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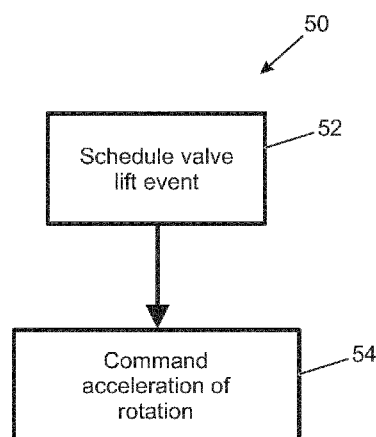


Fig 5

(57) Abstract: A method (50) of controlling an electromagnetic valve actuator (400) having a rotatable camshaft (404) for actuating a valve (440) of an engine (20), the method (50) comprising: scheduling (52) a valve lift event comprising an opening phase from zero valve lift to a peak valve lift, and a closing phase from peak valve lift to zero valve lift; commanding (54) the electromagnetic valve actuator (400) to accelerate rotation of its rotatable camshaft (404) at constant or variable acceleration during at least one or more of: the opening phase; the closing phase; a portion of the opening phase as well as a portion of the closing phase; and commanding the electromagnetic valve actuator (400) to cease rotation or reverse a direction of rotation of its rotatable camshaft (404) after the closing phase and before the commencement of the next valve lift event associated with the valve (440).

METHOD OF CONTROLLING A VALVE TRAIN

TECHNICAL FIELD

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The present disclosure relates to a method of controlling a valve train. In particular, but not exclusively it relates to a method of controlling a valve train of an engine of a vehicle.

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Aspects of the invention relate to a method, a controller, a system, an engine, a vehicle and a computer program.

BACKGROUND

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A traditional reciprocating internal combustion engine uses valves (typically poppet valves) to control gas flow into and out of the cylinders, facilitating combustion. A valve train is a system that controls the operation of the valves.

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An example valve train comprises a rotatable camshaft. The camshaft comprises one or more lobes. Each lobe pushes on a valve directly or indirectly, by camming action, to displace (lift) the valve from a closed position to an open position. The valve train comprises valve return springs. Each valve return spring biases the valve to displace the valve from the open position to the closed position when the lobe is no longer pushing the valve. The shape of the lobe and design of the valve return springs dictates the resulting displacement over time of the valve from its closed position.

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In some cases the camshaft can be controlled to vary the valve timing or valve opening. For example timing can be adjusted by changing the phasing of the camshaft with respect to a combustion cycle. The peak valve lift can be adjusted by controlling the separation of the camshaft from the valve.

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SUMMARY OF THE INVENTION

It is an aim of the present invention to provide an improved method of controlling a valve train.

Aspects and embodiments of the invention provide a method, a controller, a system, an engine, a vehicle and a computer program as claimed in the appended claims.

Acceleration of rotation refers to rate of change of angular velocity, not to rate of change of radial velocity. Allowing the cessation of rotation and/or reversal of rotation of the camshaft between valve lift events advantageously provides more possibilities for improving the efficiency of the valvetrain.

In some examples, the commanded acceleration of the rotatable camshaft is constant during at least one or more of: the opening phase; the closing phase; a portion of the opening phase as well as a portion of the closing phase.

Commanding constant acceleration refers to commanding constant finite positive acceleration, constant finite negative acceleration, and in some cases constant zero acceleration. This provides the advantage of reducing root-mean-square (RMS) energy consumption by the electromagnetic valve actuator, compared to, for example, commanding an instantaneous change in angular velocity at an instant in time. This is because the energy consumption is substantially proportional to the square of the required acceleration.

The commanded acceleration of the rotatable camshaft may be non-zero throughout one or more of: the entire opening phase; the entire closing phase.

This provides the advantage of reducing the RMS energy consumption, in the situation where the average angular velocity required in the closing phase differs from the average angular velocity required in the opening phase.

The method may comprise: scheduling rotation of the rotatable camshaft in advance of the opening phase into an operating position for lifting the valve at the start of the opening phase; and commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft at constant acceleration during the scheduled rotation.

This provides the advantage of reducing the RMS energy consumption, in the situation ('park-to-open' phase) where the rotatable camshaft needs to be accelerated from a starting angular velocity (usually zero), at a park position, to the angular velocity required for the opening phase, at the operating position for lifting the valve at the start of the opening phase.

The method may comprise: commanding the electromagnetic valve actuator to cause, during the scheduled rotation in advance of the opening phase, the one of the following rotation behaviours of the rotatable camshaft that results in the lowest overall root-mean-square acceleration of rotation of the rotatable camshaft in performing the scheduled rotation:

5 constant acceleration of rotation; constant acceleration of rotation preceded by or followed by constant velocity of rotation (angular velocity); or constant positive acceleration of rotation followed by constant negative acceleration of rotation.

10 This provides the advantage of reducing the RMS energy consumption in the 'park-to-open' phase. The most efficient of the above rotation behaviours for this 'park-to-open' phase varies depending upon the ratio of the required angular rotation of the rotatable camshaft to the required angular rotation of the crank during the 'park-to-open' phase.

15 The above features of the 'park-to-open' phase are equally applicable to a 'close-to-park' phase in which the rotatable camshaft needs to be accelerated from an angular velocity, at the end of the closing phase, to an ending angular velocity (usually zero), at the park position.

In the 'close-to-park' phase the method may comprise: scheduling rotation of the rotatable camshaft after the closing phase in advance of a next valve lift event; and commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft at constant acceleration during the scheduled rotation.

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The method may comprise: commanding the electromagnetic valve actuator to cause, during the scheduled rotation, the one of the following rotation behaviours of the rotatable camshaft that results in the lowest overall root-mean-square acceleration of rotation of the rotatable camshaft in performing the scheduled rotation: constant acceleration of rotation; constant velocity of rotation followed by constant acceleration of rotation; or constant non-zero acceleration of rotation followed by constant different non-zero acceleration of rotation.

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The method may comprise: commanding the electromagnetic valve actuator to cease rotation of its rotatable camshaft after the closing phase before the commencement of the next valve lift event associated with the valve.

Scheduling a 'parking' of the rotatable camshaft provides the advantage of reducing the likelihood of a closing phase of a first valve event interfering with an opening phase of a next valve event.

- 5 In some examples, the cessation of rotation may be scheduled so that the rotatable camshaft ceases rotation at one of a plurality of distinct angular positions dependent on detent locations of the electromagnetic valve actuator.

10 This provides the advantage that the distinct angular positions can be predetermined so that little or no energy is required for holding the camshaft in the park position. Detent locations are specific to the permanent magnets of the electromagnetic valve actuator.

15 The method may comprise: commanding the electromagnetic valve actuator to change the acceleration of rotation of its rotatable camshaft after the closing phase of the valve lift event or another valve lift event and before the commencement of the next valve lift event associated with the valve, comprising biasing the timing of the change in acceleration to prevent unintentional valve lift after the closing phase and before the commencement of a next valve lift event.

20 Enabling temporal biasing of the reversal point between valve lift events provides the advantage of a compromise between allowing operating the valvetrain efficiently, while avoiding unintentional valve re-opening.

25 The method may comprise: commanding the electromagnetic valve actuator to cause, during a scheduled rotation from the end of the closing phase of the valve lift event to the beginning of a next opening phase of a next valve lift event, the one of the following rotation behaviours of the rotatable camshaft that results in the lowest overall root-mean-square acceleration of rotation of the rotatable camshaft in performing the scheduled rotation: cessation of rotation of the rotatable camshaft; a change in the acceleration of the rotatable
30 camshaft; or continuous constant-acceleration rotation of the rotatable camshaft.

Enabling a decision between parking, a knee point, and continuous rotation between valve lift events advantageously provides more possibilities for improving the efficiency of the valvetrain.

The method may comprise: commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft at constant acceleration throughout one or more of: the entire opening phase; the entire closing phase; the entire opening phase as well as the entire closing phase.

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This provides the advantage of reducing the RMS energy consumption.

The method may comprise: commanding the electromagnetic valve actuator to reverse a direction of rotation of its rotatable camshaft, changing the angular velocity of the rotatable camshaft from a positive value during the opening phase to a negative value during the closing phase.

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This makes peak valve lift into a variable that can be controlled. This provides the advantage of enabling continuously variable valve lift control.

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The method may comprise: receiving target inputs indicative of a start timing for the valve lift event, a duration of the valve lift event, a timing of the peak lift, and optionally a lift amount of the valve at peak lift, and wherein the scheduling of the valve lift event is dependent upon the target inputs.

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The use of only these target inputs to schedule valve events means that the method can be performed in open loop. This provides the advantage that minimal to no feedback is required, avoiding oscillations in scheduled acceleration that can increase RMS energy consumption. In other examples limited input from feedback sensors can be beneficial.

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Constant acceleration may be a constant rate of change of angular velocity of the camshaft, over a time interval in a time domain defined by rotation of an engine crankshaft.

