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A TRANSIENT HYDROSTATIC DYNAMOMETER FOR SINGLE CYLINDER ENGINE RESEARCH

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Abstract: A new high-bandwidth transient dynamometer has been designed and is being built for application to a single-cylinder research engine. The goal of this system is to accurately reproduce all of the dynamic, instantaneous torques that this single-cylinder would experience if it were in a multi-cylinder engine. This is accomplished by calculating these instantaneous torques in real time using a detailed dynamic model of the engine, and applying them by means of a unique high-bandwidth transient dynamometer system. This hardware-in-the-loop system would both extend the operational envelope far beyond what is possible with current hardware, and would now allow the single-cylinder engine to replicate the rapid transients that are experienced in multi-cylinder operation. This may well open up many new areas of research in the transient operational regime, while maintaining the open accessibility and attractive attributes of the single-cylinder engine. *Copyright © 2002 IFAC*

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1. INTRODUCTION

An important tool that has been used for many years in the internal combustion engine's engineering and development has been the single-cylinder test engine. This is typically a single cylinder, piston and head from what will eventually become a multi-cylinder engine. The single-cylinder engine is very important in research and development because it allows considerable access to the combustion chamber for instrumentation. By isolating one cylinder it is much easier to view the physical processes within that cylinder. By contrast, it would be very difficult to apply many of the modern laser diagnostics and other instrumentation typically used on these engines.

Along with these benefits come many drawbacks that limit both the operation as well as how representative the single-cylinder operation is with respect to the multi-cylinder engine. The most important drawback is the difficulty in doing representative low engine speed testing. Because there is only one cylinder to provide kinetic energy to the rotational elements, and with a 4-stroke engine this energy is only provided once every two revolutions, it is difficult to simulate multi-cylinder operation at low speeds. Typically a large flywheel is added to the single-cylinder crankshaft, and often these engines are coupled to dynamometers with very large polar moment of inertias. This prevents the engine speed from decreasing significantly between cylinder firings, but also prevents replicating the rotational dynamics that the cylinder would experience in a multi-cylinder engine. Because engine engineers and researchers would usually like the single-cylinder engine's operation to replicate what would be expected in the multi-cylinder engine, these drawbacks can cause many problems or possibly limit the utility of the information gleaned from the single-cylinder.

The authors have designed and are developing a new dynamometer that would address many of these current problems. The goal of this single-cylinder dynamometer is to replicate the instantaneous dynamics that this engine would experience if it were in a multi-cylinder engine. This is accomplished by:

1. Calculating in real time all of the dynamic torques that would be delivered to the single-cylinder by way of the crankshaft if it were actually in a multi-cylinder engine, and

2. Applying all of these torques to the single-cylinder engine by means of a very high bandwidth transient dynamometer system.

This type of application is known as a hardware-in-the-loop or HIL system, and is an extremely challenging application because of the large and quickly changing motoring torques that need to be produced. Part of the target multi-cylinder engine is in hardware (e.g., the single-cylinder and part of the crankshaft and connecting rod) and part of the target engine is in software (e.g., the remaining cylinders as well as crankshaft and other ancillary hardware that would normally effect multi-cylinder dynamics). The dynamometer provides the virtual loading from this second part thus replicating the dynamic loading that would be experienced in the multi-cylinder engine.

The embodiment of this dynamometer concept is composed of electro-hydraulic devices because of the expertise that has been developed in the Powertrain Control Research Laboratory (PCRL) at the University of Wisconsin. However, the requirements and the design of this system is very different from previous high-bandwidth dynamometer that have been developed because of the large high-bandwidth motoring requirements.

If the actual hardware is able to meet the design goals and the performance simulated by this dynamic model, then three important accomplishments will be achieved.

1. The instantaneous crankshaft speed throughout the engine cycle will be identical to that which would occur in a multi-cylinder engine,

2. Very low engine speed operation would be possible with this single-cylinder system, and

3. Transient operation would now be possible with the single-cylinder engine.

The HIL concept could also be extended if desired, and a dynamic powertrain model could be added to the software so that any effects from the overall vehicle powertrain system could now be replicated with this dynamometer. Because transient operation across the engine's speed range can now be produced on a single-cylinder engine, this may well open up new areas of research in exploring the combustion and flow physics during these transients. Currently limited fuel or spark transients can be produced on single-cylinder test set-ups, but rapid speed transient such as those in a vehicle application are not possible because of the large dynamometer inertias and low-bandwidth dynamometer control systems. One very interesting area would be to examine the effect of cylinder operation during cylinder cut-out or engine restart. This operation can be easily simulated in the HIL software of the proposed system, and this operation is getting increased interest in new and future vehicles to decrease fuel consumption in both conventional and hybrid vehicles.

