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Timing diagrams and their use in mechanism design

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The Mechanisms Committee, which first met in 1975, is continuing the work that previously was the responsibility of the former Gearing and Mechanisms Committee, which first met in November 1964. Like the earlier Committee it has the cooperation of many engineers and scientists in industry, research establishments and universities from whom much assistance and information is being received.

TIMING DIAGRAMS AND THEIR USE IN MECHANISM DESIGN

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TIMING DIAGRAMS AND THEIR USE IN MECHANISM DESIGN

1. NOTATION AND UNITS

The units used in this Item are predominately SI.

b_1, b_2	general displacements (see Sketch 4.1)	m
g	acceleration due to gravity	m/s ²
H	follower lift of cam corresponding to one motion segment	m
T	time for complete movement	s
t	time from datum	s
t_1, t_2, t_3, t_4	time from datum defining start or finish of an action (see Sketch 4.1)	s
u_p	normalised angle of cam rotation from TDC to die opening	-
w	normalised follower displacement	-
w'	non-dimensional follower velocity	-
w''	non-dimensional follower acceleration	-
Y	maximum linear displacement of clamp (Example 1)	m
y	displacement from datum at time t	m
$\dot{y}$	velocity at time t	m/s
$\ddot{y}$	linear acceleration at time t	m/s ²
$\theta_1, \theta_2, \theta_3$	angle of drive shaft rotation equivalent to components of operating time of Code Selector Magnets (see Sketch 6.13)	degree
θ_e	angle of drive shaft rotation equivalent to energising time of Code Selector Magnets (see Sketch 6.13)	degree
Φ	total angle of cam rotation corresponding to one motion segment	degree
ϕ_p	angle of cam rotation from TDC to die opening	degree
ω	angular velocity	rad/s

Subscripts

min, max relates to minimum and maximum, respectively

2. INTRODUCTION

The contemporary need to design new machinery of increasing complexity to achieve optimum performance with minimal development of a prototype has stimulated the preparation of various procedures to aid the design process. Of these, timing diagrams, even in outline form, can provide a valuable aid by assisting the designer to appreciate the operation of a concept, to identify critical details and to test its feasibility by, for example, ensuring the synchronisation of operating members and adequate time for actuators to operate. The final version of the timing diagram, defining the operation of the production version of the machine, provides a concise definition of operation with vital data for detail design, assembly, testing, maintenance and trouble-shooting.

This Item describes a means of constructing timing diagrams, beginning from the incomplete information to be anticipated when the design is begun. The basic construction procedure is explained in Section 4 and illustrated by examples in Section 6.

At the conceptual stage of machine design, timing diagrams provide a methodical means of determining the operating requirements to be met and the constraints imposed by the principal functions and assist in the recognition of crucial problems. These diagrams enable the merits of alternative solutions to be compared by identifying from the order-of-magnitude values estimated at this stage in the process such factors as high accelerations (and hence large forces or torques) either subjectively or in conjunction with such computer programs as Osmec (Items 97023^[11] and 97026^[12]) and Oscan (Items 00013^[13] and 00014^[14]). Synchronisation problems and wasted cycle time are also highlighted to assist further the identification of the preferred solution. As the design progresses, successive diagrams may be expected to contain increasing detail, such that it may be helpful to construct specific extracts to scale. Thus the preliminary timing diagram of Example 2 (Section 6.2) is supplemented by an enlargement to test the significance of a tolerance.

A timing diagram can consist of a sequence of simple graphs to show separately the displacement on a common time base of critical components, such as the end effector* of every operating assembly and actuator comprising the unit or machine.

It can be easiest to begin by constructing the diagram for normal operation of the machine. Frequently it is clearest to include at least two successive working cycles so that every action is shown once from start to finish. Even more consecutive cycles may be needed when it is necessary to define alternative modes of operation, such as inhibiting an output upon demand whilst the machine continues to operate. Likewise, the complete sequence of events during start-up and shut-down is liable to involve several cycles; the last is unlikely to be needed until a later stage in the design process.

