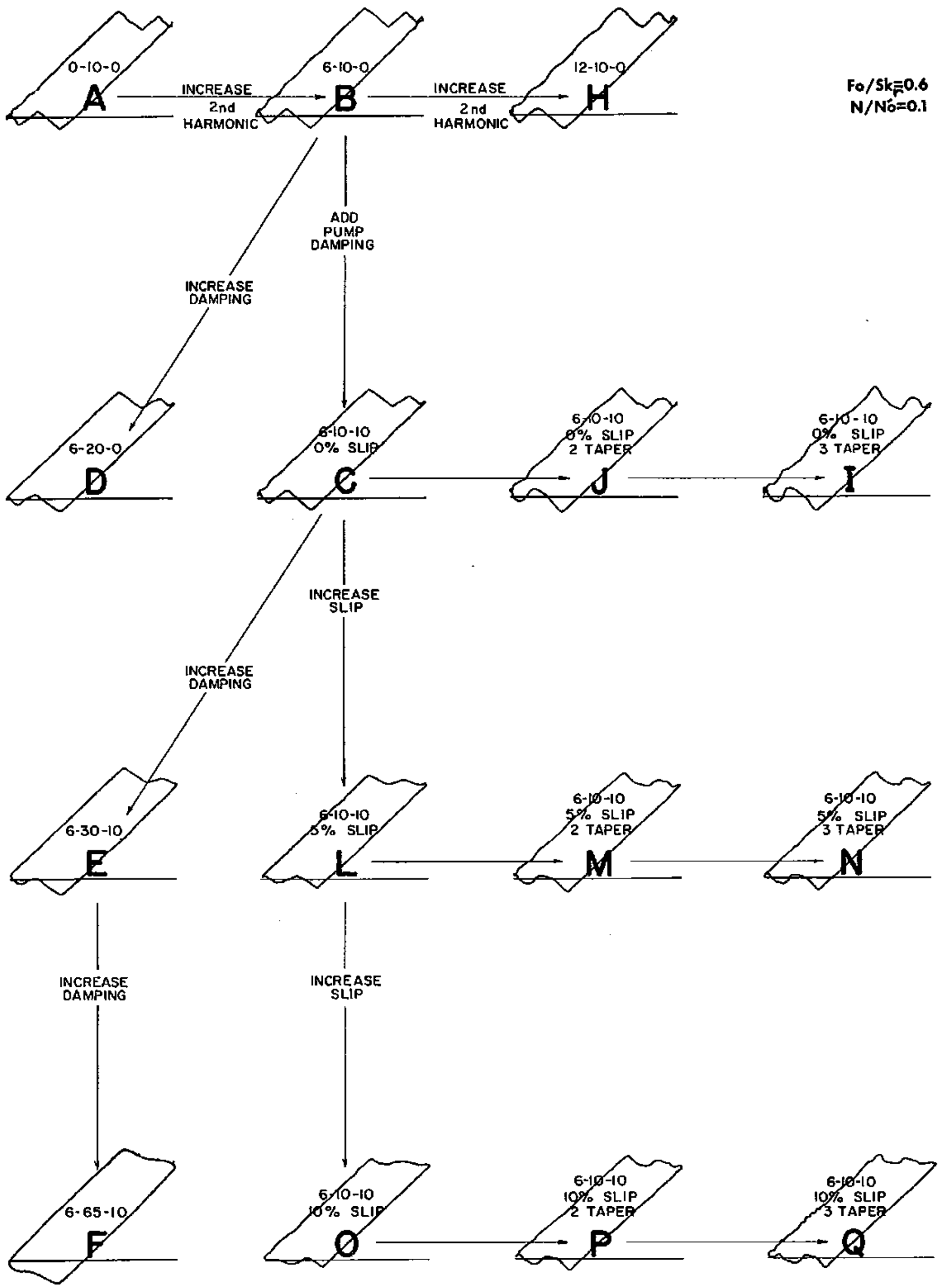
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3 TAPER
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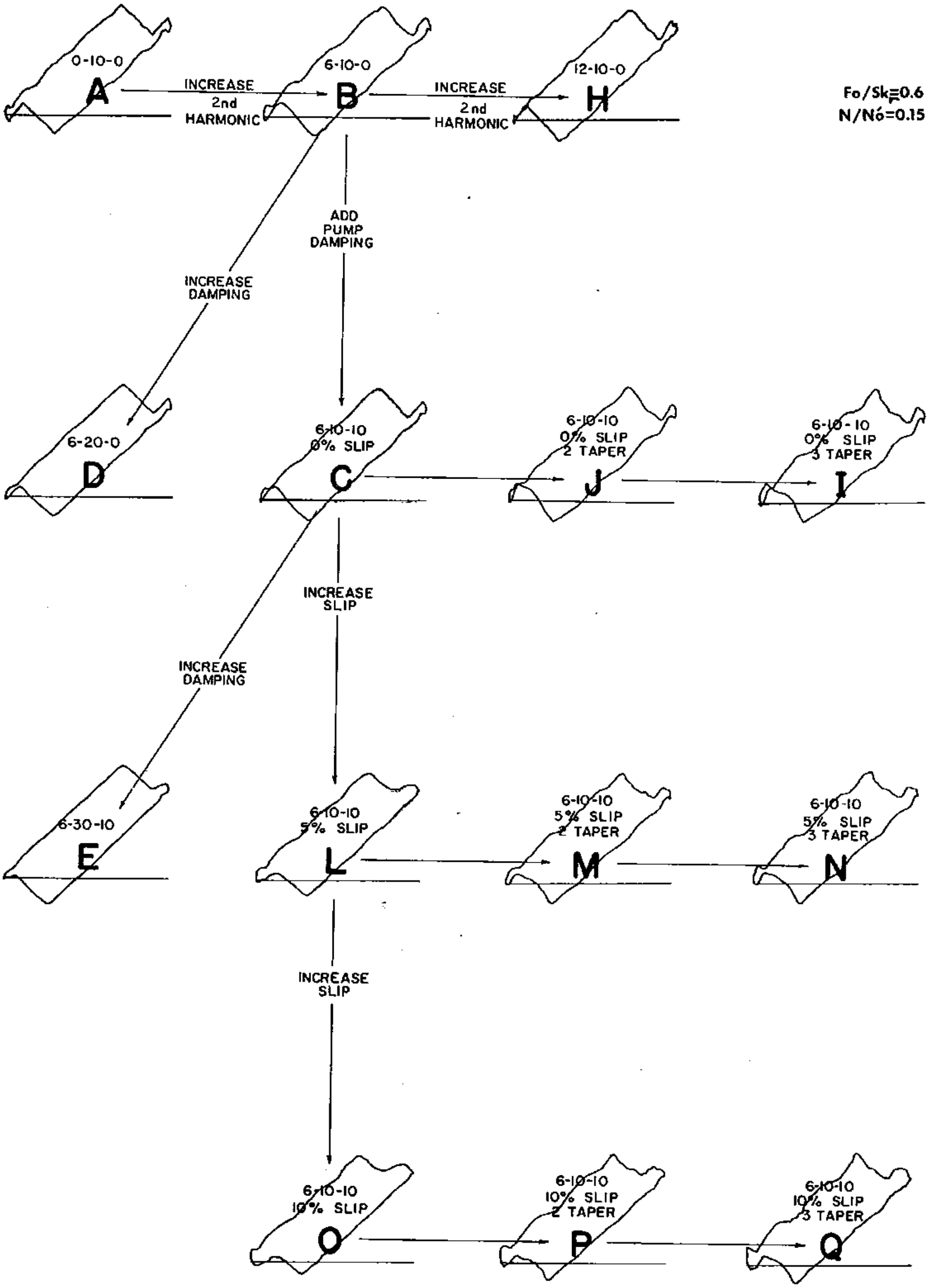
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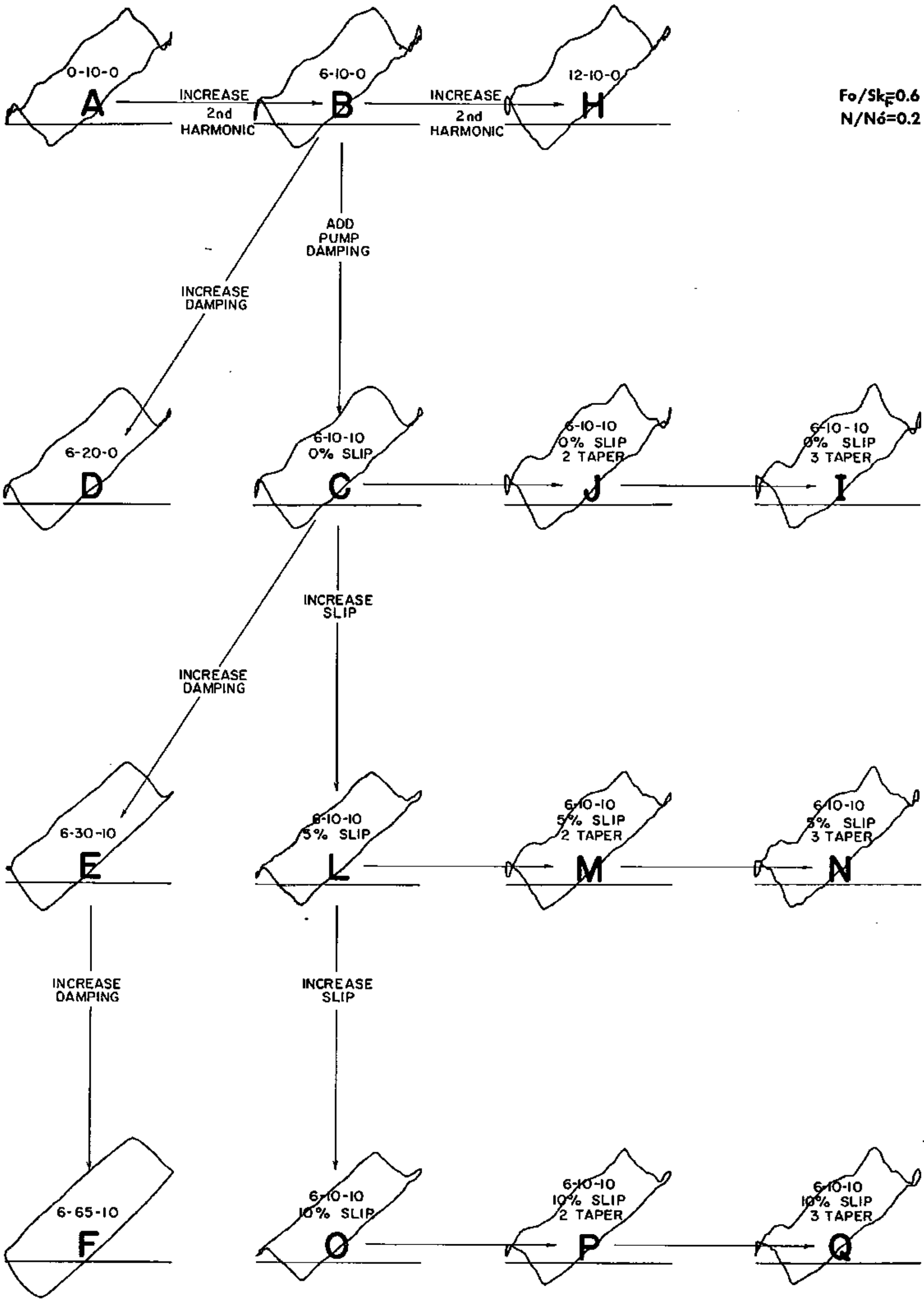
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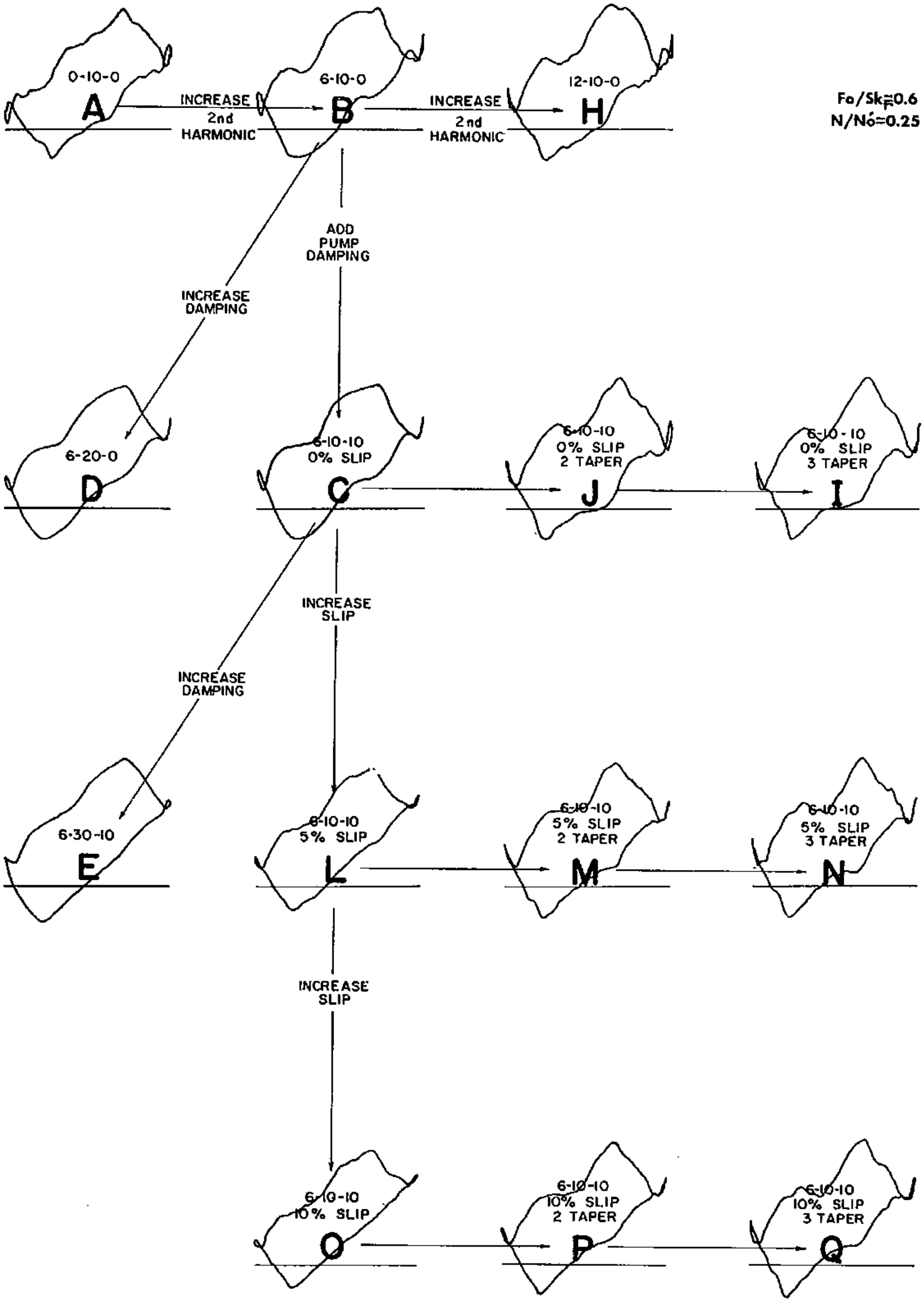

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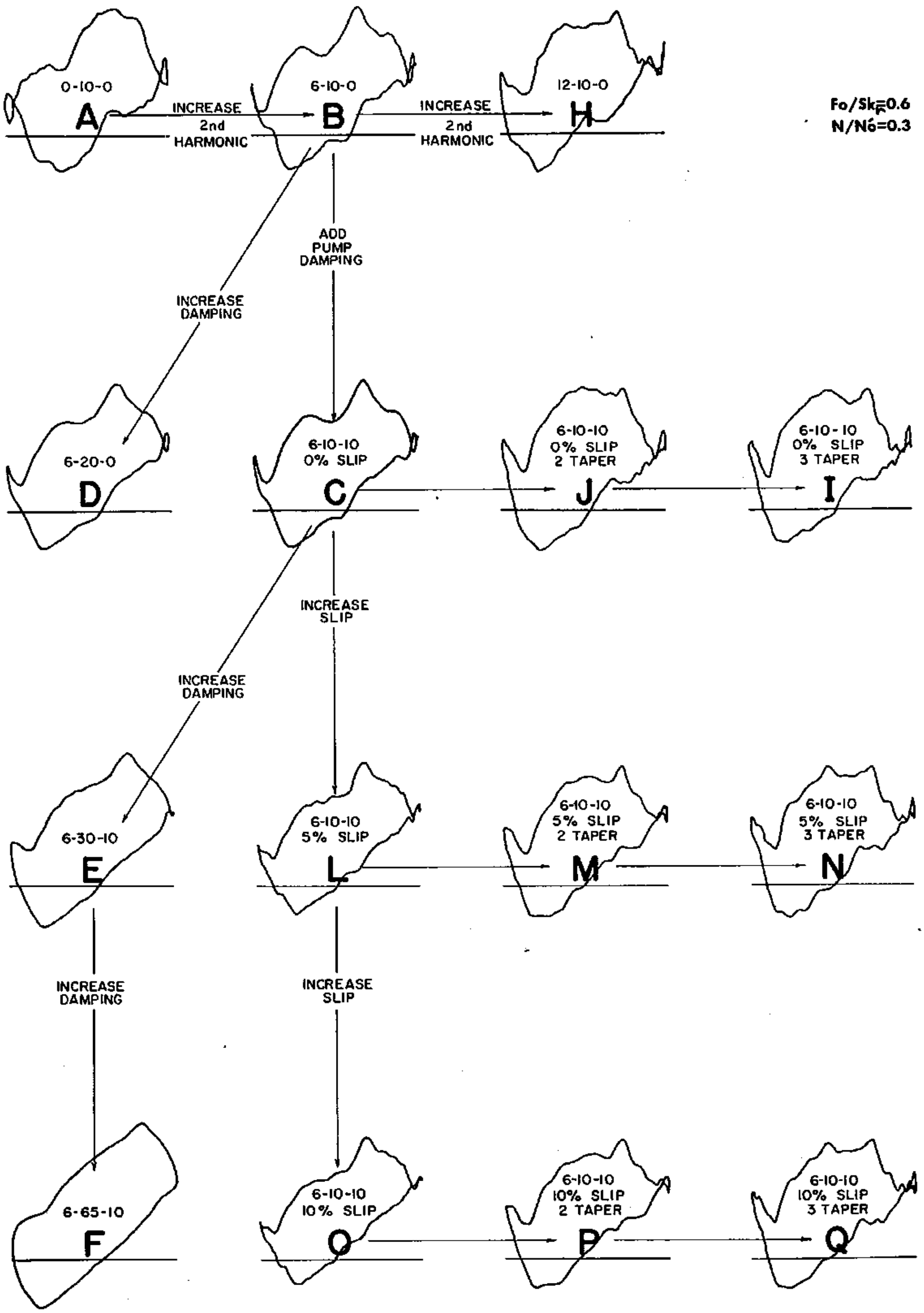
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DAMPING
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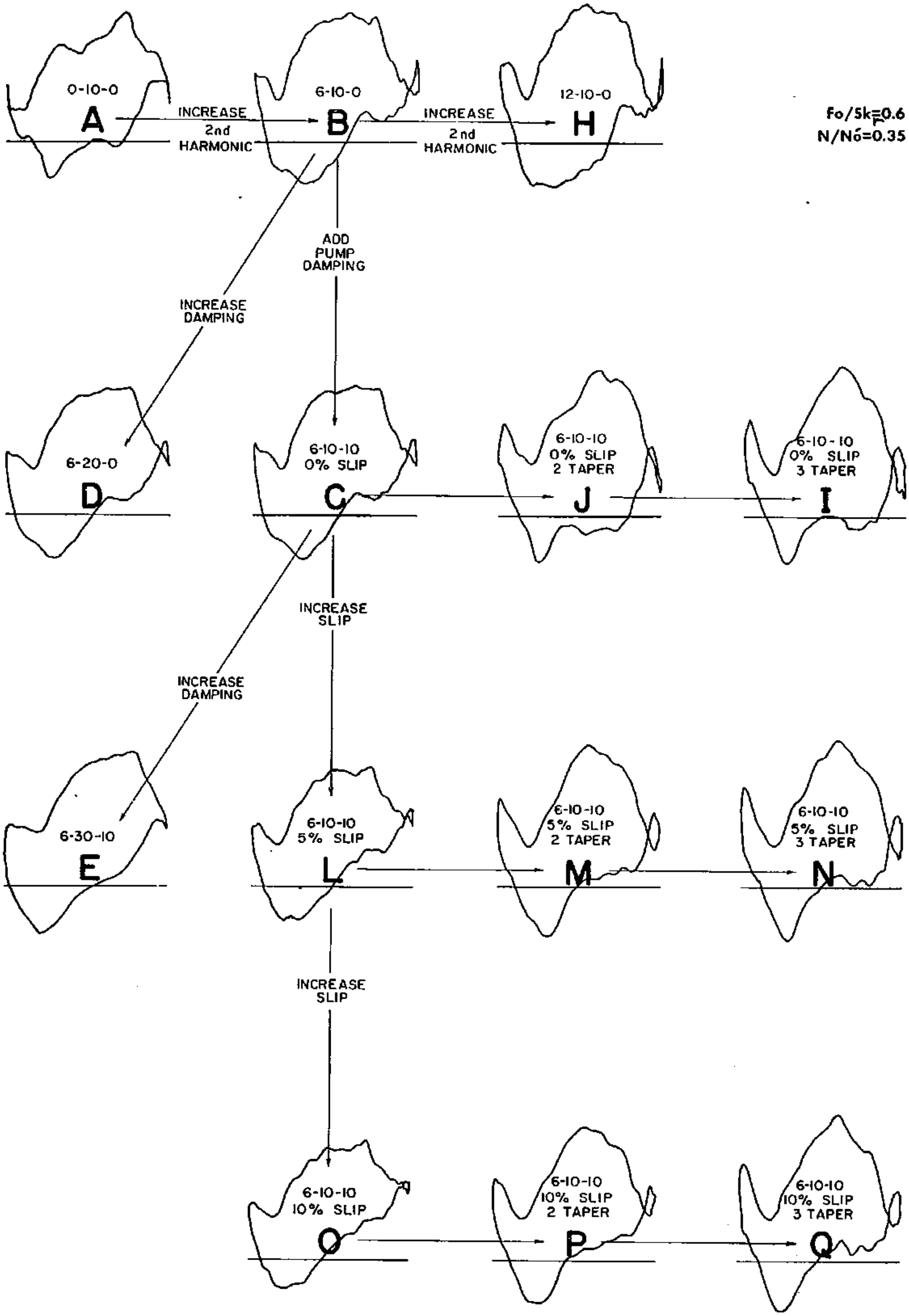