According to another aspect of the invention there is provided a method of controlling an electromagnetic valve actuator having an actuating element for actuating a valve of an engine, the method comprising: scheduling a valve lift event comprising an opening phase from zero valve lift to a peak valve lift, and a closing phase from peak valve lift to zero valve lift; and commanding the electromagnetic valve actuator to accelerate its actuating element at constant or variable acceleration during one or more of: the opening phase; the closing phase; a portion of the opening phase as well as a portion of the closing phase; and commanding the

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electromagnetic valve actuator to cease rotation or reverse a direction of rotation of its rotatable camshaft after the closing phase and before the commencement of the next valve lift event associated with the valve

- 5 According to some, but not necessarily all aspects of the disclosure there is provided a method of controlling an electromagnetic valve actuator having a rotatable camshaft for actuating a valve of an engine, the method comprising: scheduling a valve lift event comprising an opening phase from zero valve lift to a peak valve lift, and a closing phase from peak valve lift to zero valve lift; and commanding the electromagnetic valve actuator to accelerate rotation of its
10 rotatable camshaft at constant acceleration during at least one or more of: the opening phase; the closing phase; a portion of the opening phase as well as a portion of the closing phase.

According to some, but not necessarily all aspects of the disclosure there is provided a method of controlling an electromagnetic valve actuator having an actuating element for actuating a
15 valve of an engine, the method comprising: scheduling a valve lift event comprising an opening phase from zero valve lift to a peak valve lift, and a closing phase from peak valve lift to zero valve lift; and commanding the electromagnetic valve actuator to accelerate its actuating element at constant acceleration during one or more of: the opening phase; the closing phase; a portion of the opening phase as well as a portion of the closing phase.

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According to some, but not necessarily all examples of the disclosure there is provided a method of controlling a valve actuator having an actuating element for actuating a valve of an engine, the method comprising: commanding the valve actuator to accelerate its actuating element at constant acceleration.

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According to a further aspect of the invention there is provided a method of controlling an electromagnetic valve actuator having a rotatable camshaft for actuating a valve of an engine, the method comprising: scheduling a first valve lift event having a first characteristic, for a first combustion cycle associated with the valve; scheduling a second valve lift event having a
30 second different characteristic, for a second combustion cycle associated with the valve; and in the transition between the first valve lift event and the second valve lift event, commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft to the rotational speed required for enabling the second valve lift characteristic, using only finite acceleration. In some examples, the second characteristic corresponds to a different peak
35 valve lift and/or a different rate of valve lifting, compared to the first characteristic.

This provides the advantage of reducing RMS energy consumption by the electromagnetic valve actuator, compared to, for example, commanding an instantaneous change ('step') in angular velocity whenever control switches from one valve lift characteristic (e.g. late valve opening) and another valve lift characteristic (e.g. early valve opening).

In some examples, the first valve lift event comprises a valve opening phase and a valve closing phase, wherein the first characteristic is associated with a first rotational speed of the rotatable camshaft at the beginning of the valve opening phase of the first valve lift event, and wherein the second valve lift event comprises a valve opening phase and a valve closing phase, wherein the second characteristic is associated with a second different rotational speed of the rotatable camshaft, at the beginning of the valve opening phase of the second valve lift event.

According to some, but not necessarily all examples of the disclosure there is provided a method of controlling a valve actuator having an actuating element for actuating a valve of an engine, the method comprising: commanding the valve actuator to accelerate its actuating element without any step changes in acceleration.

According to a further aspect of the invention there is provided a controller comprising means for performing the method. The means may comprise at least one processor; and at least one memory, including computer program code; the at least one memory and the computer program code configured to, with the at least one processor, cause the controller at least to perform the method.

According to a further aspect of the invention there is provided a system comprising: the controller; and a desmodromic electromagnetic valve actuator controlled by the controller. According to a further aspect of the invention there is provided an engine comprising the controller. According to a further aspect of the invention there is provided a vehicle comprising the controller or the engine.

According to a further aspect of the invention there is provided a computer program comprising instructions that, when executed by one or more processors, cause a controller to perform at least the method.

According to a further aspect of the invention there is provided a method, a controller, a system, a cylinder head, an engine, a vehicle or a computer program as described with reference to the accompanying drawings.

5 Within the scope of this application it is expressly intended that the various aspects, embodiments, examples and alternatives set out in the preceding paragraphs, in the claims and/or in the following description and drawings, and in particular the individual features thereof, may be taken independently or in any combination. That is, all embodiments and/or features of any embodiment can be combined in any way and/or combination, unless such
10 features are incompatible. The applicant reserves the right to change any originally filed claim or file any new claim accordingly, including the right to amend any originally filed claim to depend from and/or incorporate any feature of any other claim although not originally claimed in that manner.

15 BRIEF DESCRIPTION OF THE DRAWINGS

One or more embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Fig 1 illustrates an example of a vehicle;
20 Fig 2 illustrates an example of a controller;
Fig 3 illustrates an example of a computer-readable storage medium;
Fig 4 illustrates an example of an electromagnetic valve actuator;
Fig 5 illustrates an example of a method;
Fig 6 illustrates an example representation of a scheduled valve lift event;
25 Fig 7 illustrates another example representation of a scheduled valve lift event; and
Fig 8 illustrates an example representation of a scheduled camshaft rotation between valve lift events.

DETAILED DESCRIPTION

30 The Figures illustrate a method 50 of controlling an electromagnetic valve actuator 400 having a rotatable camshaft 404 for actuating a valve 440 of an engine 20, the method 50 comprising: scheduling 52 a valve lift event comprising an opening phase $\theta_{G,O}$ to $\theta_{C,MOP}$ from zero valve lift to a peak valve lift, and a closing phase $\theta_{C,MOP}$ to $\theta_{C,C}$ from peak valve lift to zero valve lift; and
35 commanding 54 the electromagnetic valve actuator 400 to accelerate rotation of its rotatable

camshaft 404 at constant acceleration during at least one or more of: the opening phase; the closing phase; a portion of the opening phase as well as a portion of the closing phase.

Fig 1 illustrates an example of a vehicle 10 in which embodiments of the invention can be implemented. In some, but not necessarily all examples, the vehicle 10 is a passenger vehicle. Passenger vehicles generally have kerb weights of less than 5000 kg.

In Fig 1 the vehicle 10 comprises: an engine 20 (which may be an internal combustion engine); a cylinder head 30 of the engine 20; and a valve train 40 which may be within the cylinder head 30 or elsewhere in proximity to the engine 20.

Fig. 2 shows an example of a controller 200 of the engine 20 and/or the valve train 40.

For purposes of this disclosure, it is to be understood that the controller(s) 200 described herein can each comprise a control unit or computational device having one or more electronic processors 202. A vehicle 10 and/or a system thereof may comprise a single control unit or electronic controller or alternatively different functions of the controller(s) may be embodied in, or hosted in, different control units or controllers. A set of instructions 208 could be provided which, when executed, cause said controller(s) or control unit(s) to implement the control techniques described herein (including the described method(s)). The set of instructions may be embedded in one or more electronic processors 202, or alternatively, the set of instructions could be provided as software 206 stored in at least one memory 204 to be executed by one or more electronic processor(s) 202. For example, a first controller may be implemented in software run on one or more electronic processors, and one or more other controllers may also be implemented in software run on one or more electronic processors, optionally the same one or more processors as the first controller. It will be appreciated, however, that other arrangements are also useful, and therefore, the present disclosure is not intended to be limited to any particular arrangement. In any event, the set of instructions 208 described above may be embedded in a computer-readable storage medium 300 (e.g., a non-transitory storage medium) as shown in Fig 3 that may comprise any mechanism for storing information in a form readable by a machine or electronic processors/computational device, including, without limitation: a magnetic storage medium (e.g., floppy diskette); optical storage medium (e.g., CD-ROM); magneto optical storage medium; read only memory (ROM); random access memory (RAM); erasable programmable memory (e.g., EPROM and EEPROM); flash memory; or electrical or other types of medium for storing such information/instructions.

Fig 4 shows an example of valve train hardware, illustrated in various cross-section views.

5 Fig 4 shows a valve 440. The valve 440 is a poppet valve. The valve 440 is arranged to be opened when required to control gas flow into and/or out of the cylinders.

10 In Fig 4, but not necessarily in all examples, the valve 440 is coupled to a mechanism 420. The mechanism 420 is arranged to push the valve 440 to open the valve 440. In some, but not necessarily all examples, the mechanism 420 is arranged to pull the valve 440 to close the valve 440. The mechanism 420 is coupled to an actuating element in the form of a camshaft 404. The camshaft 404 comprises a first lobe 406 for camming the mechanism to cause pushing forces to be transmitted through the mechanism 420 for opening the valve 440. The camshaft 404 comprises a second lobe 408 for causing pulling forces to be transmitted through the mechanism 420 for closing the same valve 440, therefore the camshaft 404
15 enables desmodromic valve actuation. Different actuating elements can be used in other examples, for example linear actuators.

20 In other examples, the valve 440 is directly coupled to the camshaft 404, without any intervening mechanism 420. The first lobe 406 and second lobe 408 can be provided on different camshafts.

25 In Fig 4, the camshaft 404 is coupled to an electromagnetic valve actuator 400. The electromagnetic valve actuator 400 in Fig 4 comprises a rotor-stator pair 402, the rotor providing a rotating output. In other examples the electromagnetic valve actuator 400 can provide a linear output.

30 The camshaft 404 of Fig 4 serves two functions. The camshaft 404 firstly not only provides the lobes, but also acts as the rotor of the electromagnetic valve actuator 400 for providing the rotating output. The camshaft 404 is arranged to rotate about its rotational axis 405 extending along the length of the camshaft 404.

