(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 258 694 A2

(12) # EUROPEAN PATENT APPLICATION

(21) Application number: 87111644.8

(22) Date of filing: 11.08.87

(51) Int.Cl.[3]: F 02 P 17/00
F 02 M 65/00

(30) Priority: 11.08.86 US 895136

(43) Date of publication of application:
09.03.88 Bulletin 88/10

(84) Designated Contracting States:
DE FR GB IT NL

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(54) **Method of determining the per cylinder timing profile of an internal combustion engine.**

(57) A method of accurately determining the θ profile of an internal combustion engine measures cylinder time intervals under a rapid deceleration condition, finds the series of time intervals having the highest deceleration and assuming a constant deceleration during the series of time intervals, calculates the θ for each cylinder.

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METHOD OF DETERMINING THE PER CYLINDER TIMING PROFILE OF AN INTERNAL COMBUSTION ENGINE

This application is a continuation-in-part of application Serial No. 895,136, filed 8/11/86, now abandoned.

CROSS REFERENCE TO RELATED APPLICATION

This invention is related to application Serial No. 871,930, filed June 9, 1986, entitled METHOD OF PERFORMING A POWER BALANCE ON AN INTERNAL COMBUSTION ENGINE, in the name of Keith A. Kreft and assigned to Sun Electric Corporation.

Background of the Invention

This invention relates generally to internal combustion engine testing and, specifically, to a quick test method for determining the rotational angles Θ between successive firing events in an internal combustion engine.

In an internal combustion engine having a plurality of cylinders, a fuel/air mixture is introduced into each cylinder where it is ignited to develop power. The ignition or combustion (both referred to as a "firing event") may be by way of an electrical spark produced by a spark device in communication with the cylinder and fuel/air mixture or by injection of fuel into a cylinder that is charged with air under pressure. In a 4-cycle engine, each cylinder is subjected to a firing event once for every two revolutions of the engine. In a conventional engine, a distributor comprises a mechanically rotating shaft carrying a cam for operating a set of breaker points and a rotor contact for distributing high voltage energy from an ignition coil to the various spark plugs, in sequence. The firing events are initiated by each opening of the cam operated low voltage breaker points which causes a collapse of the magnetic field developed by in the ignition coil. This in turn induces a high voltage in the secondary winding of the ignition coil.

In most ideal engines, the rotational angles (θ) between successive firing events are equal as are the angles between the successive occurrences of each cylinder reaching its point of maximum compression, commonly referred to as "top dead center" (TDC). Engine "timing" is generally referred to as the angle through which the engine rotates between the firing event of cylinder #1 and the top dead center of cylinder #1. The measurement of this angle is in engine degrees and is generally denoted as so many degrees "before top dead center" (BTDC) or "after top dead center" (ATDC) indicating whether the firing event occurs before or after the cylinder #1 TDC.

In the ideal engine, where the above equal angle relationships are true, each cylinder firing event will have the same "timing" relationship with its respective TDC point. A worn or bent distributor shaft or a worn bushing, for example, would result in the rotational angles θ between successive firing events being unequal. This, in turn, could result in each cylinder firing with a different amount of "timing," which is not desirable.

There are many other factors which affect the θ's. The ability to determine the θ's of an engine with reasonable accuracy is a valuable tool in internal combustion engine diagnosis. The series of angles θ for the cylinders of an internal combustion engine is herein referred to as the "θ profile" of the engine. Thus, the ability to determine the θ profile, and hence any differences in these angles, can assist the technician in diagnosing defects or potential problem areas within the engine.

Another important use of the angles θ, as fully discussed in the above-referenced copending application, is in conducting a power balance test of the engine, which can yield valuable information about its operating condition. A power balance test notes the relative power contribution of each cylinder in the engine. The copending application describes a technique of determining the relative power contribution of each cylinder by comparing the relative increases in engine velocity of the engine under load for each cylinder from the time intervals between successive firing events of each cylinder. As the application describes, to calculate a correct relative velocity or acceleration rate for each cylinder, a fairly accurate measurement of the rotational angles between the firing events is required.