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INCREASE
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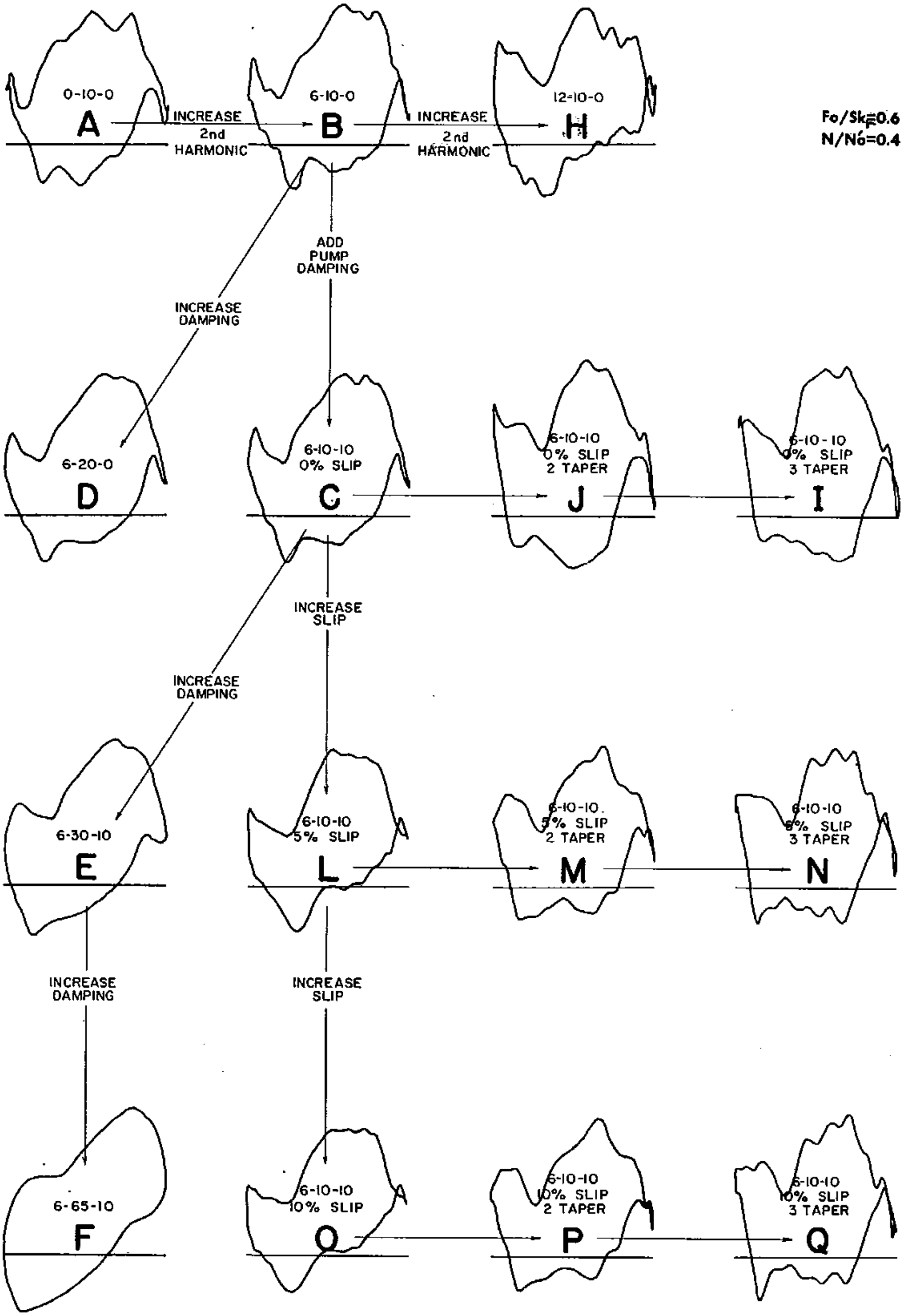
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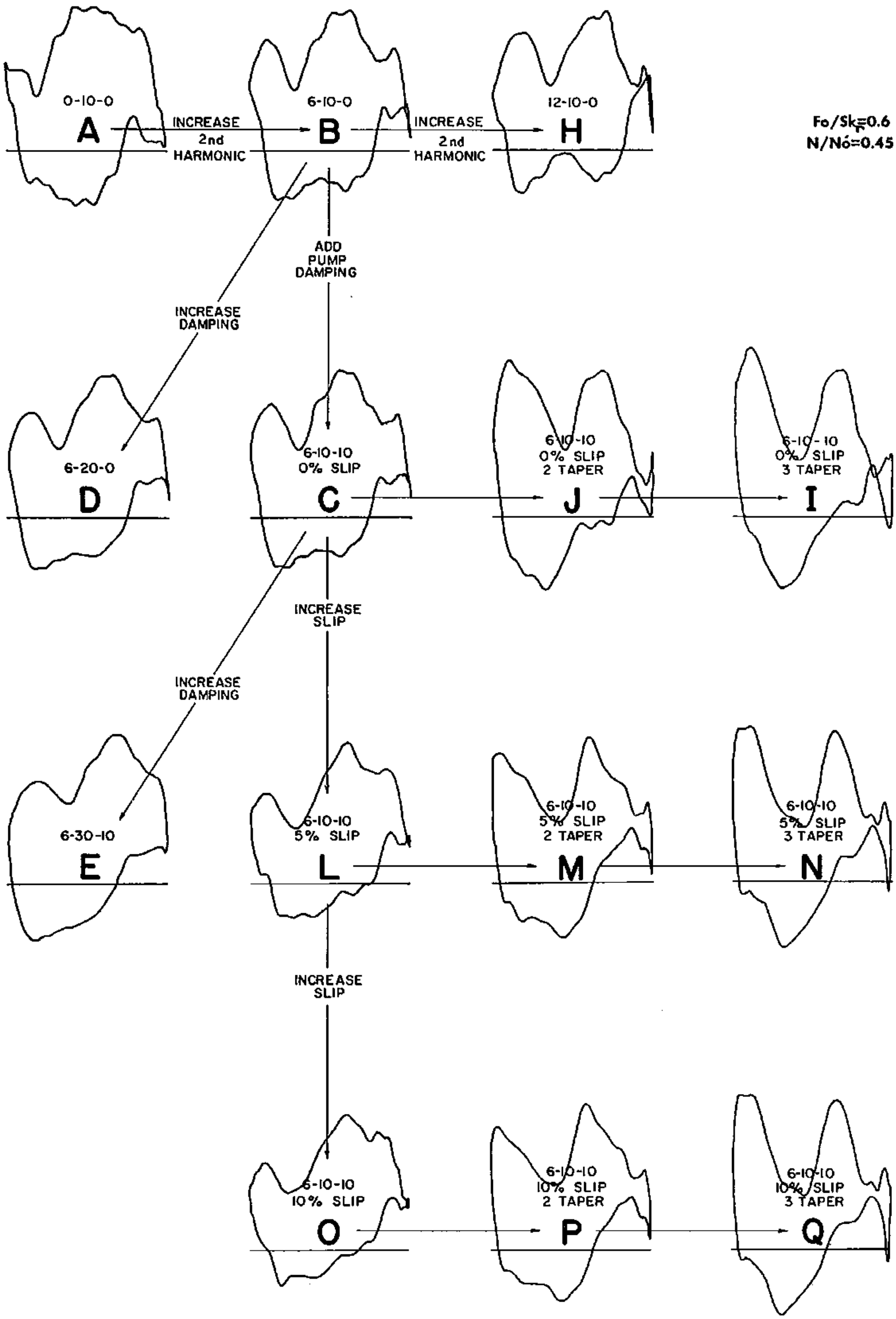
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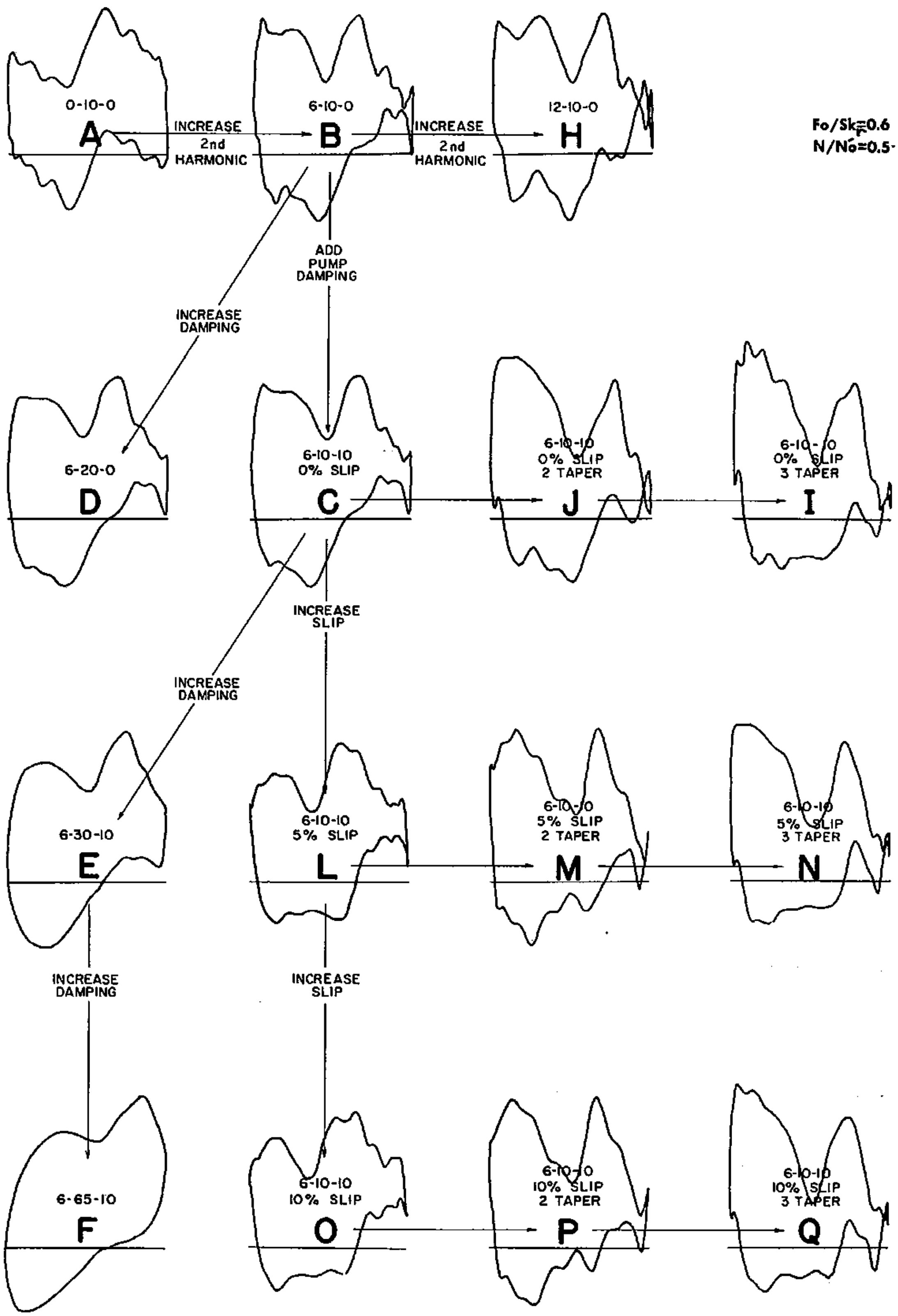
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3 TAPER
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INCREASE DAMPING
INCREASE SLIP
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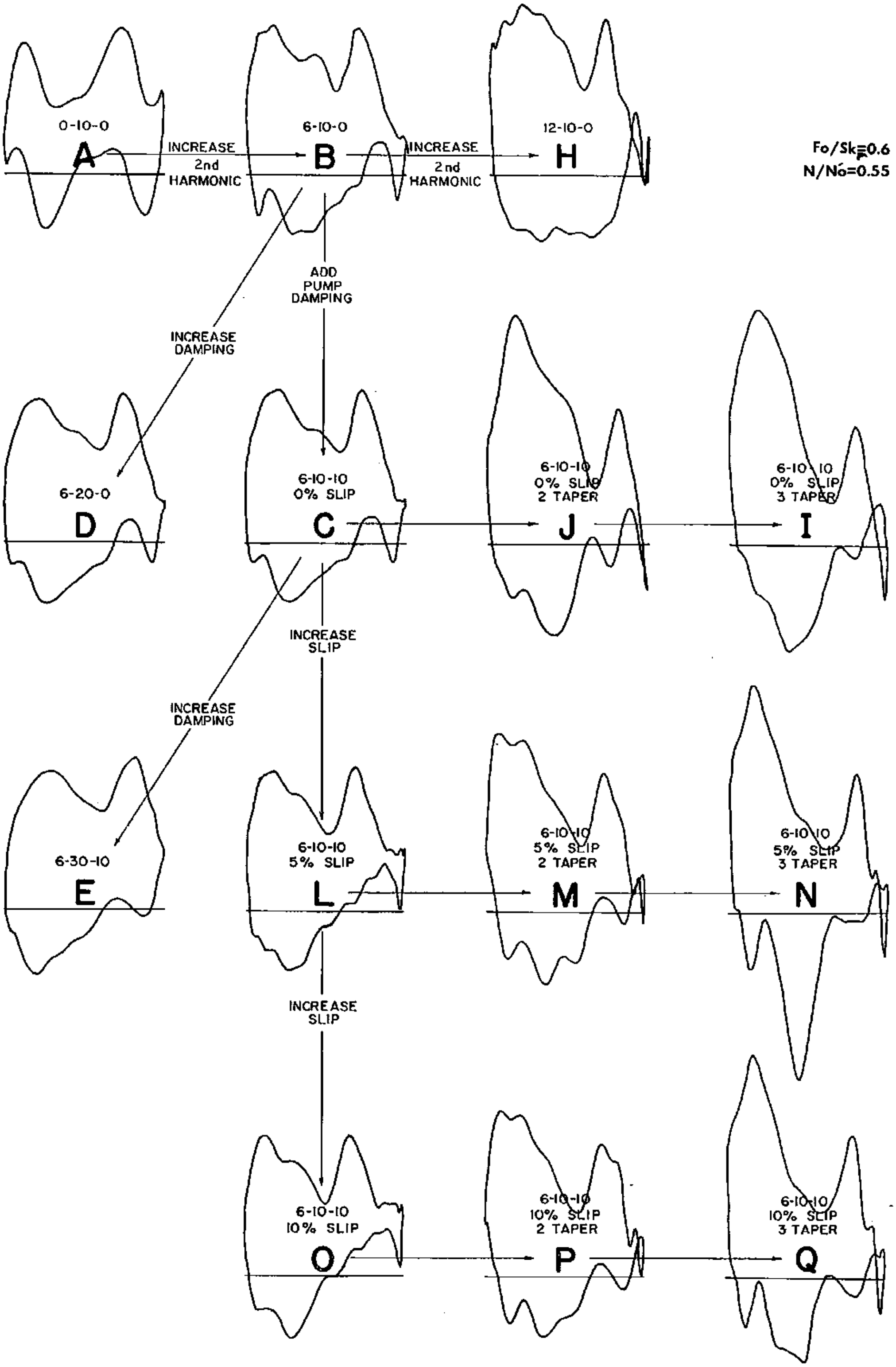
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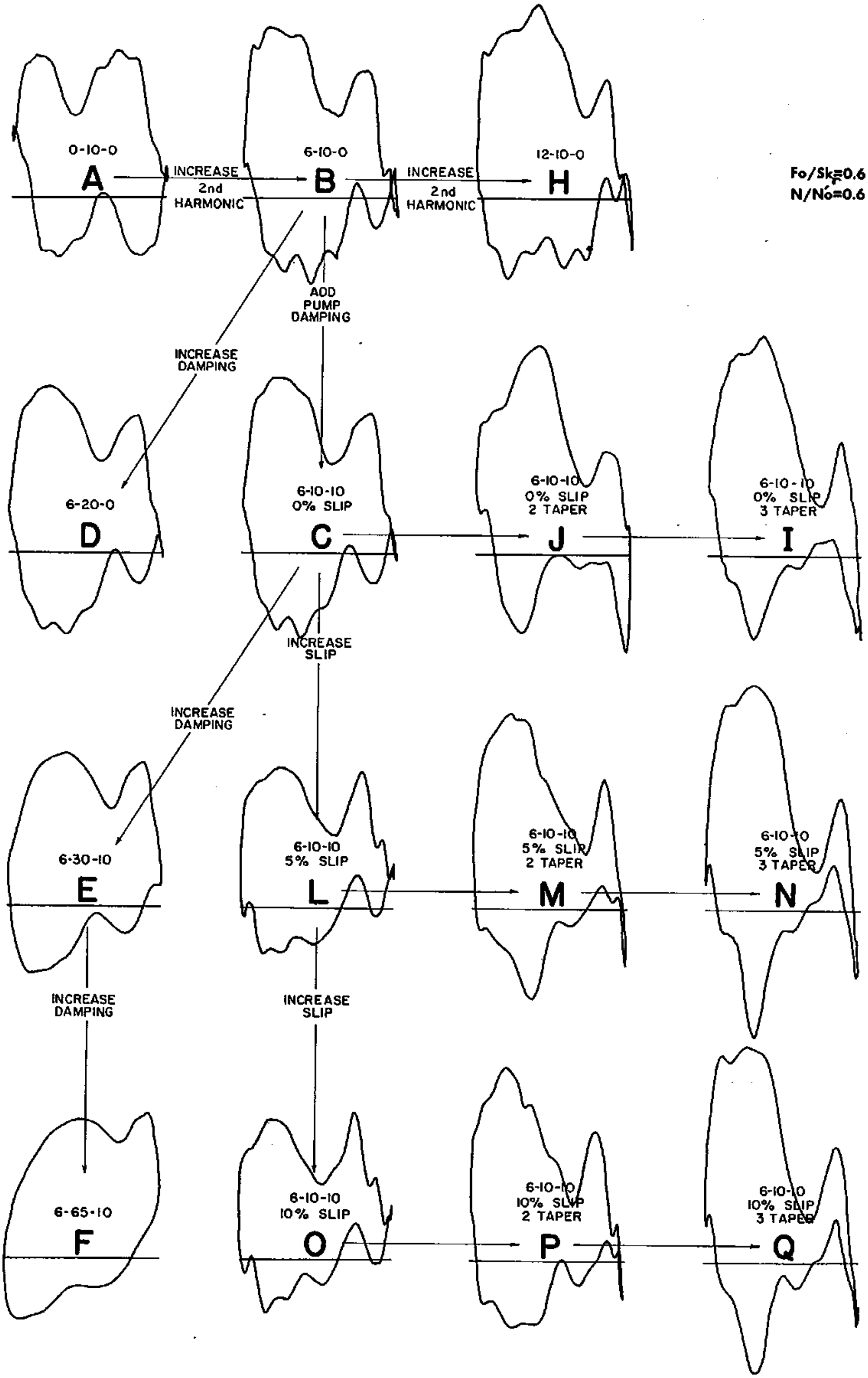