35 The angular velocity of the camshaft 404 increases when the electromagnetic valve actuator 400 is supplied with enough driving current to overcome inertia. Sufficient positive driving current supplied to the electromagnetic valve actuator 400 produces a positive acceleration (a positive change in the angular velocity of the camshaft 404), and sufficient negative driving

current produces negative acceleration (a negative change in the angular velocity of the camshaft 404).

The driving current applied to the electromagnetic valve actuator 400 is controlled by the controller 200. The operation of the controller 200 will be described in more detail.

Fig 5 shows a method of controlling the electromagnetic valve actuator 400, which can be carried out by the controller 200. The method comprises, at block 52, scheduling a valve lift event. The valve lift event comprises an opening phase from zero valve lift to a peak valve lift. With reference to the example hardware of Fig 4, the opening phase begins when sufficient force is exerted on the valve 440 to cause the valve 440 to start to open. The opening phase ends when insufficient force is exerted on the valve 440 to cause the valve 440 to lift any further, and the valve 440 will not lift any further for the remainder of the valve lift event.

The valve lift event also comprises a closing phase from peak valve lift to zero valve lift. With reference to the example hardware of Fig 4, the end of the opening phase is also the beginning of the closing phase. In some, but not necessarily all examples, the closing phase begins when sufficient force is exerted on the valve 440 to cause the valve 440 to start to move in a closing direction, towards zero valve lift. The closing phase ends when the valve 440 is closed (zero valve lift).

In some, but not necessarily all examples, a valve lift event consists of only the opening phase and the closing phase.

Example information that enables scheduling a valve lift event to be made includes software models of one or more of: mechanical properties; shape properties; electrical properties; magnetic properties; or thermal properties, of all or part of the hardware shown in Fig 4. Example shape properties include the shape of the first lobe 406 and the shape of the second lobe 408.

In some, but not necessarily all examples, one or more subsequent valve lift events are also scheduled in advance of the start of the opening phase of the valve lift event.

In some, but not necessarily all examples, scheduling takes place while the engine is running (internal combustion is occurring).

In some, but not necessarily all examples, scheduling the valve lift event comprises scheduling, in advance of the start of the opening phase of the valve lift event, one or more of: the angular position; the angular velocity; or the rate of change of angular velocity (acceleration), of the camshaft 404 at a plurality of times during the valve lift event. The electromagnetic valve actuator 400 will be controlled in a manner that causes the camshaft 404 to have the scheduled angular position, angular velocity, or rate of change of angular velocity at each of the plurality of times.

The scheduled valve lift event comprises a period of time in which acceleration of the camshaft 404 will be constant over the whole period of time. The period of time consists of one or more of: some or all of the opening phase; some or all of the closing phase; a portion of the opening phase as well as a portion of the closing phase; or the entire opening phase as well as the entire closing phase. The period or periods of constant acceleration ensures that RMS energy consumption by the electromagnetic valve actuator 400 is reduced.

The method comprises, at block 54, commanding the electromagnetic valve actuator 400 to accelerate rotation of its rotatable camshaft 404 according to the scheduled period or periods of constant acceleration. In some, but not necessarily all examples, block 54 comprises commanding the electromagnetic valve actuator 400 to perform the whole scheduled valve lift event, not only the scheduled period or periods of constant acceleration.

Commanding the electromagnetic valve actuator 400 at block 54 comprises at least transmitting a control signal that directly or indirectly controls the driving current supplied to the electromagnetic valve actuator 400 in accordance with all or part of the scheduled valve lift event. In some, but not necessarily all examples, the control signal is transmitted after the scheduling of the valve lift event has taken place.

An example detailed control strategy will now be discussed, some or all of which can form part of block 52 of the method of Fig 5.

The control strategy starts by receiving target inputs. The target inputs represent high level constraints that must be met. The target inputs may be determined by, for example, an engine control unit, before being transmitted to the controller 200.

The target inputs comprise a first target indicative of target start timing for the valve lift event. From this, it is possible to schedule the start of the opening phase. The time base is with respect to a combustion cycle associated with the valve 440. Timing can be expressed as a crank angular position ('crank angle'), for example 0 degrees of crank angle represents the start of a four-stroke combustion cycle and 720 degrees of crank angle represents the end of the four-stroke combustion cycle. In an illustrative example, the target start timing for the valve lift event may occur at 180 degrees of crank angle.

The target inputs comprise a second target indicative of the duration of the valve lift event. It is possible to schedule the end of the closing phase, by adding the duration (second target) to the target start timing (first target). The start time and duration of the valve lift event is now known.

The target inputs comprise a third target indicative of a target timing of peak valve lift. In some, but not necessarily all examples, the third target can be expressed as a percentage of the above duration. In the absence of the third target, the default timing of peak valve lift could be scheduled as 50% of the above duration. At values below 50%, the closing phase will be of a longer duration than the opening phase. At values above 50%, the opening phase will be of a longer duration than the closing phase.

In some, but not necessarily all examples, the target inputs comprise a fourth target indicative of a target lift amount of the valve 440 at peak lift. This could, for example, be specified as a percentage of the maximum achievable valve lift. In the absence of the fourth target, the default lift amount at peak lift could be 100%. A full rotation of the camshaft 404 would result in the maximum achievable valve lift. If the fourth target specifies a peak valve lift below 100%, it would be necessary to reverse the direction of rotation of the camshaft 404 before the maximum achievable valve lift is reached.

Based on the target inputs, it is possible to determine the following constraints:

	Crank angular position (‘crank angle’)	Rotor (camshaft 404) angular position
Start of opening phase	$\theta_{C,O}$	$\theta_{R,O}$
End of opening phase / start of closing phase	$\theta_{C,MOP}$	$\theta_{R,MOP}$

End of closing phase	$\theta_{C,C}$	$\theta_{R,C}$
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θ refers to an angle. Subscript MOP stands for 'maximum open position' which is peak valve lift. Subscript R stands for 'rotor' which is also the camshaft 404 in this example. Subscript C stands for 'crank'.

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The next stage of the control strategy involves determining a dimensionless angular velocity coefficient Ca for each phase:

$Ca = \text{planned rotor (camshaft) angular rotation} / \text{planned crank angular rotation}$

$$Ca = \Delta\theta_R / \Delta\theta_C \quad (\text{Eq. 1})$$

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The angular velocity coefficient Ca represents the rate of change of angular velocity of the rotor $\Delta\theta_R$, with respect to a time domain defined by rotation of the crankshaft.

The average angular velocity coefficient for the opening phase, applying the constraints of Eq.

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1, can be determined:

$$Ca1 (\text{opening phase}) = (\theta_{R,MOP} - \theta_{R,O}) / (\theta_{C,MOP} - \theta_{C,O})$$

For example, if the rotor is to rotate from 120 degrees to 200 degrees over the entire opening phase and the crank is to rotate from 270 degrees to 370 degrees over the entire opening phase, the average angular velocity coefficient is:

20

$$Ca1 (\text{opening phase}) = (200 - 120) / (370 - 270)$$

$$Ca1 (\text{opening phase}) = 0.80$$

In this example the average angular velocity coefficient of the rotor is 0.80 (i.e. the average angular velocity of the rotor must be 0.80 times the average crank angular velocity) for the opening phase.

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The average angular velocity coefficient for the closing phase, applying the constraints of Eq. 1, can also be determined:

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$$Ca2 (\text{closing phase}) = (\theta_{R,C} - \theta_{R,MOP}) / (\theta_{C,C} - \theta_{C,MOP})$$

For example, if the rotor is to displace from 200 degrees to 300 degrees over the entire closing phase and the crank is to rotate from 370 degrees to 450 degrees over the entire closing phase, the average angular velocity coefficient is:

$$Ca_2 \text{ (closing phase)} = (300 - 200) / (450 - 370)$$

$$Ca_2 \text{ (closing phase)} = 1.25$$

In this example the average angular velocity coefficient of the rotor is 1.25 (i.e. the average angular velocity of the rotor must be 1.25 times the average crank angular velocity) for the closing phase.

Fig 6 and Fig 7 are graphs, each having angular velocity coefficient Ca as the y-axis, and the x-axis is time in a time domain defined by rotation of the crankshaft θ_c . Line 601 in Fig 6 and line 701 in Fig 7 represent different schedules for valve lift events.

With reference to Figs 6 and 7, a positive gradient of Ca over a time interval in the time domain indicates that the angular velocity of the rotor must increase (positive acceleration) relative to the angular velocity of the crank. A negative gradient of Ca over the time interval indicates that the angular velocity of the rotor must decrease (negative acceleration) relative to the angular velocity of the crank. A zero gradient of Ca over the time interval indicates that the angular velocity of the rotor does not need to change (zero acceleration) relative to the angular velocity of the crank.

Different gradients of Ca (different accelerations) at different points in a valve lift event achieve different angular velocities of the rotor (relative to the angular velocity of the crank) at different points in the valve lift event. This in turn determines the angular position profile of the rotor at different points in the valve lift event. The angular position profile of the rotor in turn determines the displacement behaviour of the valve 440 at different points in the valve lift event. For example, ignoring changes in crank angular velocity (e.g. assume constant engine rpm), if Ca_2 is higher than Ca_1 then the valve 440 is closed at a faster rate than it is opened. If Ca_2 is less than Ca_1 then the valve 440 is closed at a slower rate than it is opened.