Patents are being sought for the general concept as well as the proposed system design. These would be joint patents held by the Wisconsin Alumni Research Foundation (WARF) at the University of Wisconsin and General Motors (sponsors of this research). The patent titled ”Internal Combustion Engine Simulation and Testing” was submitted to the USPTO in February 2002.

2. DETAILS OF THE SINGLE-CYLINDER TRANSIENT TEST SYSTEM

Dorey and Wang (1989) explored the potential for a hydrostatic dynamometer. Additional development in the Powertrain Control Research Lab at the University of Wisconsin – Madison (Babbitt and Moskwa, 1999) lead to a refined transient hydrostatic dynamometer with many unique test capabilities. The new dynamometer is based on these technologies but is unique in that it not only can rapidly change the magnitude of the applied torque to the engine, it can change the torque direction. This allows the dynamometer to switch between absorbing and motoring torque several times during each four-stroke combustion cycle of the engine.

2.1 Dynamometer Hydraulics

The dynamometer consists of a hydraulic motor and a hydraulic pump for generating motoring and absorbing torque, respectively. Figure 1 shows the layout for the hydraulic circuit.

To minimize energy loss and reduce the hydraulic supply power requirement, especially in the absorbing mode when no motoring torque is required, a bypass loop was added to the motor circuit. The bypass loop is basically a check valve between the inlet and outlet ports of the motor. It allows the servovalve on the motor outlet to be completely closed when motoring torque is not required. Since motoring torque is only required about 50 percent of the time, this feature reduces the power supply power requirement by about 50 percent.

Accumulators are used on the motor supply and return lines to allow constant fluid flow to/from the power supply during the momentary on/off cycling of the servovalve.

2.2 Dynamometer Driveline

As a baseline for comparison, a conventional electric dynamometer configuration is shown in Figure 2. The engine and dynamometer are each attached independently to a steel bedplate in the floor. The dynamometer is trunnion mounted with torque being measured by a load cell. The drive shaft has flexible couplings to compensate for misalignment and dampen vibration in the driveline. Dynamometers of this type typically have a resonance point at low speed, which often limits the low speed testing capability and inhibits good control of instantaneous torque to the test engine.

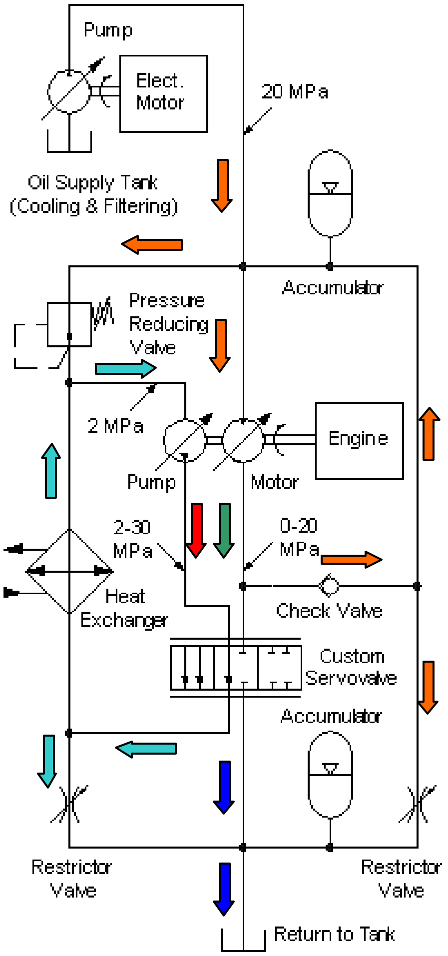

Figure 1: New single-cylinder transient dynamometer hydraulic circuit.

The new transient dynamometer is shown in Figure 3. It takes advantage of low inertia hydraulic components and a unique driveline that is very rigid to eliminate the resonant vibration problem. The resonant point for this system is well above the operating range of the engine.

A cutaway view of the driveline is shown in Figure 4. The driveline consists of three main components: a small flywheel, an in-line torque transducer, and a torsionally ridged coupling. The distance from the crankshaft to the dynamometer shaft is approximately fifteen centimeters.

Since this dynamometer is designed to test engines with very rapid torque reversals over a wide speed range, a special mounting system was utilized. Rather than attach the engine and dynamometer separately to the test cell bedplate, the pumps are attached to an aluminium pump mount, which in turn is attached to the engine. The pump mount acts as a torque reaction tube for the pumps. The mount improves alignment accuracy, increases stiffness, and provided protection from the rotating parts of the driveline.