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INCREASE DAMPING
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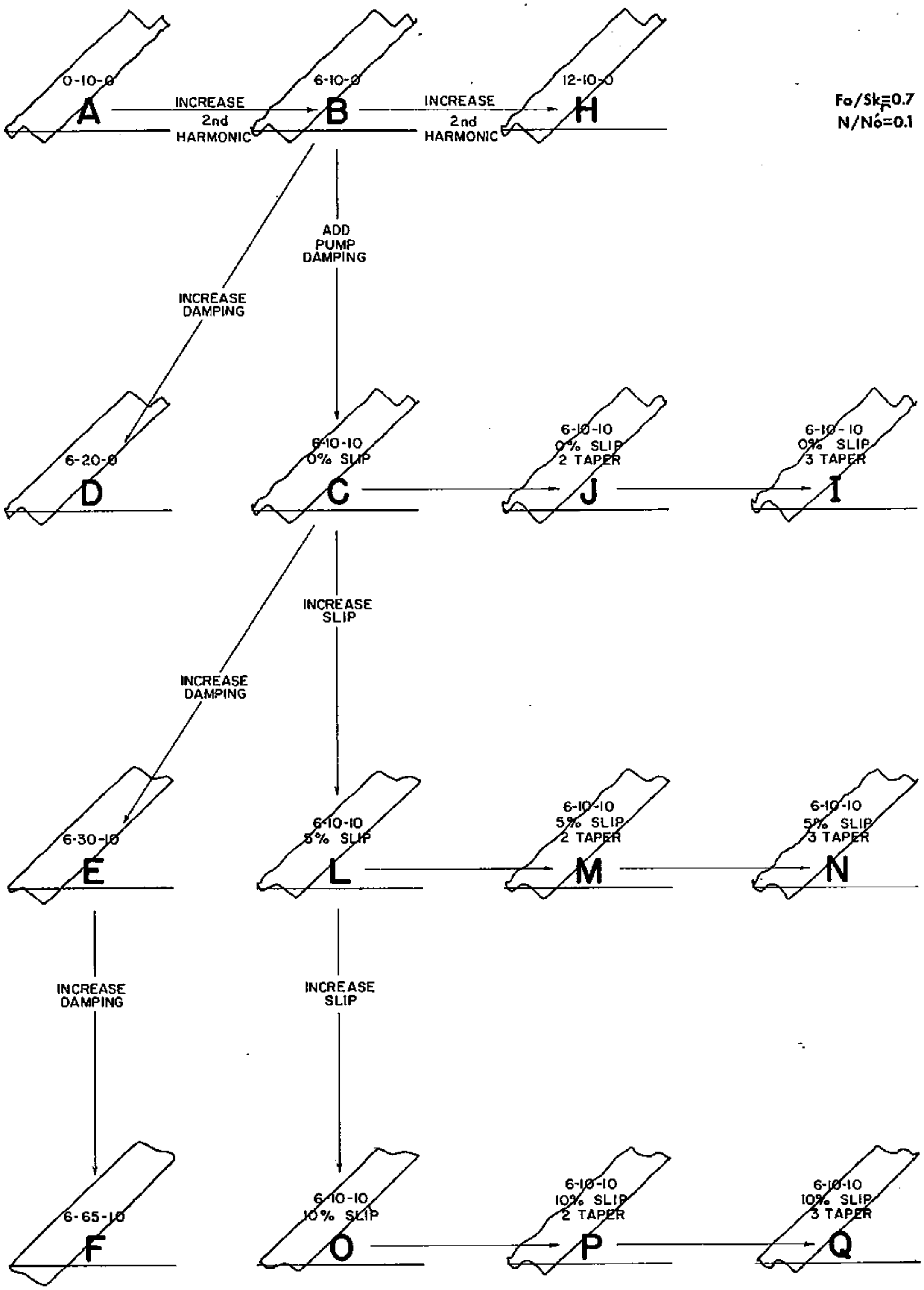
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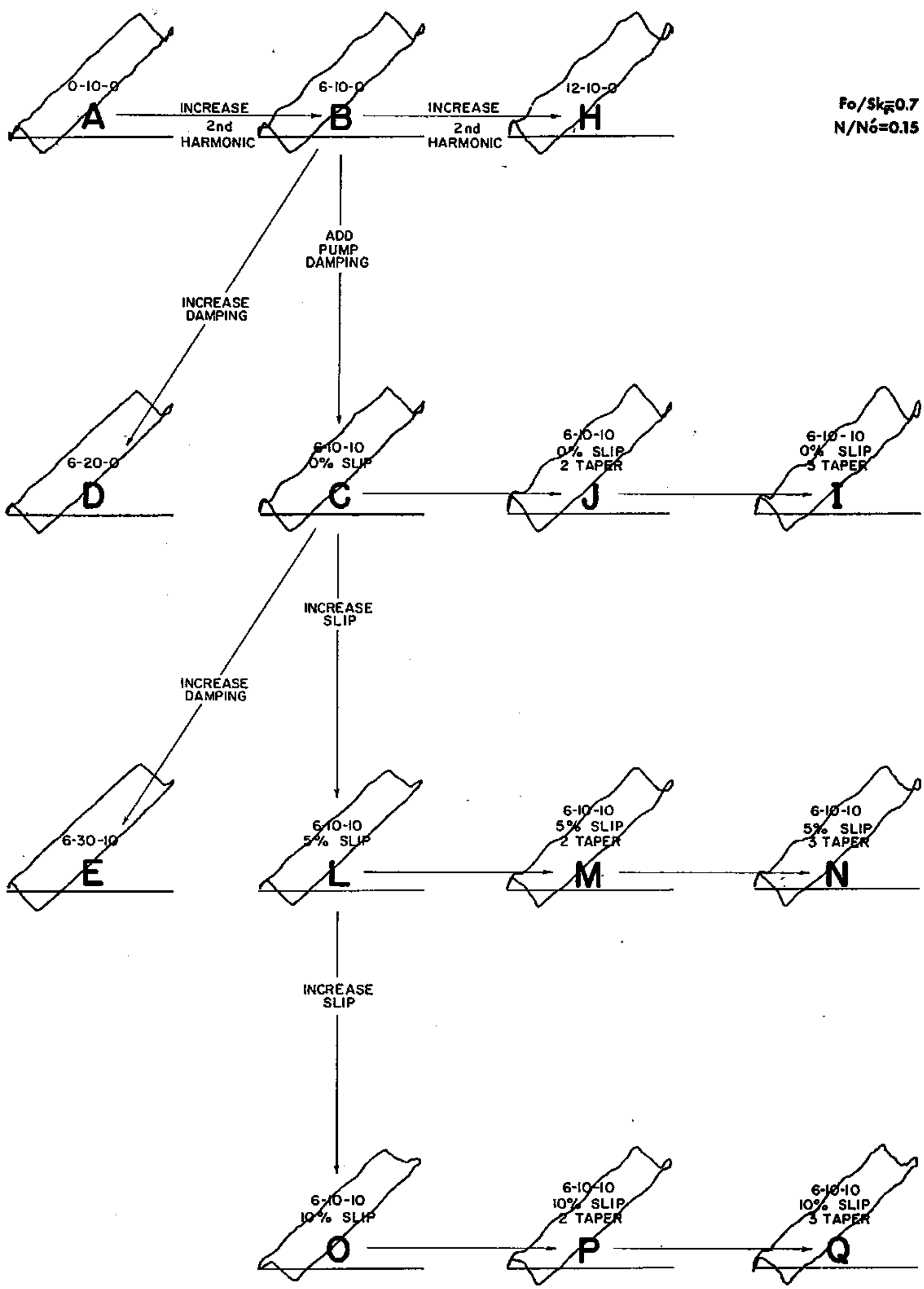
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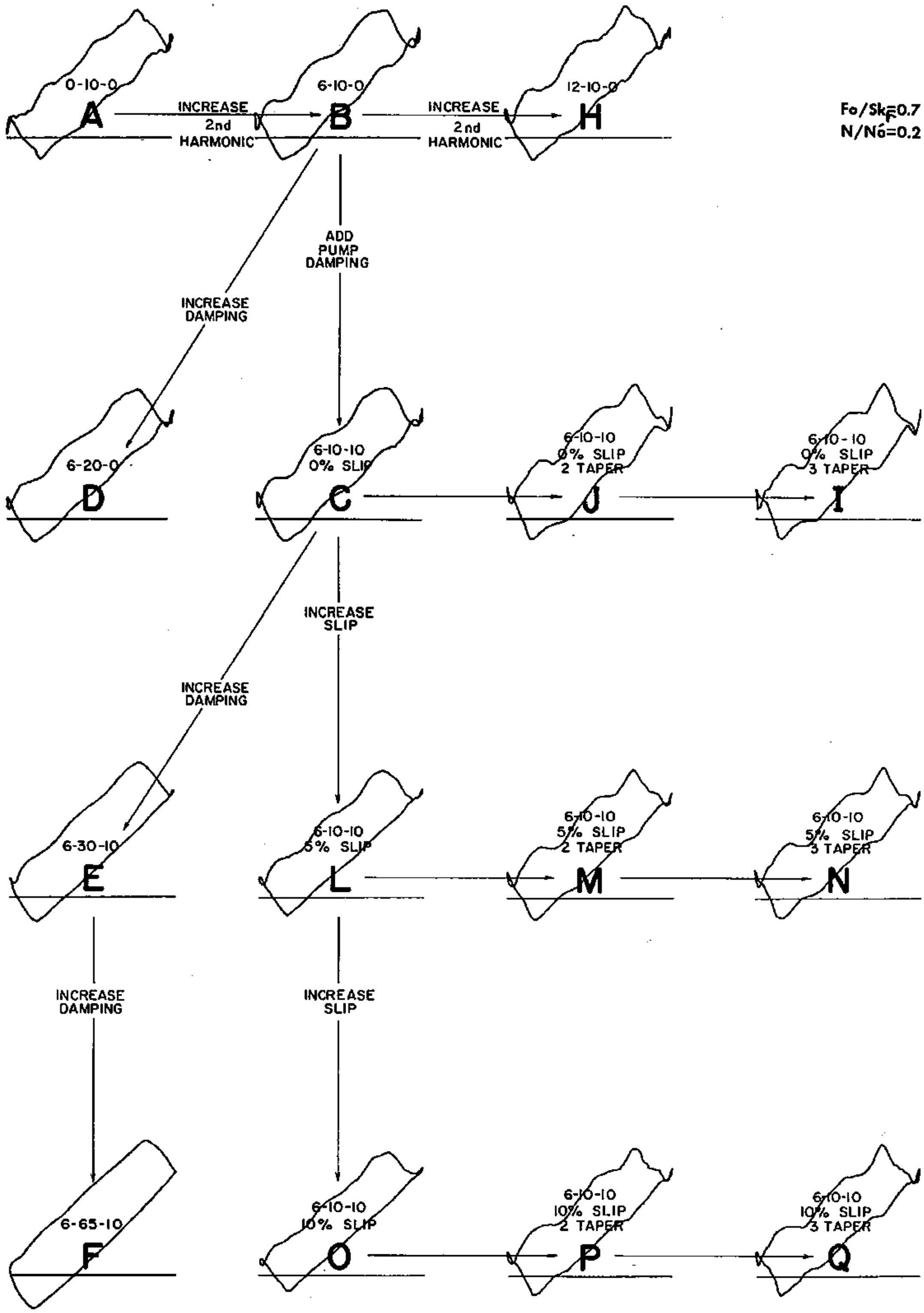
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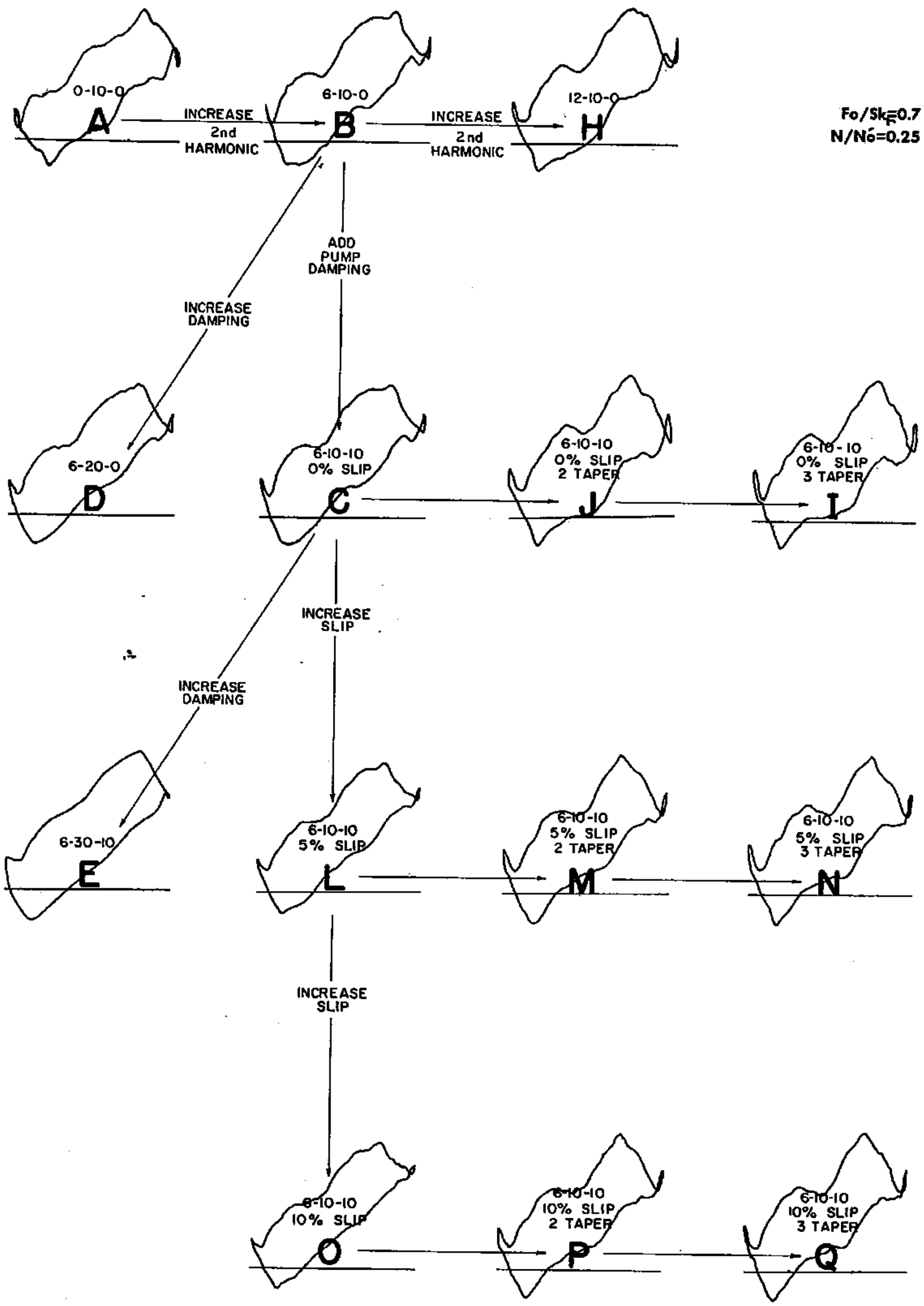

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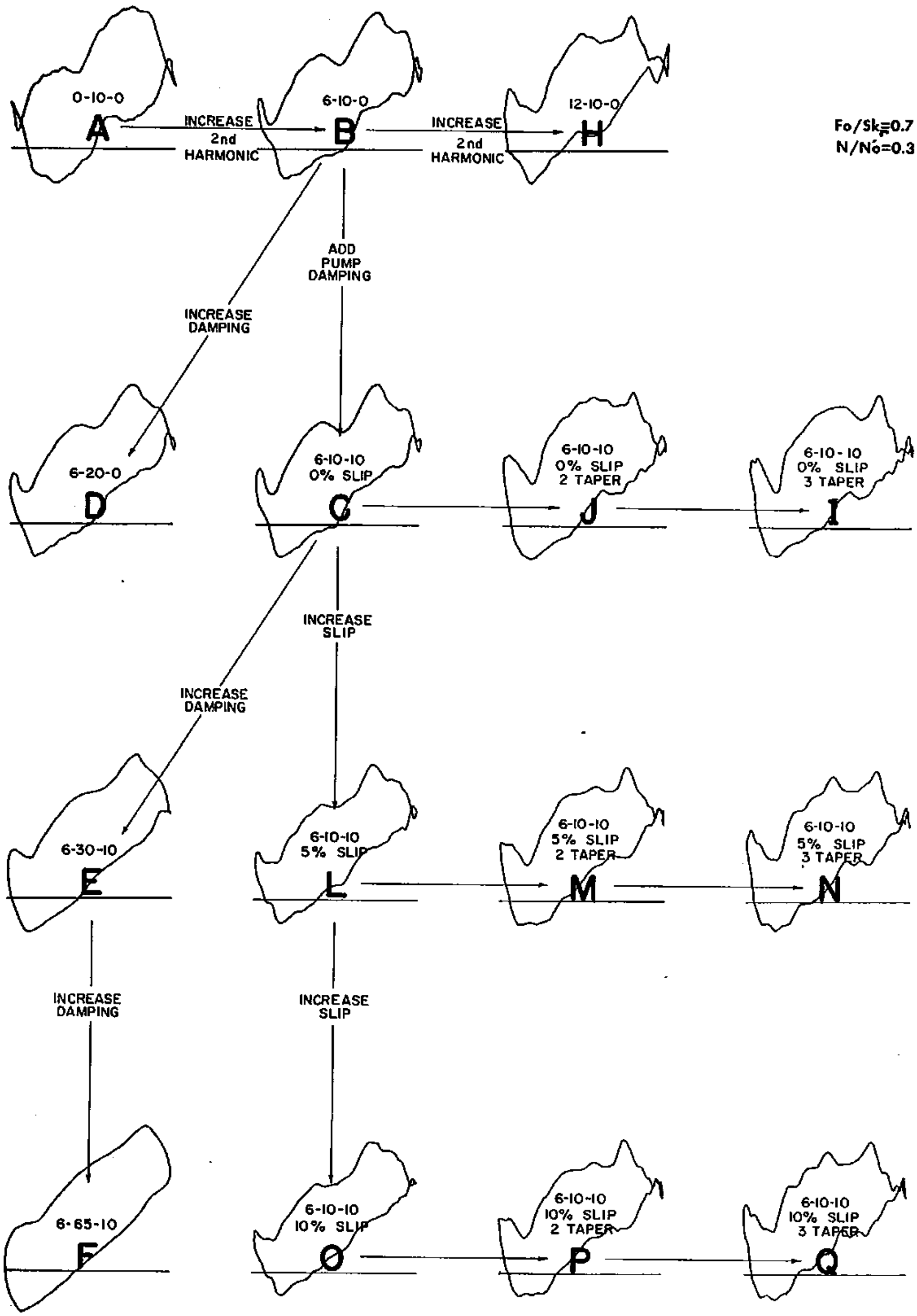

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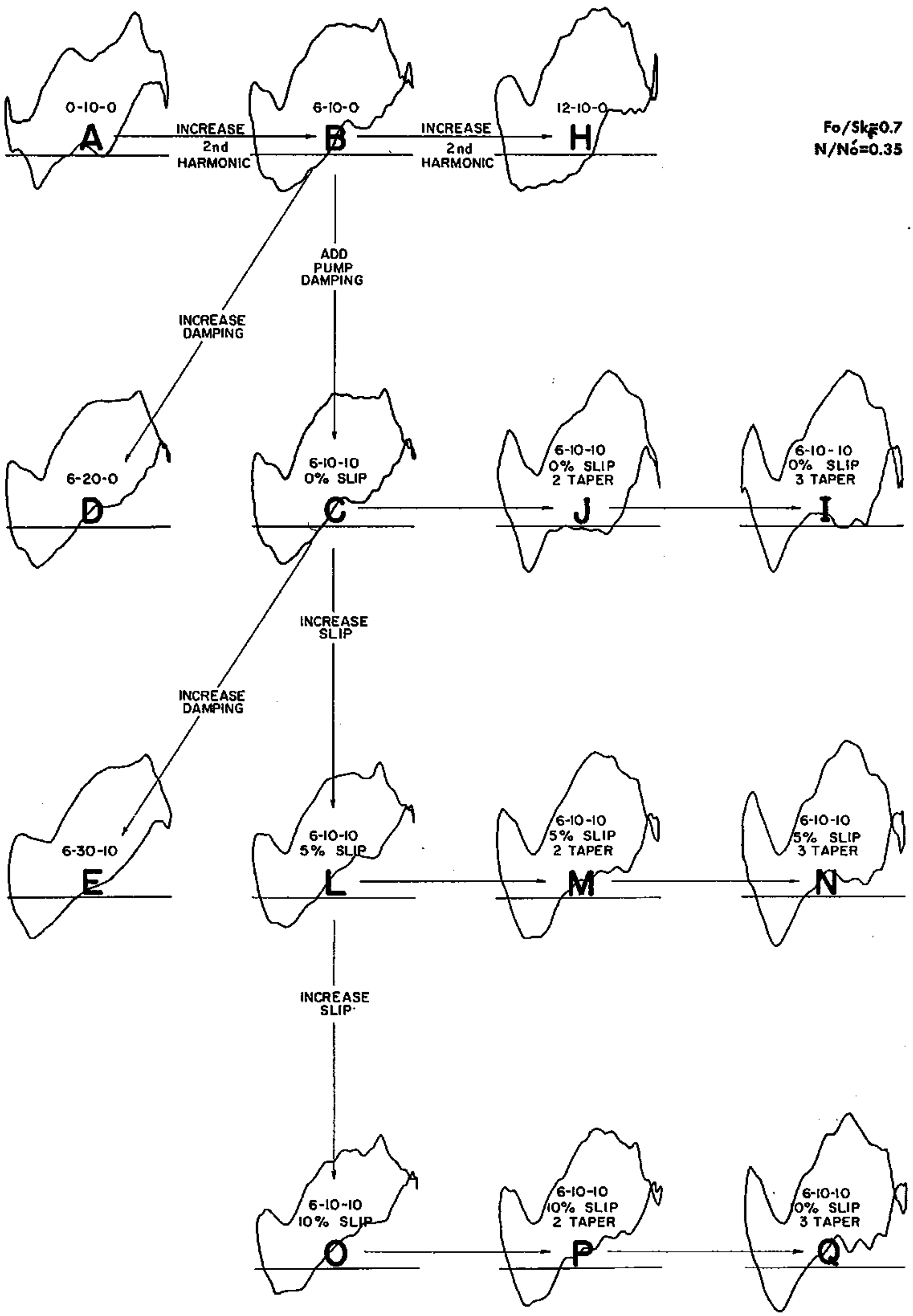