The advantage of scheduling a valve lift event using a dimensionless velocity coefficient Ca , expressing the rate of change of rotor angular position determined using a time domain defined by rotation of the camshaft, is that Ca is independent of crank angular velocity and so the schedule does not have to be recalculated as engine speed changes. The rate of implementation of the schedule can simply be dependent upon information from a crank position/angle sensor. This reduces computational requirements and maintains transient response of the valve train 40 to rapid changes in engine conditions.

It is possible to schedule a valve lift event such as the schedules 601 or 701 schematically illustrated in Fig 6 and Fig 7 and command the electromagnetic valve actuator 400 to perform the scheduled valve lift event.

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The schedule 601 of Fig 6 comprises: a constant $Ca1$ portion 602 in which $Ca=Ca1$ over the entire opening phase; and a constant $Ca2$ portion 604 in which $Ca=Ca2$ over the entire closing phase. Constant Ca for the entire duration of the opening phase means that constant zero acceleration is scheduled for the entire opening phase. Constant Ca for the entire duration of the closing phase means that constant zero acceleration is scheduled for the entire closing phase. In Fig 6, but not necessarily in all examples, $Ca2$ and $Ca1$ are different.

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The control strategy can be enhanced to further reduce energy consumption, as discussed below.

15

One enhancement includes scheduling the valve lift event to comprise a period of time in which acceleration of the rotor will be constant and non-zero over the whole period of time, i.e. Ca has a positive or negative gradient over the whole period of time. The period of time consists of one or more of: some or all of the opening phase; some or all of the closing phase; a portion of the opening phase as well as a portion of the closing phase; or the entire opening phase as well as the entire closing phase. The non-zero acceleration is scheduled so as to reduce the size of, or to eliminate, step changes in Ca such as the step change between $Ca1$ and $Ca2$ at $\theta_{C,MOP}$ (Fig 6).

20

The schedule 701 of Fig 7 is determined according to the enhanced control strategy. The schedule 701 of Fig 7 includes phases of constant non-zero acceleration.

25

A process for producing a schedule such as the schedule 701 will be described in more detail. For the purposes of explanation, it will be helpful to refer to the points A to H on the schedule 701 of Fig 7. The points A to H are plotted at the following crank angles along the crank rotation axis:

30

A. A beginning point within an engine combustion cycle which is taken to represent the beginning of the schedule shown in Fig 7. The crank angle at point A is $\theta_{C,A}$ and the rotor angle at point A is $\theta_{R,A}$.

- B1 and B2. Between the beginning of the schedule and the beginning of the opening phase.
- C. The beginning of the opening phase, beginning the valve lift event. The crank angle at point C is $\theta_{C,O}$ and the rotor angle at point C is $\theta_{R,O}$. In some, but not necessarily all examples, the valve 440 is an intake valve and point C can represent the start of an intake stage of a combustion cycle. Alternatively, the valve 440 can be an exhaust valve and point C can represent the start of an exhaust stage of the combustion cycle.
- D. During the opening phase, optionally at 50% of the duration of the opening phase.
- E. The end of the opening phase. In this example, E is also at the beginning of the closing phase. The crank angle at point E is $\theta_{C,MOP}$ and the rotor angle at point E is $\theta_{R,MOP}$.
- F. During the closing phase, optionally at 50% of the duration of the closing phase.
- G. The end of the closing phase, thereby ending the valve lift event. The crank angle at point G is $\theta_{C,C}$ and the rotor angle at point G is $\theta_{R,C}$. In some, but not necessarily all examples, the valve 440 is an intake valve and point G can represent the end of an intake stage of a combustion cycle. Alternatively, the valve 440 can be an exhaust valve and point G can represent the end of an exhaust stage of the combustion cycle.
- H. An ending point which occurs after point A. In some, but not necessarily all examples, the duration of A to H is the duration of a full combustion cycle. Point H does not necessary indicate a schedule stopping point. In some examples, the schedule can continue beyond point H. The crank angle of point H is $\theta_{C,H}$ and the rotor angle of point H is $\theta_{R,H}$.

An example scheduling process for determining a schedule such as the schedule shown in 701 will be described. Although a particular order of operations is given below, this is not intended to limit the operations of the scheduling process to occurring in any particular order.

Firstly a straight line intersecting point E is determined. A 'line' represents a vector of Ca on the graph of Fig 7. If the line is straight, the line represents a phase of constant acceleration. If the gradient of the straight line is non-zero, the line represents a phase of constant non-zero acceleration. Although lines are referred to, the process is not limited to line-fitting, regression

or geometry-based algorithms and is applicable to any process or algorithm that schedules equivalent rotor acceleration behaviour.

The line DE in the opening phase is straight. The line DE is extended to C to form straight line CDE. The line EF in the closing phase is straight. The line EF is extended to G to form straight line EFG. The lines CDE and EFG have the same or different gradients. If the control strategy allows, lines CDE and EFG will have the same gradient and will form a straight line CDEFG.

In some, but not necessarily all examples, the average Ca calculated from the area under the curve of line CDE must be equal to $Ca1$. The average Ca calculated from the area under the curve of line EFG must be equal to $Ca2$. This ensures that the resulting valve lift behaviour is substantially as required by the target inputs. In some, but not necessarily all examples, the value of Ca at point D is $Ca1$, and the value of Ca at point F is $Ca2$.

In some, but not necessarily all examples, it would be desirable for the value of Ca at point C to be positive and non-zero, to avoid unnecessary reversal of rotor rotation before the start of the opening phase. In this example, a minimum threshold value of Ca is required at point C. In some, but not necessarily all examples, in the event that Ca at point C is saturated to match the minimum threshold value, it is further necessary to recalculate Ca at other points in the opening phase and the closing phase to ensure that the average Ca calculated from the area under the curve of line CDE matches $Ca1$ as described above, and to ensure that the average Ca calculated from the area under the curve of line EFG matches $Ca2$ as described above. This recalculation can result in the gradient of line CDE decreasing and the gradient of line EFG increasing.

If the target inputs include a fourth target specifying a lift amount of <100% of maximum achievable valve lift, it would be necessary to reverse the direction of rotation of the rotor when the target lift amount has been reached (referred to herein as 'bounce mode'). This means that $Ca2$ would be negative.

To achieve bounce mode and to satisfy the target inputs the scheduling is made such that Ca at points F and G is negative. In some examples: point E is fixed at $Ca=0$; Line DE is straight and has a negative gradient; in some examples, line CDE is straight and has a negative gradient; Line EF is straight and has a negative gradient; and in some examples, line EFG is straight and has a negative gradient. As described above, it may be required that the average

Ca calculated from the area under the curve CDE matches $Ca1$, and the average Ca calculated from the area under the curve EFG matches $Ca2$. In some, but not necessarily all examples, the value of Ca at point D is $Ca1$, and the value of Ca at point F is $Ca2$.

- 5 So far the process has determined the vector of line Ca from points C to G. The entire opening and closing phases have been scheduled, therefore the valve lift event has been scheduled.

In some, but not necessarily all examples, additional scheduling is required. For example, the value of Ca at point A may differ from the required value of Ca at point C (arrival Ca at point C). For example, the value of Ca at point A may be zero, because the rotor is not rotating at all (it is 'parked'). It will therefore be necessary to schedule a change in Ca from point A to point C (referred to herein as a 'park-to-open' phase). The value of Ca at points A and/or C represent constraints in the schedule. The required average angular velocity coefficient $Ca3$ between points A and C is:

15

$$Ca3 \text{ (park-to-open phase)} = (\theta_{R,A} - \theta_{R,O}) / (\theta_{C,A} - \theta_{C,O})$$

The most efficient Ca schedule for the park-to-open phase is the one of the following lines that results in the lowest overall RMS acceleration of rotation of the rotatable camshaft 404 for the park-to-open phase:

20

- CV0. A straight line A to B2, having a constant non-zero first gradient, followed by a straight line B2 to C, having a constant different non-zero second gradient. Optionally, the first gradient and the second gradient are of opposite signs;
- CV1. A straight line starting at A, or after A (i.e. after an initial pause phase), having a constant non-zero positive gradient, and extending to C; or
- 25 CV2. A straight line A to B1, having a constant non-zero positive gradient, followed by a straight line B1 to C, having a zero gradient.

In some, but not necessarily all examples, line CV2 does not provide the lowest RMS acceleration of rotation if $Ca3$ is less than 1.1 or greater than two. Line CV1 does not provide the lowest RMS acceleration of rotation if $Ca3$ is less than two. Line CV0 does not provide the lowest RMS acceleration of rotation if $Ca3$ is less than zero or greater than four. Lower RMS acceleration of rotation is linked with lower RMS energy consumption.

30

In some, but not necessarily all examples, point B2 is fixed along the crank rotation axis at 50% of the crank rotation from A to C. Point B1 is fixed along the crank rotation axis at $2(S - R/Ca(C))$ where $Ca(C)$ is Ca at point C, S is the crank rotation during the park-to-open phase ($\theta_{C,O} - \theta_{C,A}$), and R is the rotor rotation during the park-to-open phase ($\theta_{R,O} - \theta_{R,A}$).

5

In some, but not necessarily all examples, the average Ca calculated from the area under the curve of the chosen line CV0, CV1 or CV2 must be equal to $Ca3$.