When a machine operates at a nominally 'constant' speed it is recommended that the time base be duplicated with another defining the rotation of a principal shaft, to provide data for both detail design and machine assembly.

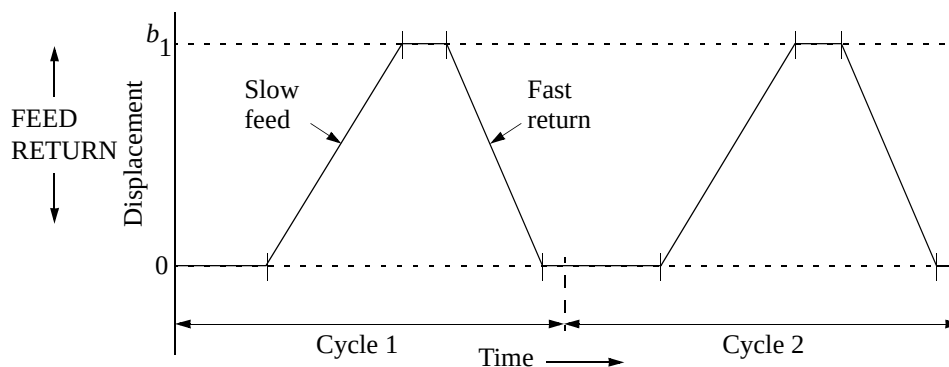
A different type of timing diagram, known as a 'flow diagram', can be used to illustrate the progress of successive workpieces through a machine. For example, a flow diagram provides a means of determining the timing of sensors for monitoring the presence or absence of workpieces progressing through a machine. In combination with a timing diagram, the flow diagram can be used to establish the logic for progressively overriding these checks through successive cycles during start-up.

* A general term for the output drive member of any mechanism or actuator.

3. THE USE OF TIMING DIAGRAMS

A timing diagram is a sequence of simple graphs drawn to a common time base which is used to work out and define the operation of an assembly of mechanisms and, possibly, electro-mechanical devices or hydraulically or pneumatically actuated devices forming a unit or a complete machine.

The abscissa of the diagram defines the time base, the displacement of the end effector of every sub-assembly or actuator being defined separately on the ordinate, as illustrated in Sketch 3.1.



Sketch 3.1 Representation of a mechanical movement

Remembering that both linear and angular displacements of varying magnitude may be anticipated, it is frequently undesirable to specify a uniform scale: clarity is the vital criterion. In many cases, especially when a new design is begun, it is adequate to approximate the movements by straight lines: later, when synchronisation of actions and/or precision points become critical, it may be necessary to draw movements accurately to scale, as shown in Sketch 6.13. In addition, it can be helpful to add the times or reference angles for the start and finish of movements, for precision points, for energising an actuator, and so on, on the diagram for that component.

The objects of constructing Timing Diagrams include:

- (a) assisting in an understanding of the operation of proposed solutions at the conceptual stage of the design process,
- (b) determining unknown timings from interaction with other components, whilst aiming to minimise acceleration forces but providing dimensional and/or timing clearances to accommodate manufacturing and assembly tolerances and to provide settling time between co-ordinated movements,
- (c) minimising the percentage rating* of electro-mechanical devices,
- (d) ensuring that associated movements are correctly synchronised,
- (e) identifying high accelerations,

* The ratio of the time that the coil is energised to the cycle time, averaged over a sensible number of successive cycles and expressed as a percentage.

- (f) assessing the efficiency of a proposal by identifying any inactive periods within a cycle,
 - (g) assisting in the comparison of alternative solutions,
 - (h) providing data for detail design,
 - (i) determining, possibly on a flow diagram, the times when the progress of the product can be monitored as it moves through the machine
- and
- (j) recording and communicating the operation of the production machine, providing data for assembly, inspection, testing and maintenance.

4. CONSTRUCTION OF TIMING DIAGRAMS

The diagram defines the operation with time of every component or mechanism of a machine to a common base of time and/or angle of rotation of a specified member, using a separate line to record the displacement with respect to time of the end effector of each device. It is recommended that changes, such as the start of a mechanical movement or the breaking of an electrical current, be defined clearly by marking boundary positions on every line.