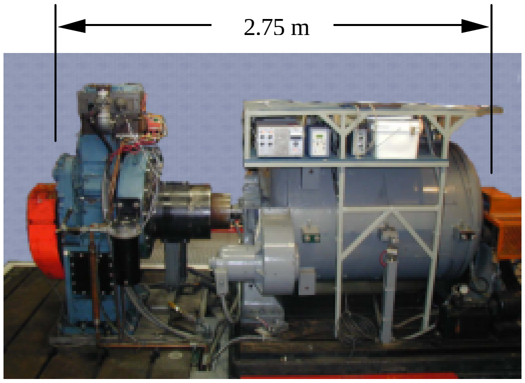

Figure 2: Conventional dynamometer set-up for testing a single-cylinder research engine.

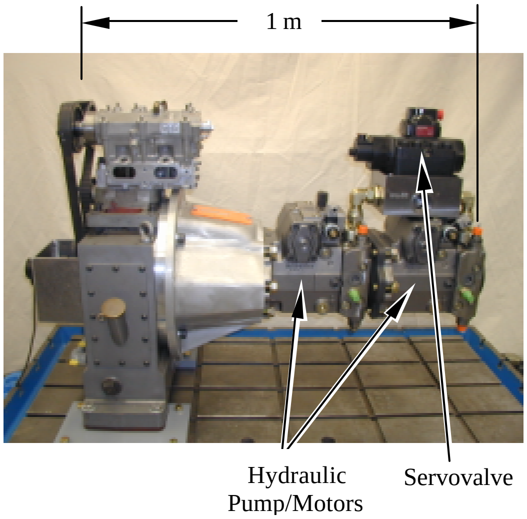

Figure 3: New transient single cylinder hydrostatic dynamometer.

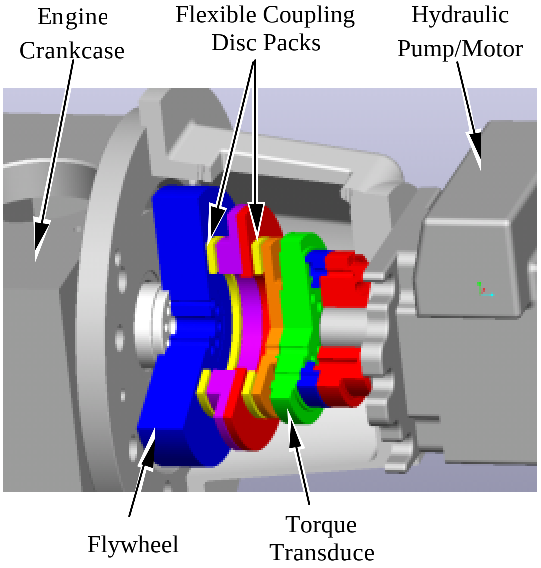

Figure 4: Transient single cylinder dynamometer driveline layout.

2.3 Integration Hardware and Software

The entire system, including the engine, is controlled with a rapid-prototyping control system from dSPACE. Block diagram control models are developed with MATLAB/Simulink software from the MathWorks. Software from dSPACE is then used to generate C code from the block diagrams and prepare the code for implementation with the dSPACE hardware.

All the instrumentation and data acquisition is accomplished with a personal computer running Control Desk software from dSPACE. The PC is linked to the dSPACE control hardware through an optical interface cable.

For added safety, a programmable logic controller is utilized to independently monitor and shut down the system if any of the sensors indicate operation outside the normal range.

3. SIMULATION MODELING

A MATLAB/Simulink model of the dynamometer was developed prior to building the system. The model was used to evaluate different components and to investigate the response characteristics.

The model contains four main parts: an inertia model used to evaluate engine/dynamometer speed and crankshaft position, an instantaneous engine torque model, a dynamometer control model, and a hydraulic system model. A description of each part of the model follows.

3.1 Inertia Model

Equation 1 was used as the basis for this analysis. It shows a relationship between torque and the engine/dynamometer acceleration. Since the single cylinder engine has a short crankshaft and the driveline is very rigid and short, all of the rotating parts were considered to be one rigid component. This eliminated the multiple degrees of freedom that would normally be required if a flexible driveline were used in the analysis.

$$J\ddot{q} + \frac{1}{2}\frac{\partial J}{\partial q}\dot{q}^{2} = \sum Torques \tag{1}$$

To further simplify the inertia model, the torque caused by the reciprocating mass was included in the engine torque model. Equation 1 was then simplified to the form shown by equation 2.

$$J\ddot{q} = T_{engine} + T_{dynamometer} \tag{2}$$

Here $T_{dynamometer}$ represents the torque from the dynamometer model while T_{engine} represents the torque from the engine model. The J term represents the rotating inertia of the hydraulic pumps, the driveline components, the engine crankshaft, and the rotating mass of the connecting rod based on a lumped mass model. The resulting block diagram for the system is shown in Figure 5.