10

Regarding points G and H, in some, but not necessarily all examples, the value of Ca at point H differs from the required value of Ca at point G (departure Ca at point G). For example, the value of Ca at point H may be zero, because the rotor is not rotating at all (it is 'parked'). It will therefore be necessary to schedule Ca from point G to point H (referred to herein as a 'close-to-park' phase). The value of Ca at points G and/or H represent constraints in the schedule. The required average angular velocity coefficient $Ca4$ between points G and H is:

15

$$Ca4 \text{ (close-to-park phase)} = (\theta_{R,C} - \theta_{R,H}) / (\theta_{C,O} - \theta_{C,H})$$

20

The most efficient Ca schedule for the close-to-park phase is the one of the following lines that results in the lowest overall RMS acceleration of rotation of the rotatable camshaft 404 for the close-to-park phase:

25

CV3. A straight line from G to a point between G and H (e.g. 50% of the crank rotation from G to H along the crank rotation axis), having a constant non-zero first gradient, followed by a straight line from that point to H, having a constant different non-zero second gradient. Optionally, the first gradient and the second gradient are of opposite signs;

CV4. A straight line starting at G, having a constant non-zero negative gradient (or a positive gradient if $Ca2 < 0$) and extending to H, or to a point between G and H (i.e. followed by a pause phase to H of zero Ca); or

30

CV5. A straight line from G to a point between G and H (e.g. to a point along the crank rotation axis at $2(S - R/Ca(G))$ where $Ca(G)$ is Ca at point G, S is the crank rotation during the close-to-park phase ($\theta_{C,H} - \theta_{C,G}$), and R is the rotor rotation during the close-to-park phase ($\theta_{R,H} - \theta_{R,G}$) having a zero gradient, followed by a straight line from that point to H, having a constant negative gradient (or a positive gradient if $Ca2 < 0$).

35

In some, but not necessarily all examples, line CV5 does not provide the lowest RMS acceleration of rotation if the absolute value of $Ca4$ is less than 1.1 or greater than two. Line CV4 does not provide the lowest RMS acceleration of rotation if the absolute value of $Ca4$ is less than two. Line CV3 does not provide the lowest RMS acceleration of rotation if the absolute value of $Ca4$ is less than zero or greater than four.

In some, but not necessarily all examples, the average Ca calculated from the area under the curve of the chosen line CV3, CV4 or CV5 must be equal to $Ca4$.

In some, but not necessarily all examples the cessation of rotation of the camshaft 404 is scheduled so that the camshaft ceases rotation at one of a plurality of distinct angular positions of the camshaft 404 known based on the detent locations of the electromagnetic valve actuator. Those positions may for example be pre-determined based on a known distribution of stator slots of the electromagnetic valve actuator 400.

The preceding description has provided a process for scheduling Ca from points A to H only. Ca at point H could define Ca at point A of a next schedule for a next valve lift event. In some, but not necessarily all examples, the scheduling can continue for a plurality of successive valve lift events. This can allow energy consumption to be further optimised. For example, the scheduling 'between valve lift events' (the 'close-to-park' phase following the present valve lift event and the adjoining 'park-to-open' phase for the next valve lift event) can be modified to account for the requirements of the next valve lift event, which may be different.

The different requirements, or 'characteristics', of each valve lift event may relate to a different peak valve lift and/or a different rate of valve lifting, for example. In a non-limiting use case, if Ca at point C of the next valve lift event needs to be significantly faster than Ca at point C of the prior valve lift event, the camshaft 404 may need to start accelerating before point H of the prior valve lift event, for good efficiency.

Examples of possible modifications to account for different valve lift requirements are discussed below.

For example, it may be more energy efficient to allow Ca at point H to be non-zero, so that the rotor is not parked at point H. In this example the value of Ca at point H and/or at point A is not constrained to zero, so there is effectively no 'park' constraint.

If there is no park constraint, the camshaft 404 could rotate continuously throughout the entire period between valve lift events ('continuous rotation'). The process may determine whether to schedule park or continuous rotation based on which has the lowest RMS energy consumption. Continuous constant-acceleration rotation without parking may result in lower RMS energy consumption if the most efficient 'close-to-park' phase temporally overlaps the most efficient 'park-to-open' phase.

It would be appreciated that the circumferential length of the camshaft's base circle (e.g. 180 degrees) should not be exceeded between valve lift events, to avoid unintentional valve opening. The area under the curve of the Ca graph for continuous rotation corresponds to distance travelled in terms of the angular displacement of the camshaft 404. However, if a straight line of Ca is simply scheduled from point G of a valve lift event to the next point C of the next valve lift event, the angular displacement of the camshaft 404 may exceed (>180 degrees) the circumferential length of the base circle, causing unintentionally premature valve opening.

Therefore, it may be desirable instead of scheduling continuous constant-acceleration rotations between valve lift events to schedule at least one 'knee point', i.e. a change point in the acceleration of the camshaft relative to the crankshaft, at some point between the valve lift events. The knee point may in some examples cause a reversal in the direction of rotation of the camshaft. The knee point may have a positive or a negative Ca, where negative Ca refers to a reversal of rotation of the camshaft.

Fig 8 illustrates an example of a schedule between two valve lift events, i.e. from point G of a first valve lift event to point A of the next valve lift event. Fig 8 illustrates a knee point at location I, having negative Ca.

In the event where the knee point has a negative Ca, the camshaft will rotate backwards for at least some of the time between valve lift events. It is important to prevent the camshaft 404 from rotating backwards further than it has rotated forwards since point G, otherwise an unintentional backwards re-opening of the valve 440 will occur between valve lift events.

It is also important to prevent the camshaft 404 from rotating forwards too far before it rotates backwards. Otherwise an unintentional valve lift will occur.

The knee point Ca value and timing could be controlled to ensure that the total rotation between valve lift events does not exceed the camshaft's base circle, thereby avoiding premature valve opening.

5

A knee point could be temporally biased towards the previous valve lift event (towards point G), or towards the next valve lift event (towards point C), and not necessarily be fixed halfway in-between. Enabling some biasing of the timing of the knee point without necessarily constraining the Ca value of the knee point can provide a good compromise between efficiency and the need to avoid unintentional valve opening. In Fig 8, the knee point I is biased towards the first valve lift event, i.e. closer to point G of the preceding valve lift event than to point A of the next valve lift event.

10

In some examples, the process may enable only finite acceleration in the transition between valve lift events, i.e. no step changes permitted between valve events. This is particularly useful in the transition period between neighboring valve lift events having different characteristics. It might be said that in this transition period the system is switching from one valve lift 'mode' to another, e.g. between high lift mode and low lift mode; between early valve opening and late valve opening; between early valve closing and late valve closing; between single valve opening and double valve opening (two openings in one combustion cycle); or between different modes of skew (duration of opening phase relative to duration of closing phase). Step changes of Ca are avoided in the mode transition process, to reduce energy consumption and improve reliability. Therefore, it would be understood that a process according to various, but not necessarily all aspects of the present disclosure comprises:

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scheduling a first valve lift event having a first characteristic, for a first combustion cycle associated with the valve 440;

25

scheduling a second valve lift event having a second different characteristic, for a (the next) second combustion cycle associated with the valve 440; and

in the transition between the first valve lift event and the second valve lift event, commanding the electromagnetic valve actuator 400 to accelerate rotation of its rotatable camshaft 404 to the rotational speed required for enabling the second valve lift characteristic, using only finite acceleration.

30

Once the scheduling is complete using an efficient scheduling algorithm, the schedule is processed into a control signal format that is capable of directly or indirectly commanding the

35

electromagnetic valve actuator 400 to perform the scheduled valve lift event or events. The controller 200 transmits the control signal, for commanding the electromagnetic valve actuator 400 in the manner described above.

- 5 In some, but not necessarily all examples the controller is configured to convert, in real time, the schedule from C_a to absolute angular velocity in the process of determining a particular driving electric current for the electromagnetic valve actuator. The conversion comprises multiplying C_a by real-time crankshaft speed measured by a crankshaft position sensor or the like. This ensures that implementation of the schedule adapts on the fly to allow for changes
10 in engine speed.

The conversion may be executed at high frequency, for example in 0.5 millisecond increments or faster, such as 0.2 millisecond or 0.1 millisecond increments, depending on the capability of the processor.

- 15 Although embodiments of the present invention have been described in the preceding paragraphs with reference to various examples, it should be appreciated that modifications to the examples given can be made without departing from the scope of the invention as claimed. For example, although rotor angular velocity has been expressed as a dimensionless coefficient C_a , equivalent scheduling approaches based on real rotor angular velocity
20 (dimensions: rad/s or m/s) and a real time domain (dimensions: s) are possible.

Further, although one valve lift event has been scheduled between $\theta_{C,A}$ and $\theta_{C,H}$, in other examples multiple valve lift events can be scheduled between $\theta_{C,A}$ and $\theta_{C,H}$.

- 25 Features described in the preceding description may be used in combinations other than the combinations explicitly described.

- Although functions have been described with reference to certain features, those functions
30 may be performable by other features whether described or not.

Although features have been described with reference to certain embodiments, those features may also be present in other embodiments whether described or not.

Whilst endeavoring in the foregoing specification to draw attention to those features of the invention believed to be of particular importance it should be understood that the Applicant claims protection in respect of any patentable feature or combination of features hereinbefore referred to and/or shown in the drawings whether or not particular emphasis has been placed thereon.