In some present techniques, the Θ for each cylinder is determined by measuring the time intervals between successive firing events in an engine running at an idle speed. This technique assumes that under idle speed conditions, each cylinder is contributing a similar amount of power and that, therefore, the time interval between successive firing events is a good measure of the actual rotational travel of the engine between the firing events. Since the angular rotation of the engine over a complete sequence of firing events is known (720 degress for a 4-cycle engine), the Θ's may be quantitatively determined by proportioning the time intervals over 720 degrees. In practice, however, variation in the power contribution of each cylinder will affect the measured time intervals and, therefore, the idle running speed condition does not yield a sufficiently accurate measure of the Θ's of the cylinders and a more accurate measurement technique is desirable.

For the above reasons, it would be highly desirable to have a method of more accurately measuring the Θ profile of an internal combustion engine. Further, it would be of great value to be able to make such measurements quickly and by utilizing conventional type automotive "tune-up" equipment. For example, some automotive tests require the mounting of either a flywheel tooth sensor, or an integrated high resolution velocity sensor to the engine being tested. Because the means for attaching such sensors are unique for each type of engine, the random testing of a variety of different engine types would prove cumbersome and time consuming.

The invention is thus directed toward achieving a simple, accurate method of measuring the θ profile of an engine, with signals currently gathered and processed on most types of automotive tune-up equipment.

Objects of the Invention

A principal object of the invention is to provide a novel method of measuring the θ profile of an internal combustion engine.

Another object of the invention is to provide a novel method of accurately determining the θ profile of an internal combustion engine, utilizing signals that are currently gathered and processed by most automotive "tune-up" equipment.

Brief Description of the Drawings

Other objects and advantages of the invention will be apparent upon reading the following description in conjunction with the drawings in which:

FIG. 1 is a simplified block diagram of apparatus for performing the method of the invention;

FIG. 2 is a timing diagram illustrating the time intervals, the angles θ and the cylinder firings.

FIG. 3 is a simplified flow chart describing the method of the invention.

Description of the Preferred Embodiment

An engine rotating at a "constant" speed actually experiences a series of accelerations and decelerations, with the accelerations corresponding to the combustible mixtures in the cylinders being ignited. A cylinder that is substandard in its power contribution will not accelerate the engine as much as one that is contributing fully to engine power (speed). This deviation is reflected in the "time interval" between firing events in successive cylinders, with a cylinder that is not contributing full power to the engine having a "longer time interval" than a cylinder that is contributing full power. The invention in the copending application describes and claims a novel method of performing a power balance while utilizing only the internal loads of the unloaded engine itself. In the preferred embodiment the Θ's of the cylinders are determined and used to enhance the accuracy of the power balance.

The Θ profile clearly can greatly influence the time intervals between successive cylinder firing events. While many engine tests are performed based upon an assumption that the Θ's for the cylinder are equal, the ability to determine the Θ for each cylinder enables one to obtain much more accurate test results. The Θ for each cylinder is calculated from data taken or captured during an engine deceleration condition and then used to more accurately determine the relative velocity, relative acceleration and relative power contribution attributable to each cylinder during an engine acceleration condition. It will be appreciated that "cylinder" is used broadly to denote the power producing unit of an internal combustion engine including the cylinder, piston, connecting rod, spark plug, fuel injector, and the like.

The method of the present invention is also applicable to non-spark ignited internal combustion engines, such as diesel engines. In diesel engines, a cylinder firing event may be detected by means of some type of transducer associated with each cylinder. Thus, to practice the invention, pickup means are required for sensing the cylinder firing events. The pickup means may either sense the actual cylinder firing, or sense a signal that is used to generate the actual firing or sense a signal that is a result of a cylinder firing, and generate therefrom a pulse train to mark the cylinder firing events. Additionally, a pickup for identifying or labelling a reference cylinder and its associated time interval is provided to synchronize the firing event data received. Such means are well known in the art.