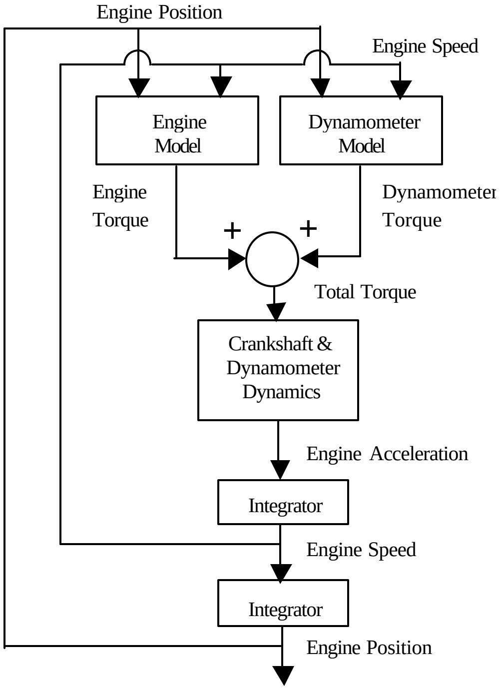

Figure 5: Block diagram model of engine and dynamometer interaction

3.2 Engine Torque Model

The engine torque model calculates the instantaneous wide-open throttle torque that is applied to the rotating components of the system by the engine. It is based on cylinder pressure and the reciprocating piston and connecting rod mass. The equations for combustion torque and inertia torque were developed using a force balance analysis similar to Mabie and Reinholtz (1987). Figure 6 shows the resulting torque for a single cylinder of a production 4.2L V-6 engine.

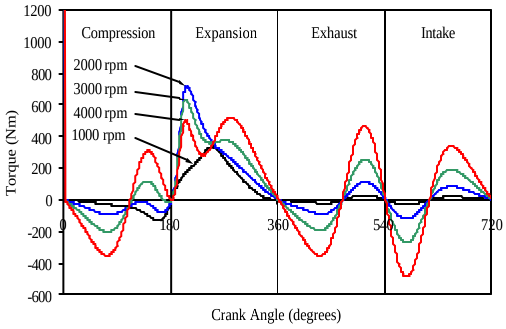

Figure 6: Total torque applied to the crankshaft by the piston and connecting rod assembly in a single-cylinder engine at wide-open throttle.

Since this model was intended for component selection, friction was not considered. Friction is much less significant and is affected by many factors. As the controls for the system are refined in the future, a friction model may be added.

In addition to predicting engine torque for the simulation, the engine torque model is also used to calculate the required dynamometer torque. As the controls for the dynamometer are developed the engine torque model will become an integral part of the control system.

3.3 Dynamometer Torque Model

Two models determine the torque generated by the dynamometer. First, the dynamometer model calculates the desired torque. Then the delivered torque is calculated based on hydraulic system response. The desired dynamometer torque is calculated as shown by the block diagram in Figure 7. The last block in the diagram calculates the delivered torque using the hydraulic system model.