Typically, a timing diagram would consist of:

- (i) a common abscissa defining time and/or the angle of rotation of a principal shaft (more conveniently for mechanisms operating at a nominally 'constant' speed) through, at least, one complete working cycle of the machine,
 - (ii) an ordinate defining the displacement or action for every motion segment
- and
- (iii) the title or part number identifying that device.

It is important to appreciate that design decisions made at the preliminary stage need not be binding. Some may be arbitrary, and so subject to review, but are needed for the proposal to progress. This approach enables the preliminary timing diagram to be constructed, accepting that it may be incomplete and possibly inaccurate in some details. However, it provides the basis for assessing these decisions and acts as a means of determining unknown times.

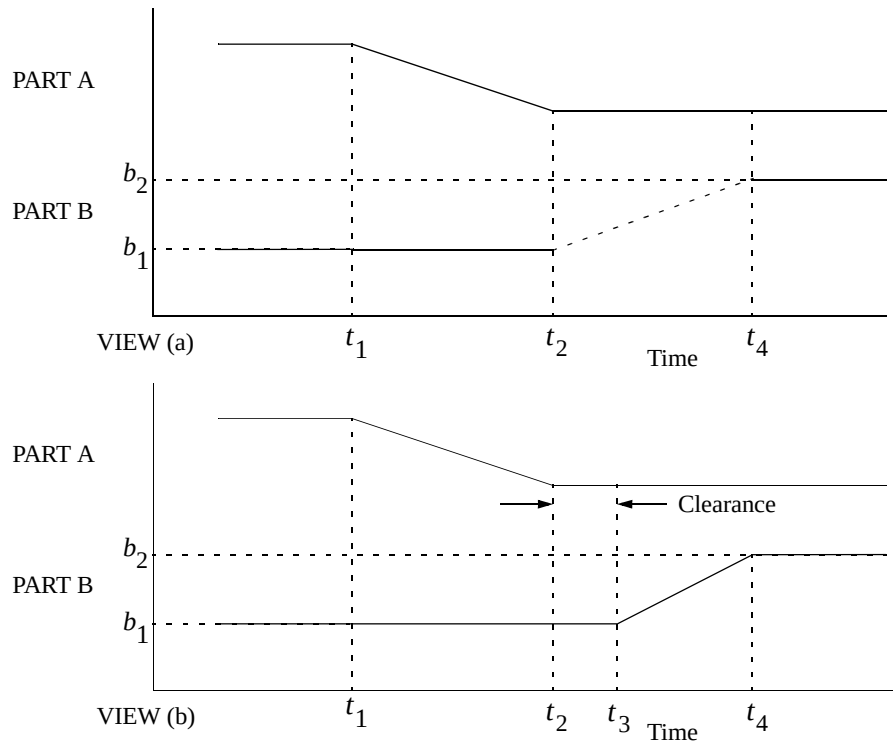
4.1 Mechanical Movements

Typically, mechanical movements are derived from cams or linkages driven from shafts running at cycle speed. Then the instantaneous location of the end effector is related to the angular rotation of that shaft. At the conceptual design stage it is generally adequate to represent mechanical movements by straight line diagrams, as shown for a single end effector in Sketch 3.1. The displacement of each end effector with respect to time is represented by a continuous line, the slope of inclined portions defining the direction of travel. Dwells are indicated by horizontal lines. As a general rule, it is advised that displacements should not be drawn to scale (note that both linear and angular movements of varying magnitude need to be shown on the same diagram). The vertical bars define the limits of motion segments and it can be helpful to add the corresponding time or angle. A subjective comparison of the velocities, and hence the peak accelerations, during the feed and return actions can be deduced from the relative slopes of the inclined portions*.

In practice it is improbable that all the times needed to construct every line completely will be known when the diagram for a new design is begun. In such cases construction should be confined to those segments which correspond to the known data, beginning with the principal mechanism, leaving breaks elsewhere, and then the process repeated for associated mechanisms in a methodical sequence. In this way unknown data, possibly defined between limits but not as specific values, can be found from the need to synchronise successive operations or by allowing the maximum available time for a movement to minimise accelerations.