5

CLAIMS

1. A method of controlling an electromagnetic valve actuator having a rotatable camshaft for actuating a valve of an engine, the method comprising:

5 scheduling a valve lift event comprising an opening phase ($\theta_{C,O}$ to $\theta_{C,MOP}$) from zero valve lift to a peak valve lift, and a closing phase ($\theta_{C,MOP}$ to $\theta_{C,C}$) from peak valve lift to zero valve lift;

commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft at constant or variable acceleration during at least one or more of:

10 the opening phase;

the closing phase;

a portion of the opening phase as well as a portion of the closing phase; and

commanding the electromagnetic valve actuator to cease rotation or reverse a direction of rotation of its rotatable camshaft after the closing phase and before the commencement of the next valve lift event associated with the valve.

2. A method as claimed in any preceding claim, wherein the commanded acceleration of the rotatable camshaft is constant during at least one or more of:

the opening phase;

20 the closing phase;

a portion of the opening phase as well as a portion of the closing phase.

3. A method as claimed in any preceding claim, wherein the commanded acceleration of the rotatable camshaft is non-zero throughout one or more of:

25 the entire opening phase;

the entire closing phase.

4. A method as claimed in any preceding claim, comprising:

scheduling rotation of the rotatable camshaft in advance of the opening phase into an operating position for lifting the valve at the start of the opening phase; and

30 commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft at constant acceleration during the scheduled rotation.

5. A method as claimed in claim 4, comprising:

commanding the electromagnetic valve actuator to cause, during the scheduled rotation in advance of the opening phase, the one of the following rotation behaviours of the rotatable camshaft that results in the lowest overall root-mean-square acceleration of rotation of the rotatable camshaft in performing the scheduled rotation:

- 5 constant acceleration of rotation;
 constant acceleration of rotation preceded by or followed by constant velocity of rotation; or
 constant non-zero acceleration of rotation followed by constant different non-zero acceleration of rotation.

10

6. A method as claimed in any preceding claim, comprising:

 commanding the electromagnetic valve actuator to cease rotation of its rotatable camshaft after the closing phase before the commencement of the next valve lift event associated with the valve.

15

7. A method as claimed in claim 6, wherein the cessation of rotation is scheduled so that the rotatable camshaft ceases rotation at one of a plurality of distinct angular positions dependent on detent locations of the electromagnetic valve actuator.

20

8. A method as claimed in any preceding claim, comprising:

 commanding the electromagnetic valve actuator to change the acceleration of rotation of its rotatable camshaft after the closing phase of the valve lift event or another valve lift event and before the commencement of the next valve lift event associated with the valve, comprising biasing the timing of the change in acceleration to prevent unintentional valve lift after the closing phase and before the commencement of a next valve lift event.

25

9. A method as claimed in any preceding claim, comprising:

 commanding the electromagnetic valve actuator to cause, during a scheduled rotation from the end of the closing phase of the valve lift event to the beginning of a next opening phase of a next valve lift event, the one of the following rotation behaviours of the rotatable camshaft that results in the lowest overall root-mean-square acceleration of rotation of the rotatable camshaft in performing the scheduled rotation:

30

- cessation of rotation of the rotatable camshaft;
 a change in the acceleration of the rotatable camshaft; or
35 continuous constant-acceleration rotation of the rotatable camshaft.

10. A method as claimed in any preceding claim, comprising:

scheduling rotation of the rotatable camshaft after the closing phase in advance of a next valve lift event; and

5 commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft at constant acceleration during the scheduled rotation.

11. A method as claimed in claim 10, comprising:

10 commanding the electromagnetic valve actuator to cause, during the scheduled rotation, the one of the following rotation behaviours of the rotatable camshaft that results in the lowest overall root-mean-square acceleration of rotation of the rotatable camshaft in performing the scheduled rotation:

constant acceleration of rotation;

constant velocity of rotation followed by constant acceleration of rotation; or

15 constant non-zero acceleration of rotation followed by constant different non-zero acceleration of rotation.

12. A method as claimed in any preceding claim, comprising:

20 commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft at constant acceleration throughout one or more of:

the entire opening phase;

the entire closing phase;

the entire opening phase as well as the entire closing phase.

25 13. A method as claimed in any preceding claim, comprising:

commanding the electromagnetic valve actuator to reverse a direction of rotation of its rotatable camshaft, changing the angular velocity of the rotatable camshaft from a positive value during the opening phase to a negative value during the closing phase.

30 14. A method as claimed in any preceding claim, comprising:

receiving target inputs indicative of a start timing for the valve lift event, a duration of the valve lift event, a timing of the peak lift, and optionally a lift amount of the valve at peak lift, and wherein the scheduling of the valve lift event is dependent upon the target inputs.

15. A method of controlling an electromagnetic valve actuator having an actuating element for actuating a valve of an engine, the method comprising:

scheduling a valve lift event comprising an opening phase ($\theta_{C,O}$ to $\theta_{C,MOP}$) from zero valve lift to a peak valve lift, and a closing phase ($\theta_{C,MOP}$ to $\theta_{C,C}$) from peak valve lift to zero valve lift; and

commanding the electromagnetic valve actuator to accelerate its actuating element at constant or variable acceleration during one or more of:

the opening phase;

the closing phase;

a portion of the opening phase as well as a portion of the closing phase; and

commanding the electromagnetic valve actuator to cease rotation or reverse a direction of rotation of its rotatable camshaft after the closing phase and before the commencement of the next valve lift event associated with the valve.

16. A method as claimed in any preceding claim, wherein constant acceleration is a constant rate of change of angular velocity of the camshaft ($\Delta\theta_R$), over a time interval in a time domain defined by rotation of an engine crankshaft.

17. A method of controlling an electromagnetic valve actuator having a rotatable camshaft for actuating a valve of an engine, the method comprising:

scheduling a first valve lift event having a first characteristic, for a first combustion cycle associated with the valve;

scheduling a second valve lift event having a second different characteristic, for a second combustion cycle associated with the valve; and

in the transition between the first valve lift event and the second valve lift event, commanding the electromagnetic valve actuator to accelerate rotation of its rotatable camshaft to the rotational speed required for enabling the second valve lift characteristic, using only finite acceleration.

18. A method as claimed in claim 17, wherein the second characteristic corresponds to a different peak valve lift and/or a different rate of valve lifting, compared to the first characteristic.

19. A method as claimed in claim 17 or 18, wherein the first valve lift event comprises a valve opening phase and a valve closing phase, wherein the first characteristic is associated with a

first rotational speed of the rotatable camshaft at the beginning of the valve opening phase of the first valve lift event, and

wherein the second valve lift event comprises a valve opening phase and a valve closing phase, wherein the second characteristic is associated with a second different rotational speed of the rotatable camshaft, at the beginning of the valve opening phase of the second valve lift event.

20. A controller comprising means for performing the method as claimed in any one of claims 1 to 19.

21. A system comprising:

the controller of claim 20; and

a desmodromic electromagnetic valve actuator controlled by the controller.

22. An engine comprising the controller of claim 20 or the system of claim 21.

23. A vehicle comprising the controller of claim 20 or the system of claim 21 or the engine of claim 22.

24. A computer program comprising instructions that, when executed by one or more processors, cause a controller to perform at least the method of any one of claims 1 to 19.

25. A method, a controller, a system, an engine, a vehicle or a computer program as hereinbefore described with reference to the accompanying drawings.