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C
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2 TAPER
J
6-10-10
0% SLIP
3 TAPER
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SLIP
INCREASE
DAMPING
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E
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L
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5% SLIP
2 TAPER
M
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3 TAPER
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INCREASE
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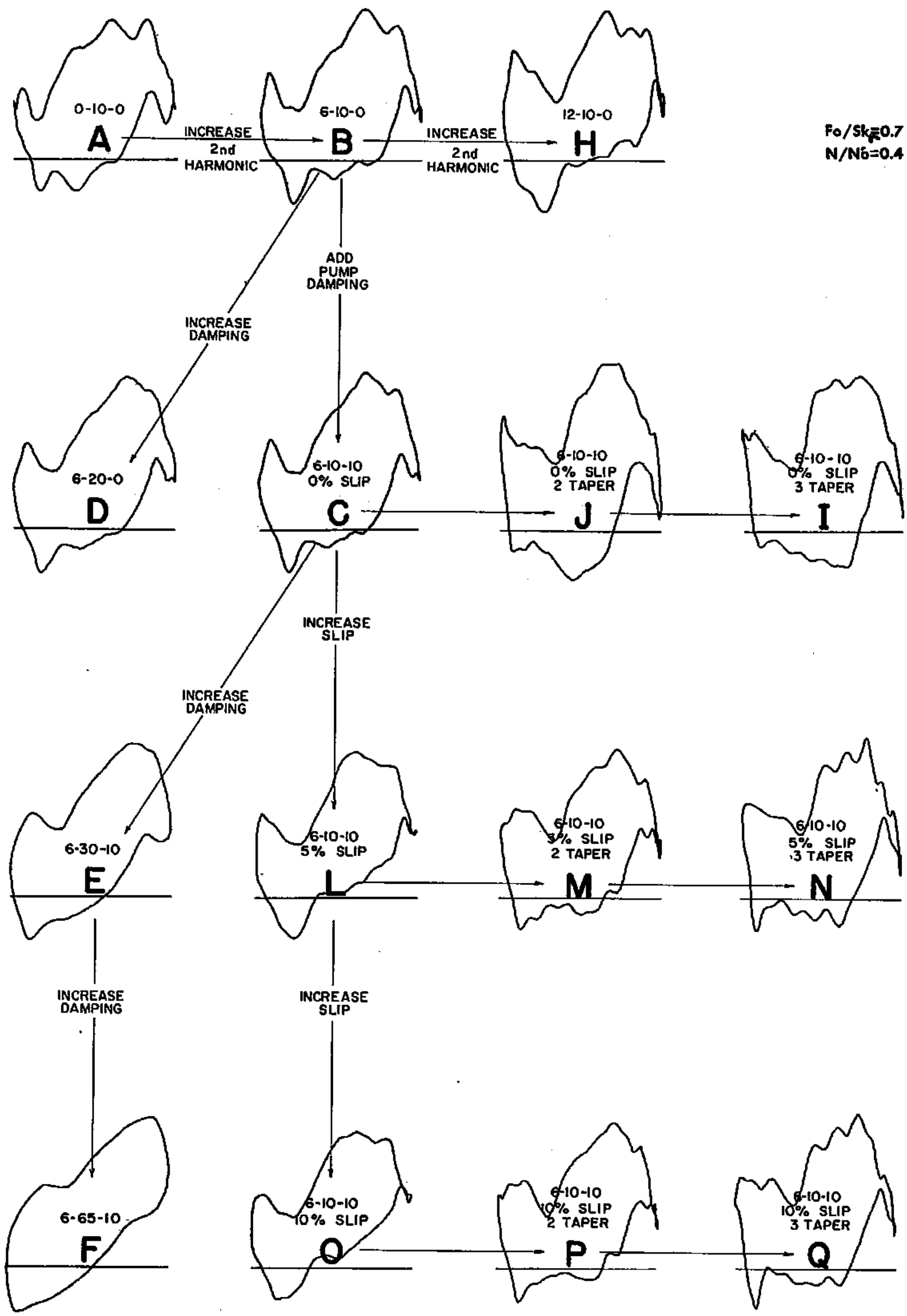