* Reference to the non-dimensional data in Item 82006^[8] or the OSCAM cam mechanism design program, Items 00013^[13] and 00014^[14], enables an order-of-magnitude estimate of the peak accelerations of a cam follower to be made. Investigation of the motion of a linkage may be carried out with the use of the OSMEC mechanism design program, Items 97023^[11] and 97026^[12].

The basic approach to this difficulty is illustrated in Sketch 4.1 which shows one portion of a timing diagram over part of a working cycle in which Part A and Part B are assumed to have interdependent functional operation. In View (a), the line associated with Part A represents the established motion of the end effector of Part A from the outer dwell position at time t_1 to inner dwell at time t_2 . Once Part A has reached inner dwell the associated Part B must complete the next action between positions b_1 and b_2 by time t_4 . Hence it follows that Part B must remain at b_1 until time t_2 .



Sketch 4.1 Portion of a timing diagram showing the allowance of clearance between synchronised mechanical movements to determine timing

Starting immediately Part A comes to rest would allow the maximum time for the movement of Part B, but then there is no allowance for the consequences of accumulated dimensional tolerances or, especially critical in high-speed operation, for Part A to settle. It is noted that dimensional tolerance variation corresponds to a specific angular rotation of the reference shaft, regardless of rotational speed, whilst the allowance for Part A to settle is time-dependent. To accommodate both the tolerance variation and the settling time for Part A in the timing for Part B, a clearance is provided after time t_2 , as shown in View (b), so the dwell of Part B is continued until time t_3 despite the implication of higher velocity and increased acceleration.

Conversely, in some cases it may be possible to **gain** time by overlapping the finish and start of two gradual operations.

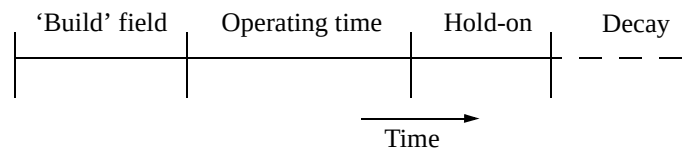
4.2 Electro-mechanical Actuators

A straight horizontal line defining only the time that the coil is energised may be used to define the operation of an electro-magnetic actuator, such as a solenoid, as shown in Sketch 4.2.

Especially when times are critical, it is desirable to show the components forming the whole, *i.e.* the energise time for the coil to 'build'* the electro-magnetic field, the operating time for the armature to close on to

* Commonly known as the 'rise' time. This term has not been used in this Item to avoid confusion with the 'rise' of a cam mechanism.

