TECHNICAL NOTE

AN AUTOMATED VARIABLE-FORCE OPERANDUM¹

Several electromechanical systems have been suggested to control automatically the force required for lever depression. In these designs, the specified force requirement can vary during bar excursion due to the breaking of a magnetic contact (Lehigh Valley Electronics lever 1604) or the changing of electrical fields (Petre, Albright, and Galloway, 1967). The automated variable-force operandum described here insures that a predetermined force requirement is reliably maintained over the range of bar travel.

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Force requirements are manipulated by magnetically anchoring solenoids to predetermined points on the arm of a lever for the duration of an increased force period. The work for any bar depression is determined by the combination of solenoids activated and the distance of bar travel. With four appropriately weighted independent solenoids, 16 different force requirements for bar depression can be scheduled.

The outer edge of the bar, to the extreme left in Fig. 1, is four times the distance from the fulcrum than the closest solenoid, and all solenoids are equidistant from each other. Referring to the solenoids as W_1 , W_2 , W_3 , W_4 , left to right, the force necessary to depress the bar is defined for an ideal lever as $\frac{1}{4}W_1 + \frac{1}{2}W_2 + \frac{3}{4}W_3 + W_4 + C$, C being equal to the force, in grams, necessary for depression without the weights attached. (The equation for linear motion is employed for simplicity, since the lever's circular travel is slight). Since each weight is an unmounted solenoid coil whose armature is permanently pivoted to the lever arm, a sole-

Fig. 1. The variable-force operandum. The outer edge of the bar is $4\frac{1}{2}$ in. to the left of the fulcrum while the solenoids, which are equidistant from each other, are $1\frac{1}{8}$ in. between centers.

noid coil is lifted, thereby increasing bar-depression force, only if it is energized.

On the system shown in Fig. 1, the lever arm and solenoid seats are brass, the frame aluminum, and the bar stainless steel. Alignment of the solenoids is maintained during travel by a nylon pin that rides freely within a guide-hole drilled in the solenoid seat on the same axis as the armature. (See Fig. 2A, B, and C.) To change solenoids, the seats are lowered within vertical slots along the back wall (not shown). The lever arm is pivoted on a roller bearing to insure smooth operation and a minimum of lateral displacement. The limits of bar travel are determined by adjustable set screws just in front of the roller bearing. The counterweight, between the set screws and the bar, partly offsets the imbalance due to the weight of the solenoid armatures pivoted on the right side of the lever. Aluminum shields between the solenoids reduce mutual attraction during electrical activation.

The adjustable set screws also serve as the contacts for a double latching relay. This configuration demands complete bar depression to signal a response and full release to reset the relay. It does not count partial responses. The lever must remain in its depressed or resting positions 20 to 25 msec in order to set or reset this relay. This time could be reduced with solid-state circuitry. With the solenoids unactivated and the lever

counterweighted to require 12 g for depression, the time required for the depressed lever to recover to its resting position is 100, 175, and 200 msec for bar travel adjusted to $\frac{1}{32}$, $\frac{1}{8}$, and $\frac{3}{16}$ in. respectively. Activated solenoids reduce the recovery time.

A multiple OR gate schedules the 16 possible combinations of solenoid activations. This permits rapid and simple scheduling from a stepping switch without backpath eliminators. A schematic diagram of the diode matrix and the four solenoids (Guardian 22DC 144C.24) is presented in Fig. 3. All diodes are 1N2070 or equivalent. The diode suppression across each solenoid is not necessary for the solenoid to operate, but with solid-state equipment coming into more frequent use, elimination of all possible transients is advisable. The diode in series with the +24-v feed protects against polarity reversal that might otherwise damage many of the diodes in the matrix and on the solenoids.

The operating characteristics and reliability of the operandum were tested by measuring (a) the bar weighting necessary to record a response, and (b) the variability of force requirement over the $\frac{3}{16}$ in. of bar travel. In test (a), weights were placed on the bar, in 1-g increments when the critical region was approached, until a response was recorded. The 16 combinations of solenoid activations were tested in random order in each of five test replications. In test (b), the

Fig. 2. Solenoid seats, and solenoids with nylon alignment pins. (A) A brass solenoid seat with alignment hole exposed. (B) Solenoid resting in the solenoid seat with alignment pin exposed through alignment hole. (This solenoid was machined to weigh 40 g). (C) A solenoid with nylon alignment pin over, and on the axis of, the hole for alignment of the solenoid seat. (This solenoid was prepared to weigh 20 g). (D) A solenoid with brass weights attached to increase weight to 160 g.

lever was slowly depressed with a Scherr-Tumico precision-dynamometer and force variations recorded.

Table 1 shows the weight required to depress the bar under all conditions of test (a). Reliability between replications is high, and the force required for depression is only slightly greater than that indicated by the formula for an ideal lever. Variability of the force requirement over the arc of lever travel during test (b) was not

appreciably greater (± 1 g) than the variability among replications in Table 1. A slight increase in friction when adjacent solenoids were weakly attracted to each

Table 1

Weight (g) required to depress lever when indicated solenoids are activated.

Solenoids Activated	Test Replications					Ideal Lever
	1	2	3	4	5	
None	12	12	12	12	12	
1 (20 g- W_1)	18	18	18	18	18	17
2 (20 g- W_2)	23	23	23	22	22	22
3 (26.6 g- W_3)	34	33	33	34	34	32
4 (40 g- W_4)	55	54	55	54	55	52
1-2	29	28	28	28	28	27
1-3	42	42	41	41	42	37
1-4	61	61	60	60	61	57
2-3	44	44	44	43	44	42
2-4	65	65	65	65	65	62
3-4	77	76	75	76	76	72
1-2-3	50	49	49	50	49	47
1-2-4	70	70	70	69	70	67
1-3-4	84	84	84	84	83	77
2-3-4	86	86	85	85	86	82
1-2-3-4	91	90	92	90	90	87

Fig. 3. A schematic diagram of the diode matrix used to schedule the various combinations of solenoid activations. For clarity the matrix is shown in its simplest form; however, fewer diodes could be employed in more efficient configurations.

other is mainly responsible for the small difference between ideal and actual force requirements as well as the slight variability during depression. In order to maintain this high-quality performance, contacting surfaces must be kept clean and grease free.

Relatively light solenoids and small force differences were employed in these tests to demonstrate the sensitivity of the instrument. A different range of force requirements could be scheduled by using heavier solenoids (Fig. 2D shows a solenoid prepared to weigh 160 g). Therefore this operandum can be used to schedule automatically a wide range of force requirements for bar depression where it is important that the scheduled force be maintained over the extent of lever travel.

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REFERENCE

Petre, R., Albright, J., and Galloway, C. A remote-controlled force operandum. *Journal of the Experimental Analysis of Behavior*, 1967, 10, 149-150.