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C
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L
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DAMPING
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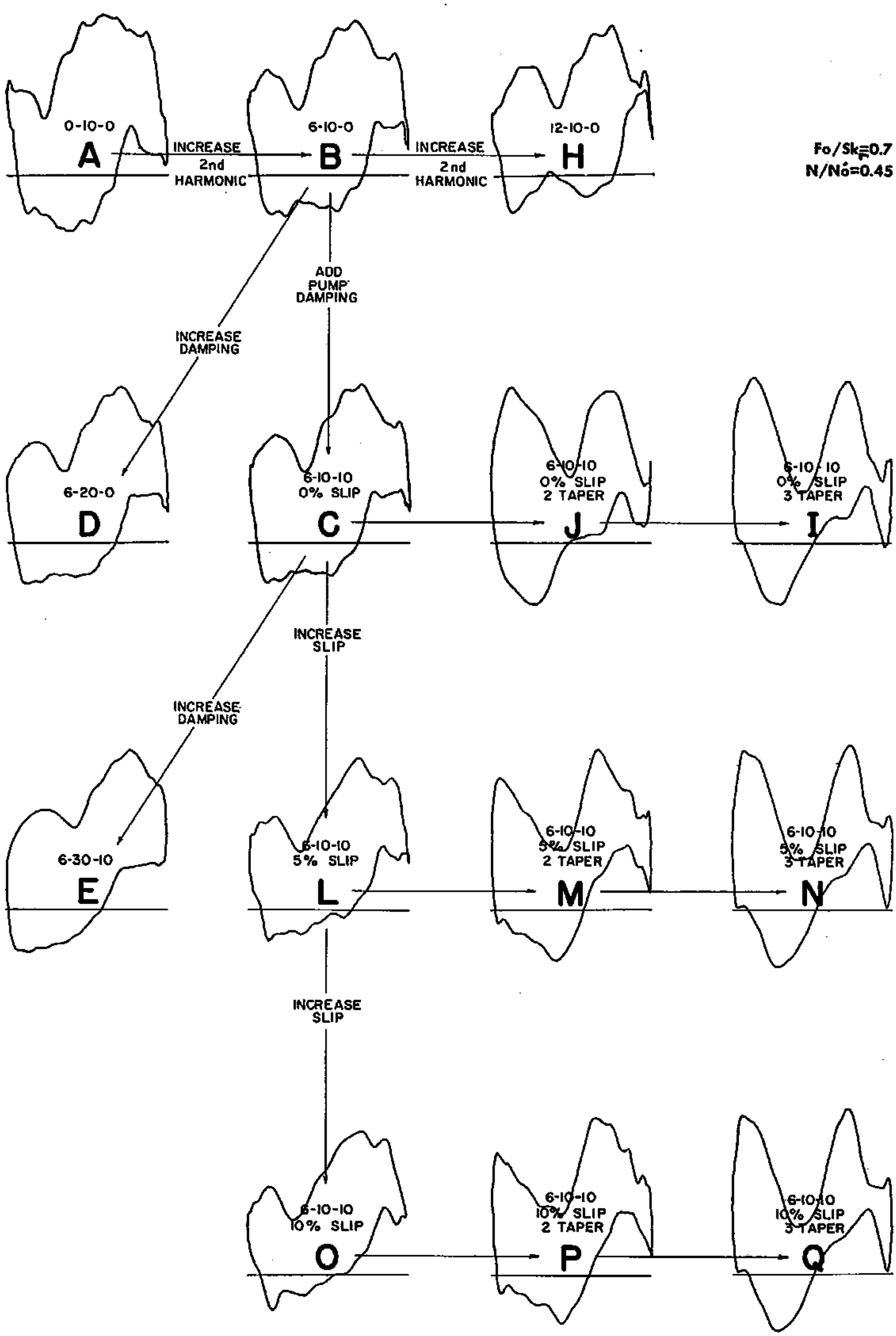
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2 TAPER
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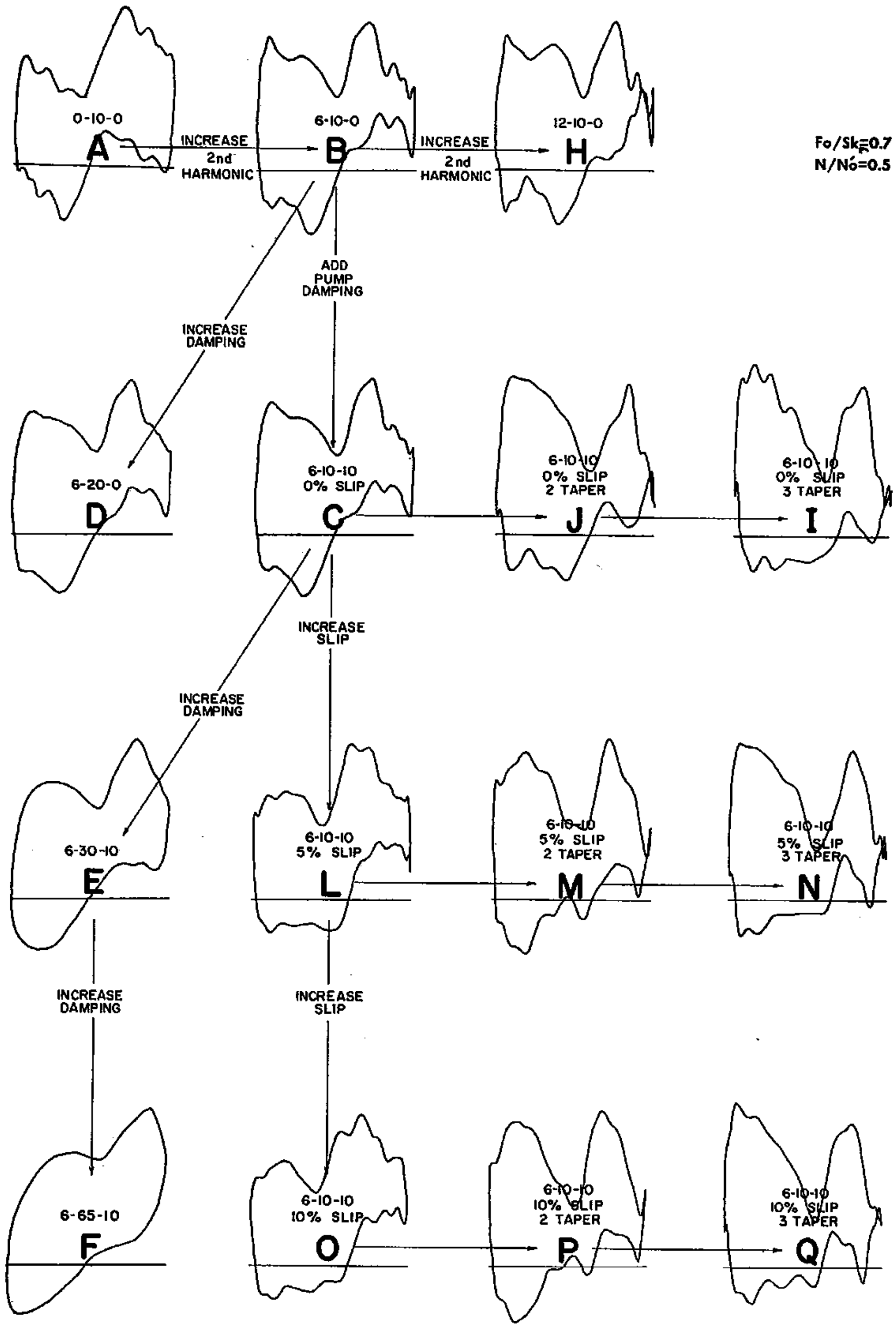
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N/No=0.5
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D
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C