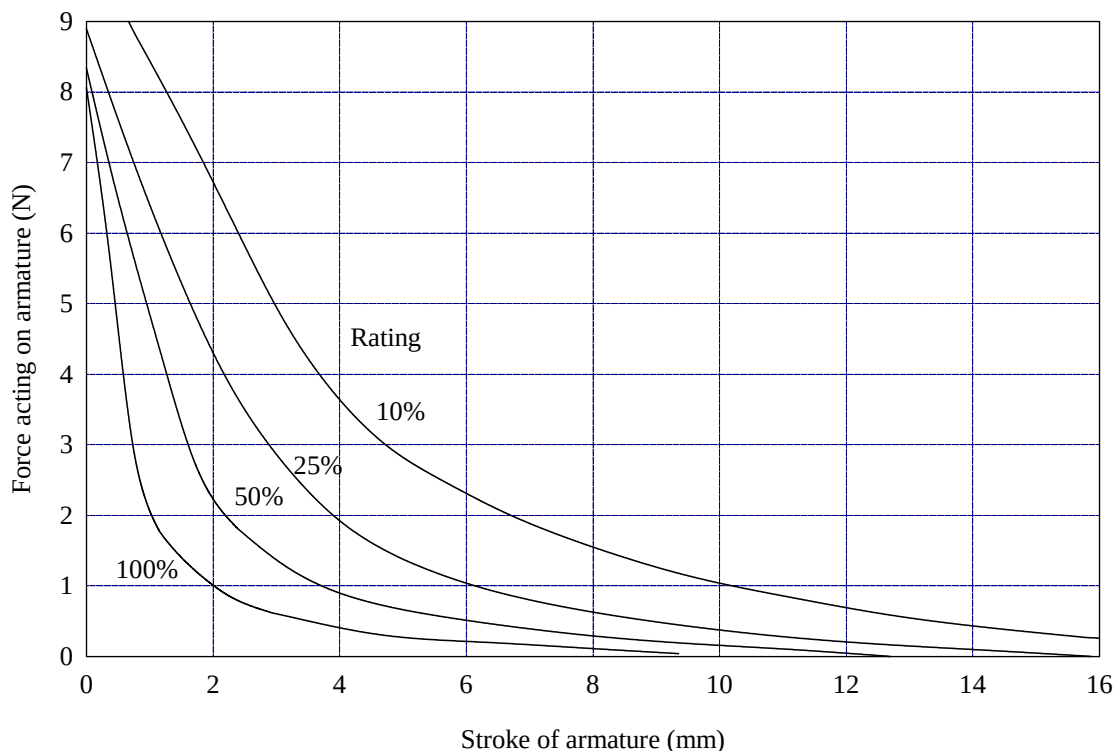
the pole face, any continuing hold-on time when the current may be reduced to minimise the heating effect and, finally, an allowance for the decay of the magnetic field^[2,3].



Sketch 4.2 Representation of an electrical function

When high operating speeds are involved, as in Example 3, the energise time to 'build' the electro-magnetic field of the coil can be a significant proportion of the operating cycle. Such cases provide a second category when it can be advantageous to overlap two operations deliberately. It can be safe to energise the coil by a significant percentage of the 'build' time before the preceding operation is completed and provide a sensible clearance between the completion of the preceding action and the beginning of the armature motion. It is essential to ensure that the duration of such an overlap is determined from the nominally constant, 'build' time of the coil: hence it applies to a specific maximum cycle speed of the machine*. This principle is illustrated in Example 2, Sketch 6.9.

The importance of this detail is illustrated by the example of the performance data for a small d.c. electro-magnet, shown in Sketch 4.3, which define the relationship between the armature stroke and the applied force at various percentage ratings of the coil. Applications of these principles are illustrated in the Examples of Section 6.



Sketch 4.3 Performance curves for a small d.c. electro-magnet at various ratings

* This technique implies precision tolerances on coil winding, the mass, size and location of the armature and the stroke of the armature. The relevant time data for varying armature strokes and percentage ratings are generally available from manufacturers. The timing diagram should also be used for minimising the percentage rating of the coil. Sketch 4.3 shows the significant increase in the force acting on the armature as the airgap diminishes. Once the armature has closed on the pole face it is desirable to reduce the current to the hold-on value compatible with the force required to minimise the heating of the coil.