In FIG. 1, engine 10 is depicted as a block with cylinders 12, 14, 16 and 18 schematically indicated in dashed lines therein. A plurality of spark plugs 20, 22, 24 and 26 are mounted to engine 10 and connected over a cluster 27 of suitable spark plug wires to an ignition source 36. It will be appreciated throughout this description that elements 20, 22, 24 and 26 may comprise diesel fuel injectors rather than spark plugs. Such would be the case for a diesel engine with cluster 27 comprising fuel lines rather than spark plug wires. Similarly, ignition source 36 is also labelled as a fuel distributor in the event a diesel engine is being tested. It will also be appreciated that a spark ignited, fuel injected system is also contemplated, although not shown or described.

Engine 10 may be equipped with conventional accessory apparatus such as a fan 28 and flywheel 30, none of which is relevant to the invention. A pair of sensors 32 and 34 are shown adjacent cluster 27, with sensor 32 being capable of picking up signal information from all cylinder firing events for cluster 27 and sensor 34 for picking up signal information from a single cylinder firing event corresponding to a reference cylinder in engine 10. For a spark ignited engine, sensors 32 and 34 are generally electrically sensitive, whereas for a diesel engine, they are typically pressure (or fluid flow) sensitive. It will be appreciated that techniques other than those illustrated or described may be used to convey the signals that are indicative of a firing event. The outputs of sensors 32 and 34 are supplied to signal conditioners 38 and 40, respectively, where, in a well-known manner, the input analog signal waveforms are converted into digital clock pulses for application to a suitable microprocessor control 42. Microprocessor control 42 may be a simple microcomputer for taking the signal information from signal conditioners 38 and 40 and processing it, in accordance with the inventive method, to produce a suitable output for an output device 44. This output may take the form of one or more of: a visual display; a printed report; or an audible message, and could consist of a Θ profile or any manipulated form of the information presented as, for example, a timing deviation or timing variation. This information may then be utilized in a variety of other tests for evaluating both overall engine performance and specific components of the engine. For example, the Θ's determined may be used to calculate the relative velocities, relative accelerations and the relative power contributions of each of the cylinders as specified in the referenced application.

FIG. 2 is a simplified showing of the relationship between cylinder firings and the engine-derived processing signals. The upper curve is a typical cylinder clock signal generated by signal conditioner 38. This is synchronized with the engine sync signal shown below when the designated cylinder (usually #1) fires (or in a diesel engine, receives injected fuel). The engine sync signal is generated by signal conditioner 40. Cylinder #1 is labelled 1 for convenience with the successively firing cylinders being labelled 2, 3 and 4, irrespective of their physically assigned numbers in the engine.

Similarly, the corresponding θ's are θ1, θ2, θ3 and θ4. The curves depicted represent a conventional four cycle, four cylinder, non "wasted spark" engine where θ1+θ2+θ3+θ4 is equal to 720 degrees since each cylinder is fired once for every two engine revolutions. The reference designations T1, T2...Tn are serially assigned to the collected time intervals as the engine "rotates" so that successive firing intervals of cylinder #1 are T1, T5, T9, etc. With reference to FIG. 1, the cylinder clock signal is supplied from signal conditioner 38 to microprocessor control 42 and the engine sync signal is supplied from signal conditioner 40 to microprocessor control 42.

The flow chart of FIG. 3 generally explains the operation of the microprocessor in the inventive method. Initially, the engine is accelerated to a high speed condition and then allowed to decelerate at a rapid rate by limiting or shutting off the fuel supply or the ignition pulses, etc. A set of cylinder firing event time interval measurements is taken during the deceleration of the engine, labels are assigned and the measured time intervals stored. These time intervals are referred to as TL(1,2...n). From this set of data, the series of TL's of a maximum negative slope are selected. It is assumed that a fairly constant deceleration of the engine occurred during this period and θ is calculated for each cylinder. The calculated θ's are quite accurate since under a rapid deceleration condition from a high speed, where the internal loading forces of the engine are high, power contribution of each cylinder is at its minimum, and therefore the effects of any small power contribution will be negligible.