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2 TAPER
J
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3 TAPER
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SLIP
INCREASE
DAMPING
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E
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5% SLIP
L
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5% SLIP
2 TAPER
M
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3 TAPER
N
INCREASE
DAMPING
INCREASE
SLIP
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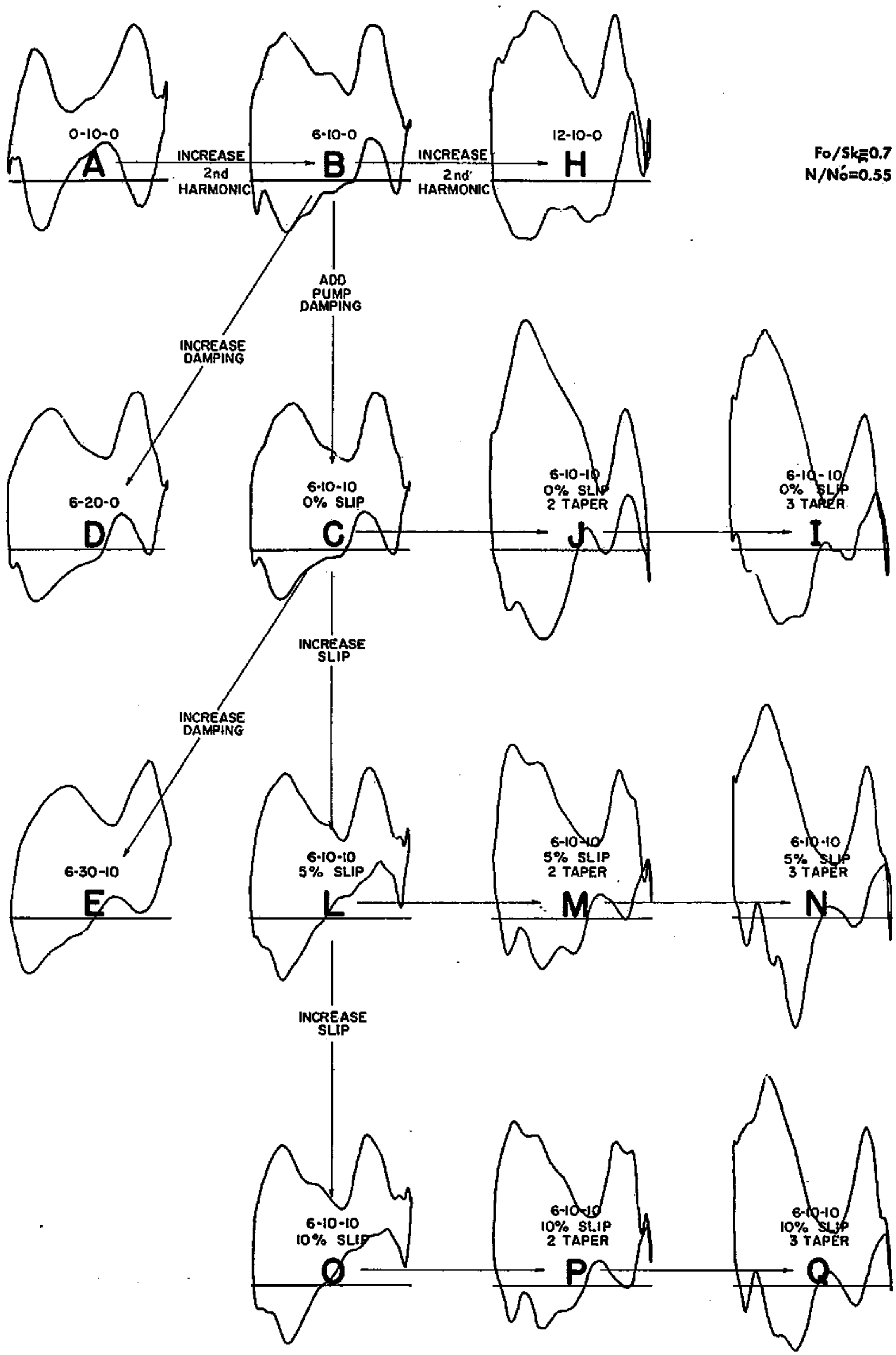
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N/No=0.55