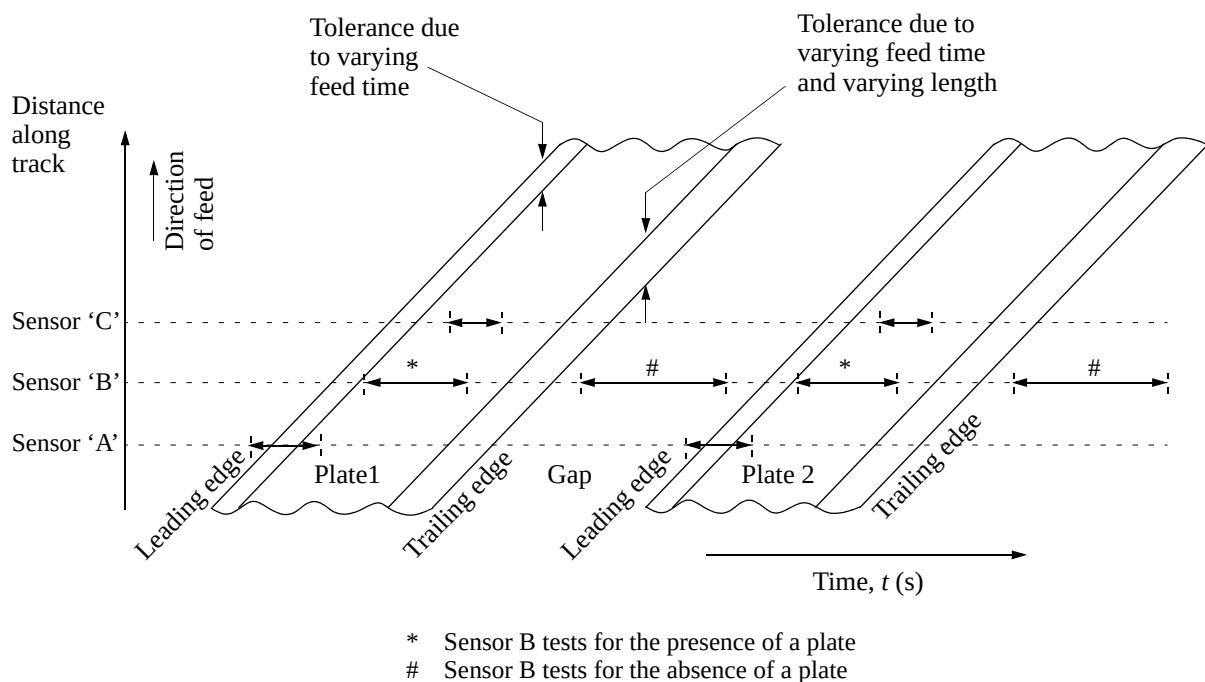
4.3 Pneumatic and Hydraulic Actuators

Pneumatic and hydraulic actuators can be represented on timing diagrams in a similar manner to that used for electro-mechanical actuators using bold or dashed lines to distinguish various types of actuator.

4.4 Flow Diagrams

A flow diagram illustrates the progress of a sequence of workpieces through a plant or machine for processing. As recommended for timing diagrams, the scale of the abscissa defines time and/or the angular rotation of an appropriate shaft but in this case of a flow diagram the principal ordinate, also to scale, defines the path of the products through the machine or plant. Operating times of units can be shown separately above or below the main diagram, in the same manner as described for timing diagrams. For clarity, so that every operation can be shown without a break, the progress of at least two successive workpieces should be shown. Operation is represented by drawing the loci of specified edges or points of the workpieces, the slope equalling the velocity at that location. Lines parallel to the ordinate define the position of fixed sensors and tooling. The intersection of these lines with the loci determines critical times, noting that flow diagrams are not restricted to strictly cyclic operation; the datum can be re-set for every workpiece. In addition, the timing of procedures such as tests for correct location, alignment and feed can be included. Hence all such factors can be checked for feasibility and to ensure that they occur in the optimum sequence.

Sketch 4.4 is a portion of a flow diagram illustrating the progress of a sequence of plates along a track. The leading and trailing edges of two successive plates are shown. The tolerance on the leading edge allows for a variation in the time the plates enter the track; that on the trailing edge is larger as it also accommodates variations in the length of individual plates. In Sketch 4.4 the fixed positions of the sensors are defined by the broken lines parallel to the abscissa. The superimposed bold lines between the arrowheads identify the times when that sensor is energised. Sensor 'A' establishes the timing datum for each plate by identifying the arrival of the leading edge. Sensor 'B' checks for any misfeed by testing for both the presence and absence of a plate at appropriate times in the cycle. Sensor 'C' measures the plate thickness.



Sketch 4.4 Portion of a flow diagram

5. DERIVATION AND REFERENCES

5.1 Derivation

The derivation lists sources that have been used in the preparation of this Item.

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7. DRUCE, G. Cam mechanisms. *Engineering Design Procedural Guide, Mechanical Positioning & Control, MPC4.1 (SEED, Loughborough)*, 1996.

5.2 References

The references given are recommended sources of information supplementary to that in this Item.

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