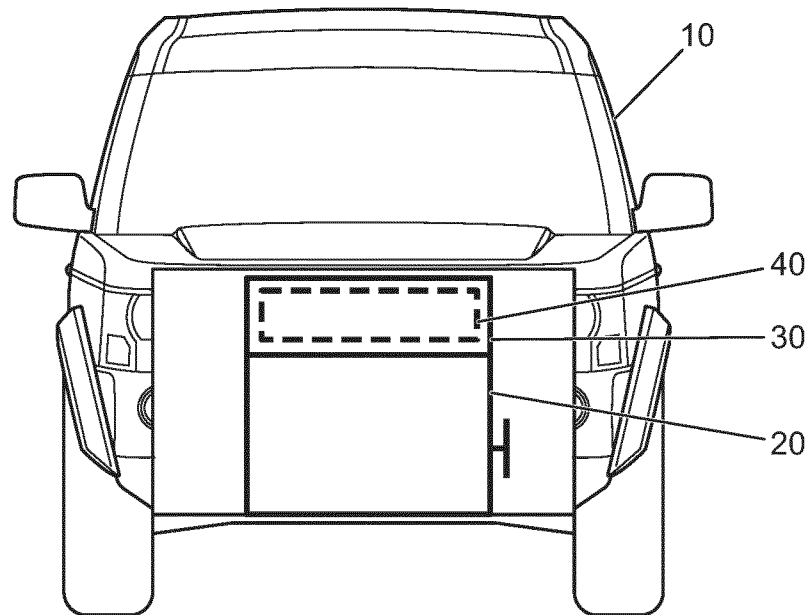


Fig 1

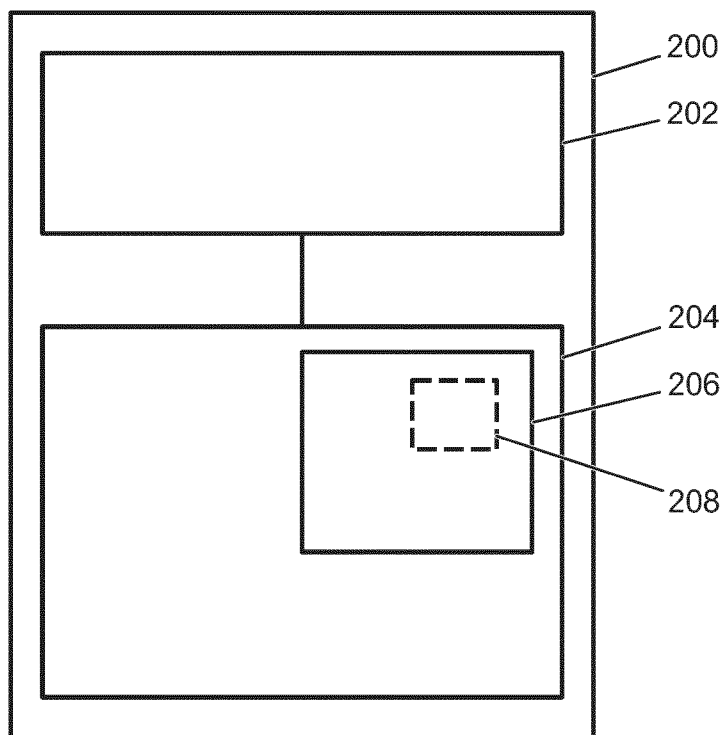


Fig 2

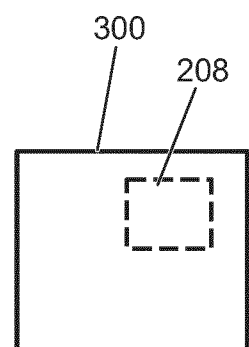
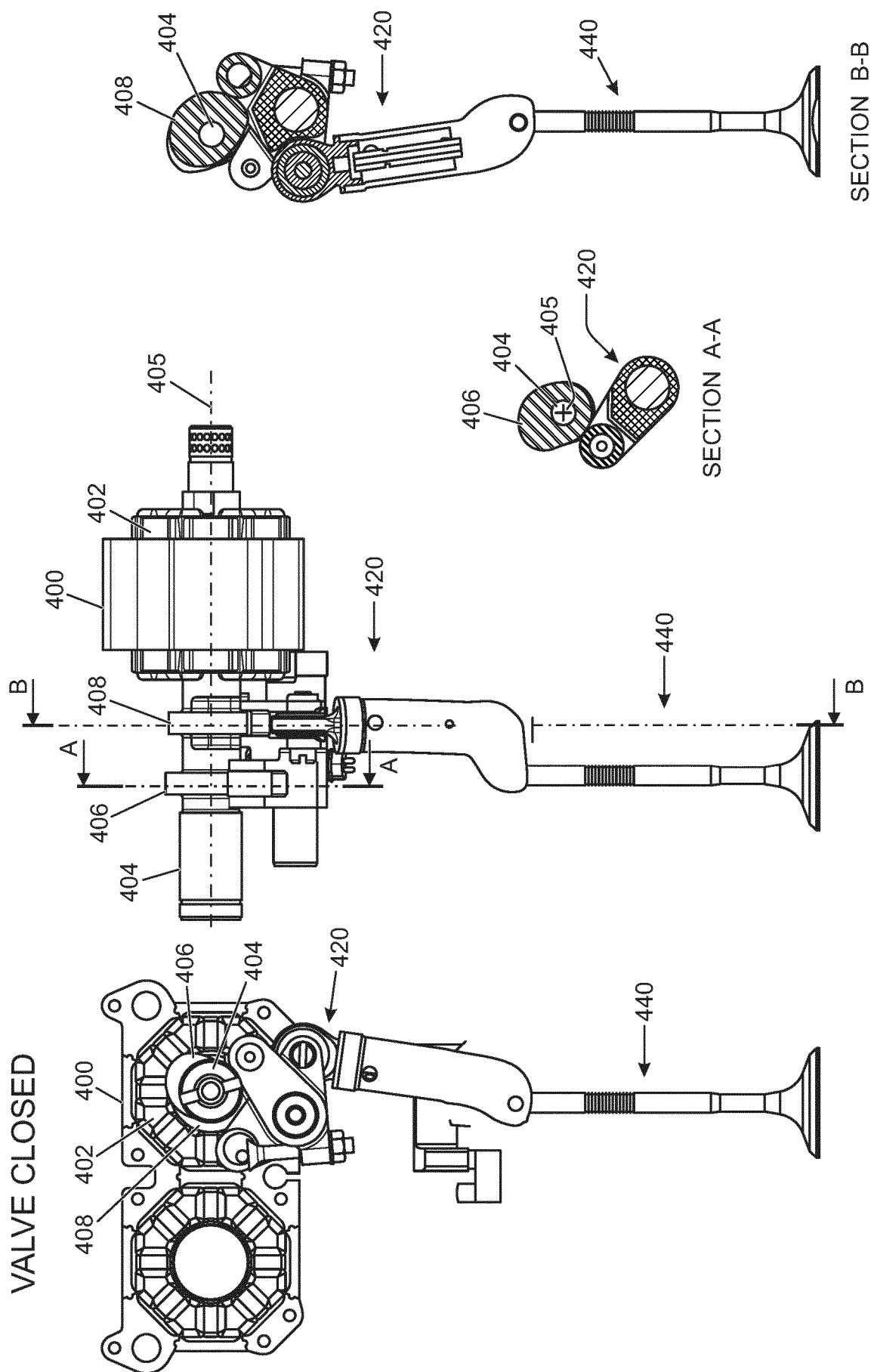