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INCREASE
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D
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C
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0% SLIP
2 TAPER
J
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0% SLIP
3 TAPER
I
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SLIP
INCREASE
DAMPING
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E
6-10-10
5% SLIP
L
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5% SLIP
2 TAPER
M
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3 TAPER
N
INCREASE
SLIP
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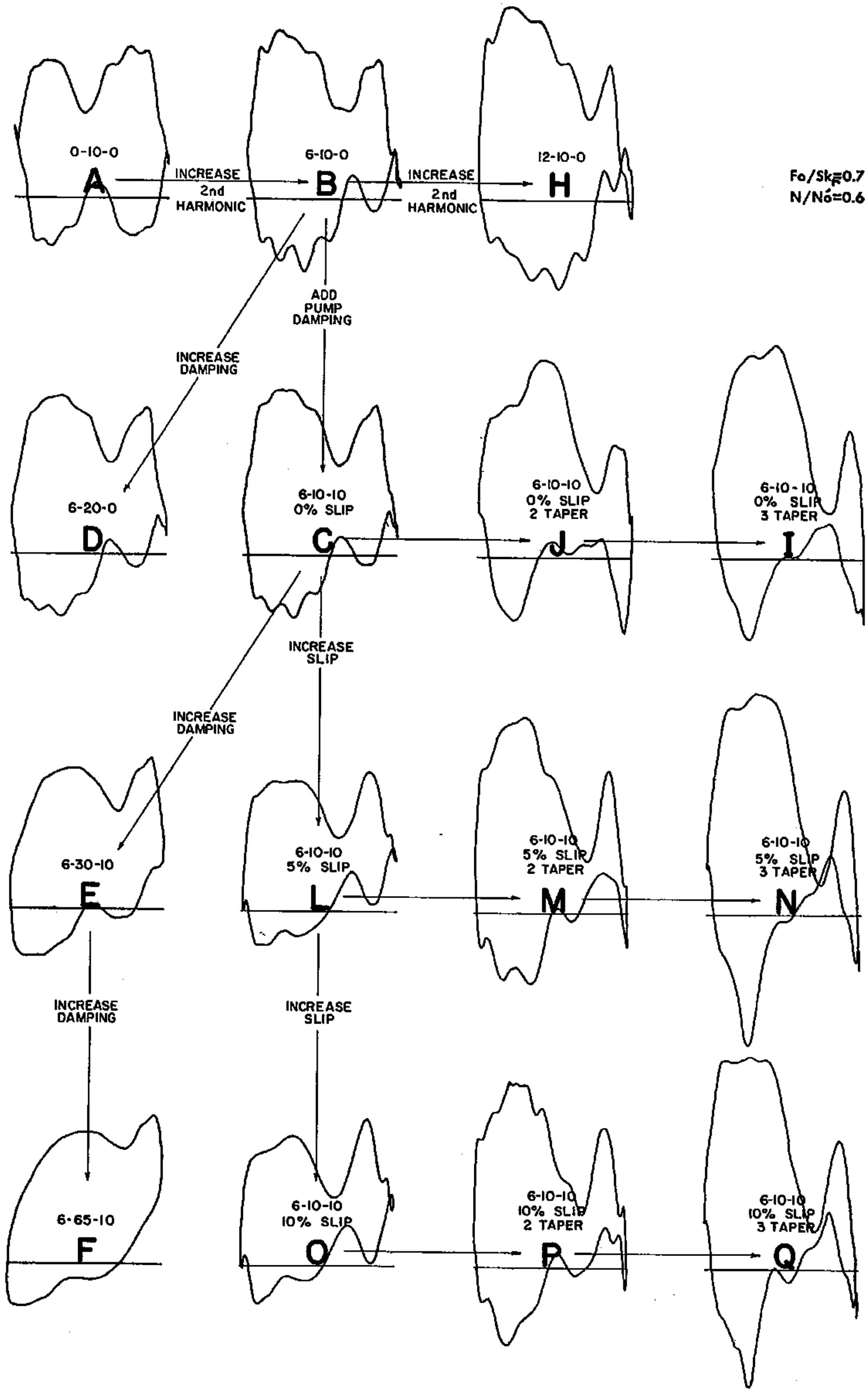
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N/No=0.6
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SLIP
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DAMPING
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E
6-10-10
5% SLIP
L
6-10-10
5% SLIP
2 TAPER
M
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5% SLIP
3 TAPER
N
INCREASE
DAMPING
INCREASE
SLIP
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F
6-10-10
10% SLIP
O
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2 TAPER
P
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3 TAPER
Q