There are a number of ways to calculate θ based upon the measured time intervals. The appendix includes a method of calculating the θ's for an engine and a computer measurement and computation.

Note that these data need not be taken under conditions requiring external loading. With the vehicle in "neutral" or "park," the engine power contribution may be terminated to obtain the deceleration data. This may be done by shutting off the fuel supply. Other means, such as disabling the ignition may be used, provided suitable signal detection means are retained, such as are available in well-known means of "cylinder shorting." Similarly the rapid deceleration data may be taken upon the release of the throttle in a snap acceleration. It is thus seen that with very limited access to the engine, specifically with knowledge only of the occurrence of firing events timed to a reference cylinder, the Θ profile of the engine may be readily and accurately determined.

It is recognized that numerous changes and modifications in the described embodiment of the invention will be apparent to those skilled in the art without departing from its true spirit and scope. The invention is to be limited only as defined in the claims.

WHAT IS CLAIMED IS:

1. A method of accurately determining the θ profile, that is the series of angles θ between successive cylinder firing events, of an internal combustion engine having a plurality of cylinders comprising the steps of:

operating the engine at a given speed;

decelerating the engine from said given speed;

measuring for all cylinders, the time intervals between successive cylinder firing events while said engine is decelerating; and

calculating θ for each cylinder from said time intervals.

2. The method of claim 1 wherein said deceleration is a rapid deceleration.

3. The method of claim 2, further including the step of selecting a contiguous group of time intervals exhibiting the highest rate of deceleration for use in calculating θ.

4. The method of claim 3 wherein said given speed is high to increase the internal loading forces of the engine.

5. The method of claim 4 wherein said step of decelerating is performed by terminating the power contribution of the engine.

6. The method of claim 5 wherein said power contribution is terminated by shutting off the fuel to the engine.

7. The method of claim 5 wherein said power contribution is terminated by disabling the ignition to the engine.

8. A method of accurately determining the Θ profile of an internal combustion engine having a plurality of cylinders comprising the steps of:

operating the engine at a high speed;

producing a rapid deceleration of said engine from said high speed;

measuring the time intervals between successive cylinder firing events while said engine is decelerating;

selecting a group of contiguous time intervals exhibiting the highest rate of deceleration from said time intervals; and

calculating Θ for each cylinder from said selected group of time intervals to produce a Θ profile of the engine.

APPENDIX

CALCULATION OF THETA

1. From the Time Intervals captured during the engine deceleration, calculate on average engine velocity for each series of X number of Time Intervals; where x is the number of cylinders.. The total distance of rotation for this series of Time Intervals is 720°. Therefore, the average (2 revolution) velocity is;

$$V_{Avg(y)} \quad \frac{(Revs)}{(Sec)} = \frac{2\ (Revs)}{\sum TI_y + TI_{y+1} + \ldots TI_{y+x-1} \quad (Sec)}$$

where x = number of cylinders, and

y = is incremented from 1 thru the total number of Time Interval measurements captured minus the number of cylinders minus one (1).

2. From the average velocities (V_{Avg}), calculate the average (2 revolution) acceleration rates using;

$$A_{Avg(y)} \quad \frac{(Revs)}{(Sec^2)} = \frac{V_{Avg(y+x)} - V_{Avg(y)} \ \frac{(Revs)}{(Sec)}}{\sum TI_{y+z} + TI_{y+z+1} \ldots TI_{y+z+x-1} (Sec)}$$

where z = $\frac{x}{2}$ rounded to the nearest integer.

x = number of cylinders

y = is incremented from 1 thru the total number of Time Interval measurements capture minus the number of cylinders minus one (1).