Fig 3

2/6



3/6

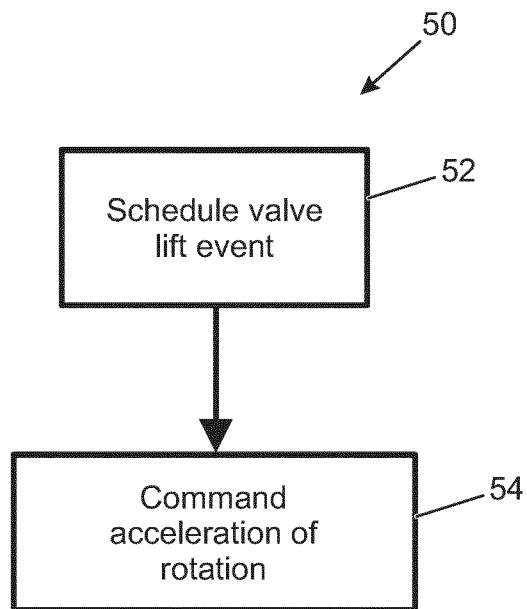


Fig 5

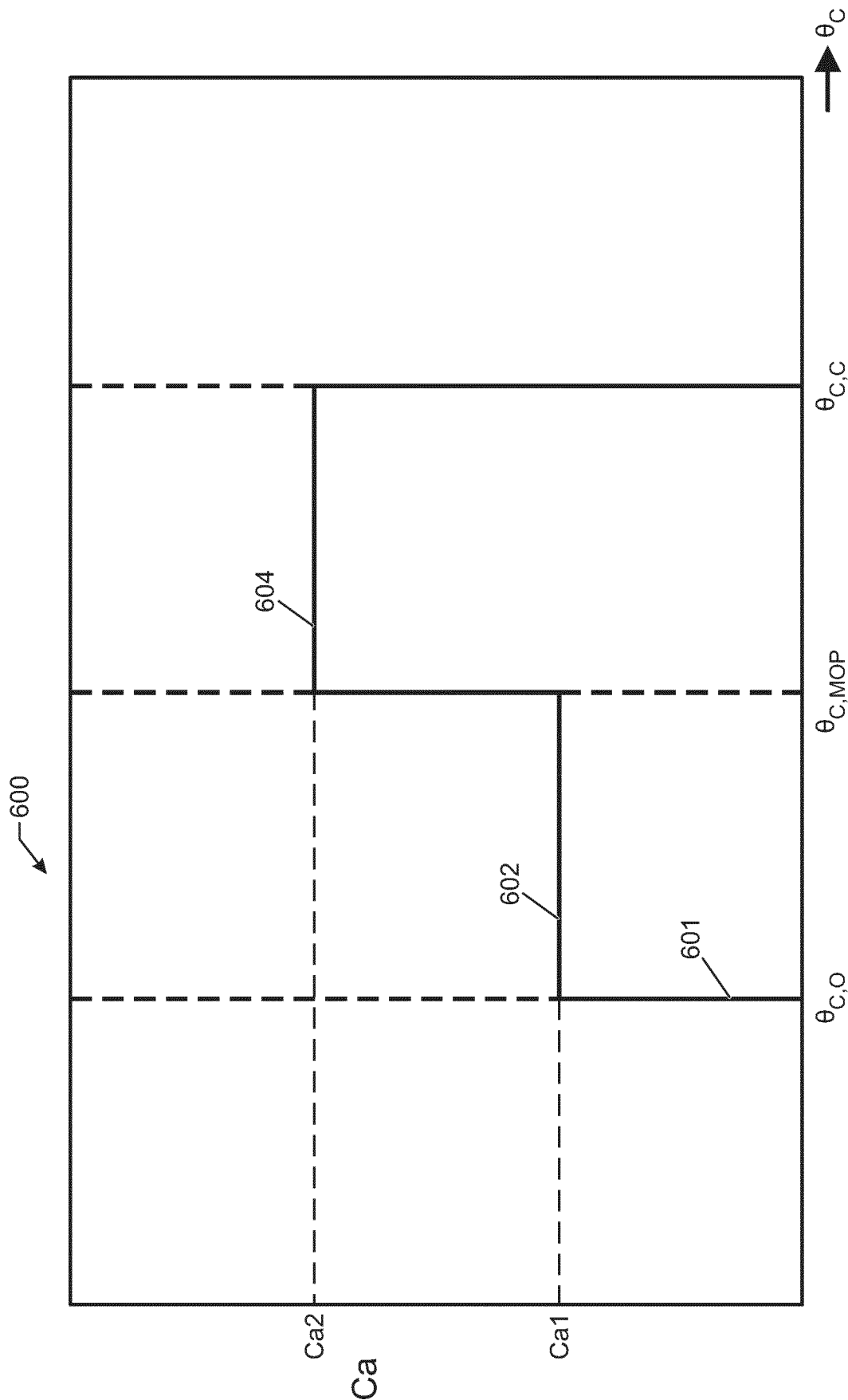


Fig 6

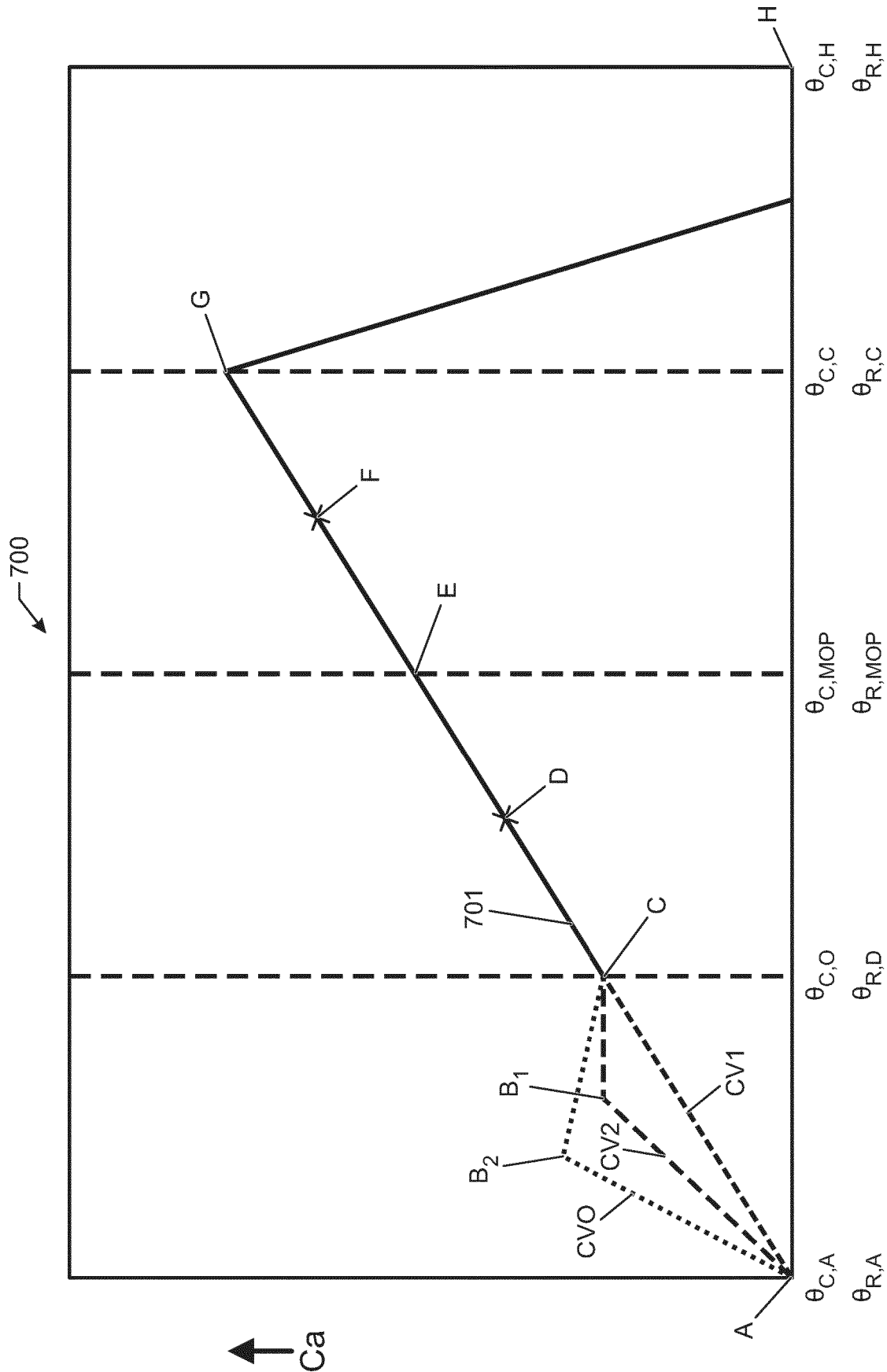


Fig 7

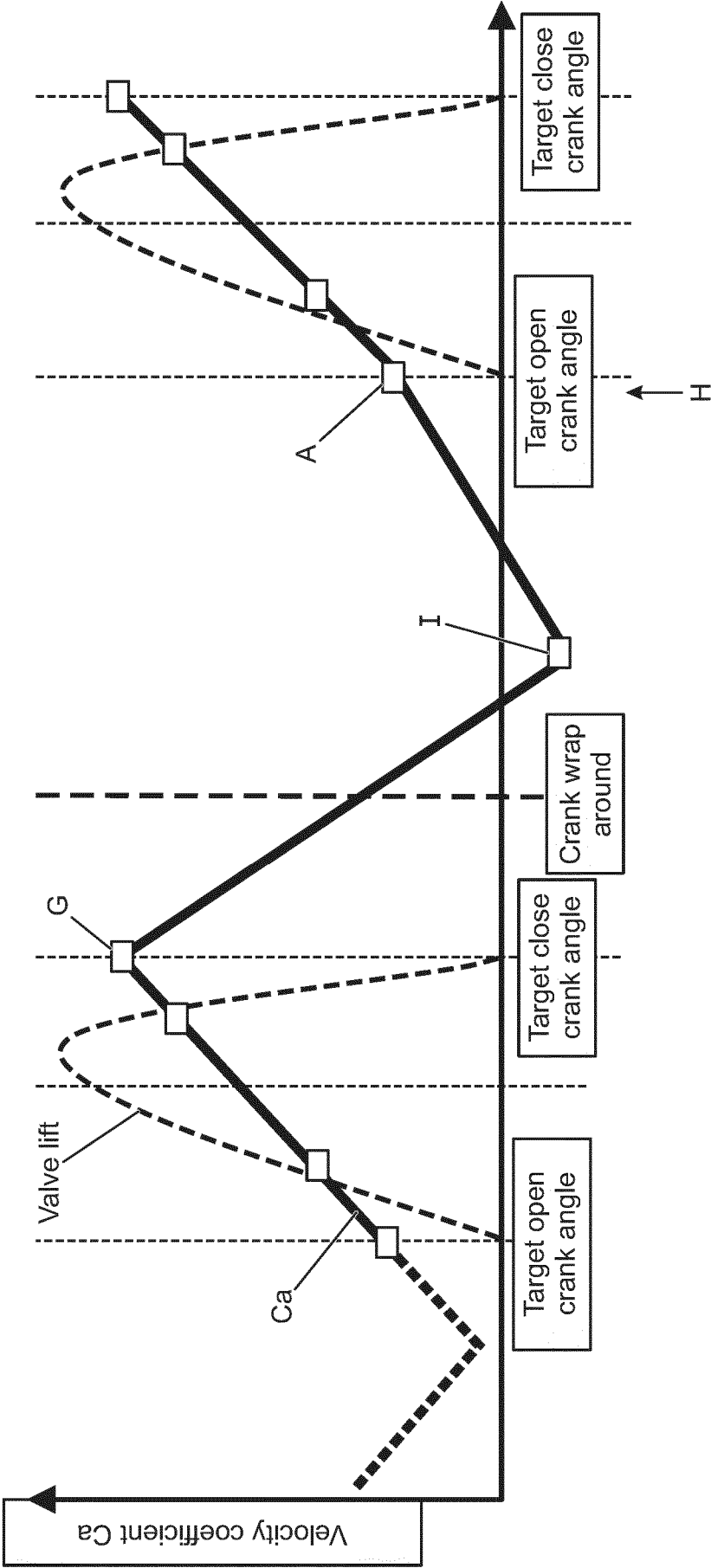


Fig 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/074239

A. CLASSIFICATION OF SUBJECT MATTER
INV. F01L9/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2007/068473 A1 (KUSAKA YASUSHI [JP] ET AL) 29 March 2007 (2007-03-29) paragraph [0001] paragraph [0056] - paragraph [0057] paragraph [0070] figures 1-7,13-19 -----	1,2,6, 10,14-20 21-25
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Further documents are listed in the continuation of Box C.



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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/074239

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A	EP 0 603 929 A1 (GEN MOTORS CORP [US]) 29 June 1994 (1994-06-29) column 5, line 2 - column 6, line 53 figures	1,15
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