The 2 revolution Time Intervals used in the calculation are shifted by a count of approximately 1/2 the number of cylinders because each V_{Avg} reading is more representative of the actual engine velocity occurring nearer the center of the 2 revolution total Time Interval.

3. Find the series of readings, one for each cylinder, having the highest rate of deceleration. Using this deceleration rate, calculate the initial velocity (V_{Corr}) for the first Time Interval in the selected series of readings.

From $d = 1/2\ at^2 + v_i t + d_i$, we can solve for v_i; knowing $d - d_i$ is equal to the change in distance, in this case 2 revolutions;
assuming a is constant and equal to the A_{Avg}; and setting t equal to the 2 revolution total Time Interval. In other words, knowing the approximate rate of deceleration and knowing how long an engine takes to rotate two (2) revolutions, we can calculate the starting, instantaneous velocity (V_{Corr}).

4. Using V_{Corr} and A_{Avg}, the distance the engine rotates thru for various time periods can be calculated. Therefore, by substituting the first Time Interval in the series, the sum of the first and second intervals, the sum of the first, second and third intervals, etc., into the equation, the distance rotated thru, from the point at which the instantaneous starting velocity (V_{Corr}) was calculated, can be determined. From within the series of X Time Interval readings;

$$d_1 = 1/2\ A_{Avg}\ (TI_1)^2 + V_{Corr}\ (TI_1),\ \text{and}$$
$$d_2 = 1/2\ A_{Avg}\ (\textstyle\sum TI_1 + TI_2)^2 + V_{Corr}(\textstyle\sum TI_1 + TI_2)$$
$$d_x = 1/2\ A_{Avg}\ (\textstyle\sum TI_1 + \ldots TI_x)^2 + V_{Corr}(\textstyle\sum TI_1 + \ldots TI_x)$$

5. Theta for each cylinder can be determined using:

$$Theta_{(y)} = 360\ (Deg)\ (d_{(y)} - d_{(y-1)})$$

where y = is incremented from 1 thru the number of cylinders, and

$$d_o = 0$$

APPENDIX

CALCULATION OF POWER CONTRIBUTION

6. Using the calculated Thetas for each cylinder, and the measured Time Intervals captured during the engine acceleration, calculate a velocity for each Time Interval using;

$$V_{y(x)} \quad \frac{(\text{Revs})}{(\text{Sec})} = \frac{\text{Theta}_{(x)}(\text{Deg})}{360\,\frac{(\text{Deg})}{(\text{Rev})}\ TI_{y(x)}\ (\text{Sec})}$$

where y = is incremented from 1 thru the total number of Time Intervals captured, and

(x) = cylinder number identification.

7. Calculate the % change in the velocity using;

$$\%\, V_{y(x)} = \frac{V_{y+1} - V_{y(x)}}{V_{y(x)}} \times 100$$

where y = is incremented from 1 thru the total number of Time Intervals captured, and

(x) = cylinder number identification.

APPENDIX

CALCULATION OF THETA FROM DECELERATION TIME INTERVAL DATA

CYL # LABEL	TIME INTERVAL (MSEC)	MEAS'MENT REFERENCE NUMBER	2 REV AVG VEL (REV/SEC)	2 REV ACCEL (REV/SEC2)	CORRECTED VELOCITY (REV/SEC)	ROTATIONAL DISTANCE (REV)	THETA (DEG)
1	4.655	1					
2	4.799	2					
3	4.826	3					
4	4.867	4	52.1254	-56.6372	52.2697	0.2537	91.3413
5	4.852	5	51.8148	-54.2312		0.5053	90.579
6	4.8	6	51.488	-50.7217		0.7529	89.1359
7	4.782	7	51.1627	-48.9316		0.9983	88.3345
8	4.788	8	50.9139	-50.0404		1.2427	87.9782
1	4.885	9	50.6855	-51.3597		1.4907	89.2789
2	5.044	10	50.435	-51.0103		1.7453	91.6742
3	5.073	11	50.1655	-49.3586		2	91.678
4	5.058	12	49.9114	-48.439			
5	5.029	13	49.6845	-49.354			
6	4.996	14	49.4866	-51.3305			
7	4.995	15	49.2223	-50.9414			
8	4.991	16	48.9189	-49.2367			
	5.068	17	48.6275	-47.5222			
	5.205	18	48.3816	-47.2432			
3	5.29	19	48.1707	-48.4726			
4	5.31	20	47.9432	-49.5728			
5	5.274	21	47.6667	-49.0069			
6	5.205	22	47.3754	-47.0112			
7	5.176	23	47.1165	-46.5716			
8	5.188	24	46.8746	-47.2468			
1	5.31	25	46.6451	-48.0545			
2	5.463	26	46.3994	-47.6905			
3	5.522	27	46.1244	-46.7179			
4	5.529	28	45.839	-45.7044			
5	5.484	29	45.5757	-45.7379			
6	5.432	30	45.3597	-47.3506			
7	5.433	31	45.1091	-47.3236			
8	5.458	32	44.826	-45.7859			
1	5.562	33	44.5484	-44.5397			
2	5.672	34	44.3066	-45.0725			
3	5.767	35	44.0645	-45.8081			
4	5.809	36	43.8126	-45.9586			
5	5.762	37	43.535				
6	5.677	38	43.2339				
7	5.681	39	42.9729				
8	5.719	40	42.7478				
1	5.853	41	42.5152				
2	5.992	42	42.266				
3	6.048	43	41.9454				
	6.054	44	41.6736				
	6.018	45					
6	5.988	46					
7	6.009	47					
8	6.03	48					

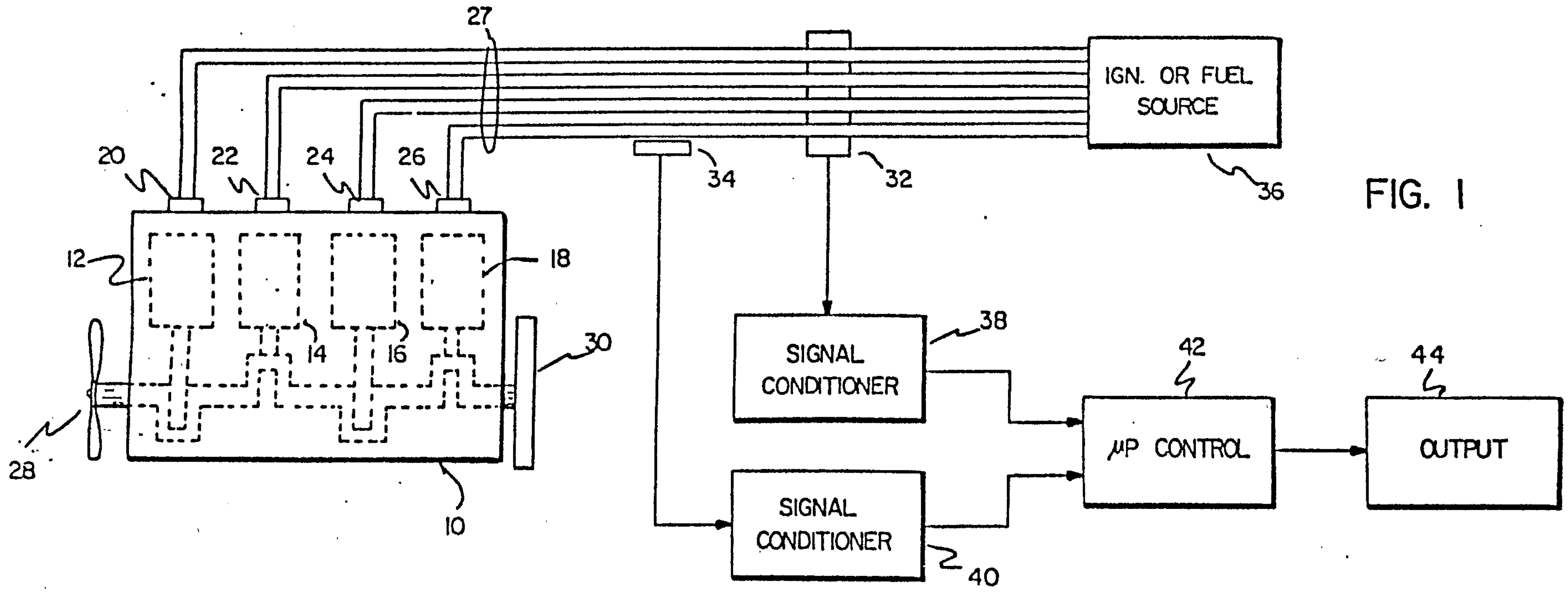

20
22
24
26
27
12
18
14
16
30
28
10
34
32
IGN. OR FUEL SOURCE
36
SIGNAL CONDITIONER
38
SIGNAL CONDITIONER
40
42
μP CONTROL
44
OUTPUT

FIG. 1

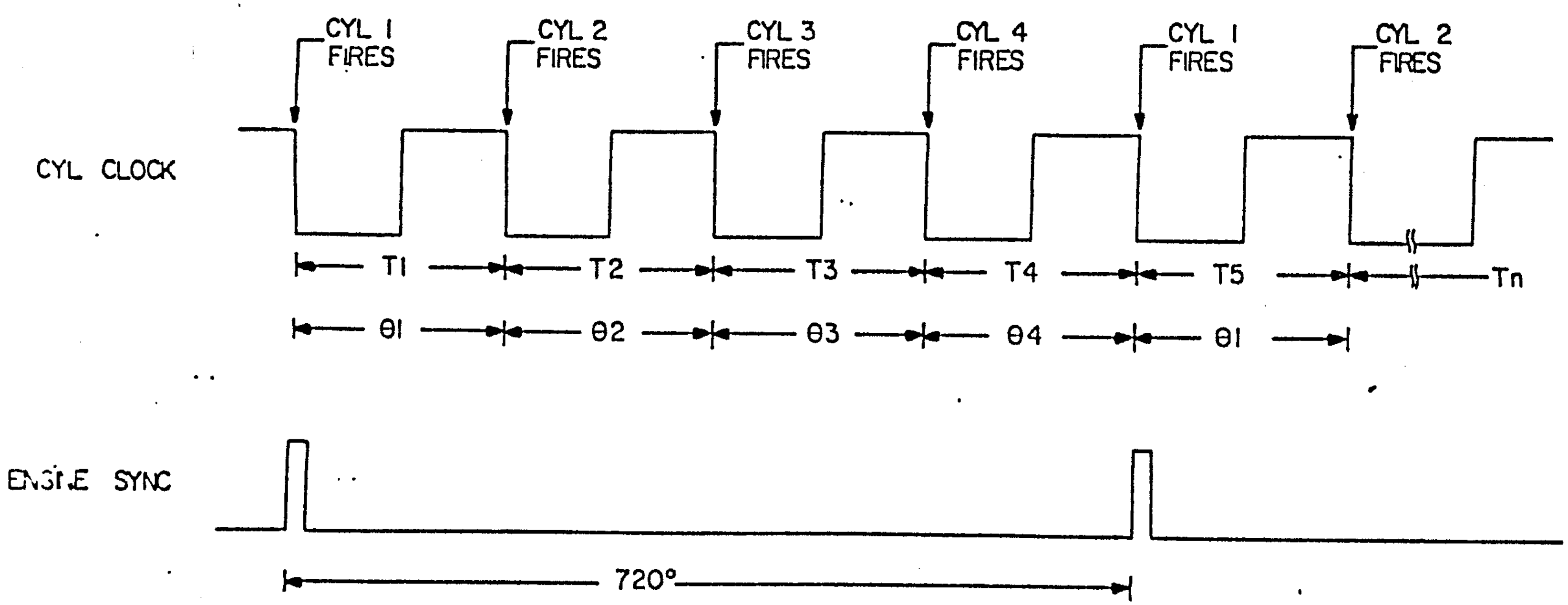
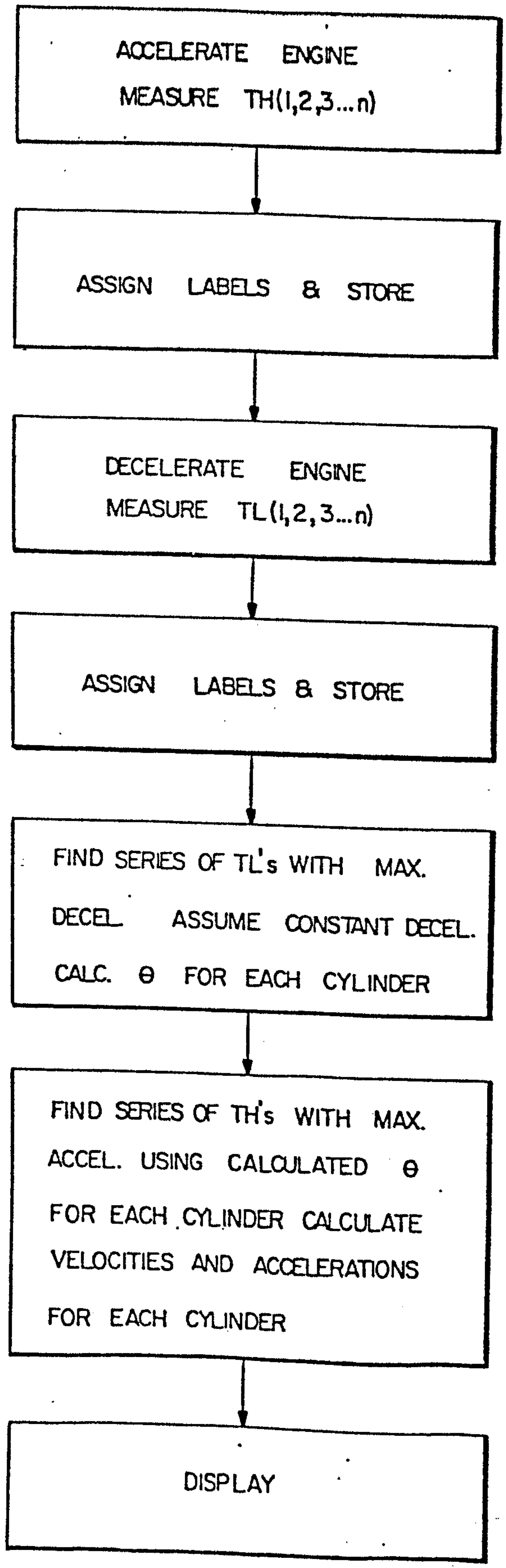

CYL 1 FIRES
CYL 2 FIRES
CYL 3 FIRES
CYL 4 FIRES
CYL 1 FIRES
CYL 2 FIRES
CYL CLOCK
T1
T2
T3
T4
T5
Tn
θ1
θ2
θ3
θ4
θ1
720°

FIG. 2

FIG. 3


ACCELERATE ENGINE
MEASURE TH(1,2,3...n)
ASSIGN LABELS & STORE
DECELERATE ENGINE
MEASURE TL(1,2,3...n)
ASSIGN LABELS & STORE
FIND SERIES OF TL's WITH MAX. DECEL. ASSUME CONSTANT DECEL. CALC. θ FOR EACH CYLINDER
FIND SERIES OF TH's WITH MAX. ACCEL. USING CALCULATED θ FOR EACH CYLINDER CALCULATE VELOCITIES AND ACCELERATIONS FOR EACH CYLINDER
DISPLAY