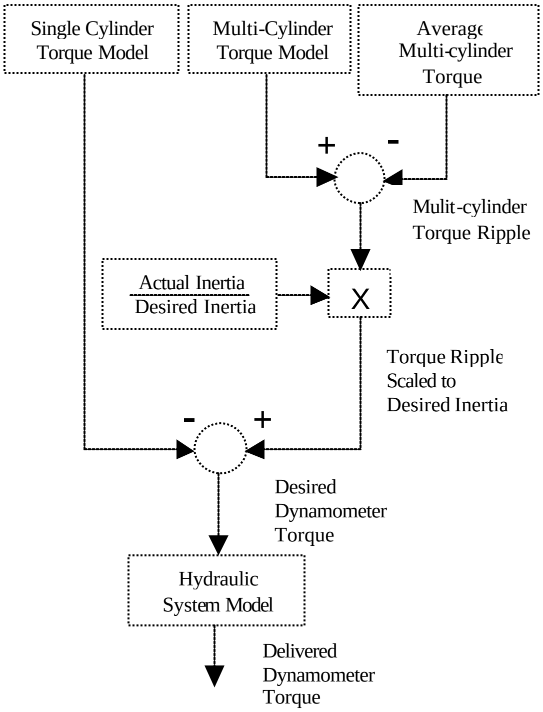

Figure 7: Block diagram model of dynamometer torque calculation

The desired torque is determined by first applying a torque equal in magnitude and opposite in direction to the torque generated by the engine. This results in no net torque being applied to the inertia of the system and the system tends to operate at a constant speed. To simulate operation of a multi-cylinder engine, torque ripple is then added to the torque signal. The magnitude of the torque ripple is adjusted to produce the desired speed fluctuation even thought the dynamometer may have inertia different from that of the system being simulated.

3.4 Hydraulic System Model

The hydraulic system model is designed to calculate the response of the dynamometer given a desired torque signal. First, the model determines the required servovalve position to achieve the desired torque and rate of torque change. The response of the servovalve is then evaluated using a second order transfer function as an approximation of valve response. The pressure of the oil between the pump/motor and servovalve is calculated based on fluid compressibility and flow rates in and out of the manifold. Finally, the dynamometer torque is evaluated using calculated pressures and pump/motor displacement.

4. SIMULATION RESULTS

An example of the speed variation that is seen in a typical six-cylinder engine is shown in Figure 8. The speed variation is principally the result of individual cylinder combustion events and inertia torque created by the slider-crank mechanism.

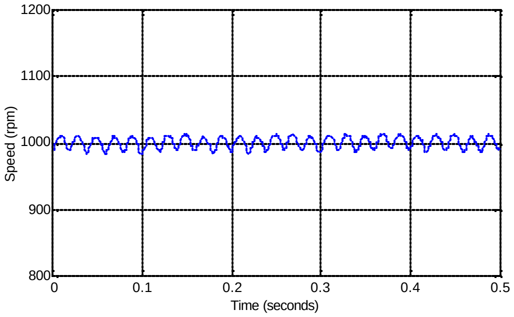

Figure 8: Speed trace of an actual six-cylinder engine.

Simulations were run to determine the effect of inertia, speed, hydraulic pump/motor size, and servovalve response time. Modifications to the model were also made to simulate operation of a conventional dynamometer control system, which applies a constant torque throughout the combustion cycle.

Figure 9 shows the variation in engine speed that occurs when a single cylinder engine is tested with a constant load torque. Changes in engine torque cause a corresponding change in engine speed. The resulting speed change is not at all representative of a multi-cylinder engine. This makes low speed testing of the engine very difficult and produces questionable data.

Figure 10 shows the result of a simulation with the new control strategy where six-cylinder torque ripple is being simulated. In this case the torque applied by the dynamometer is such that when the torque from the engine is added to it, the net torque is equal to the torque ripple from a multi-cylinder engine. This causes the single cylinder to react dynamically as if it were actually in a multi-cylinder engine.

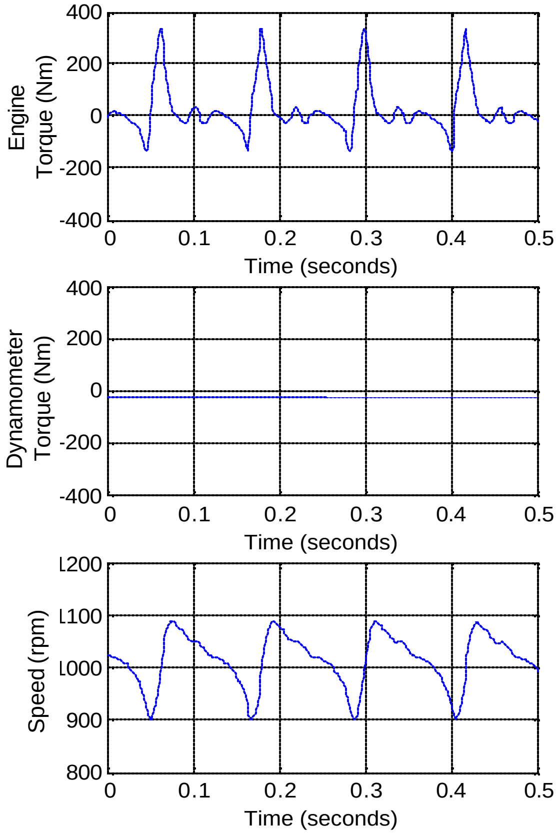

Figure 9: Simulation of a single-cylinder engine with constant dynamometer load.

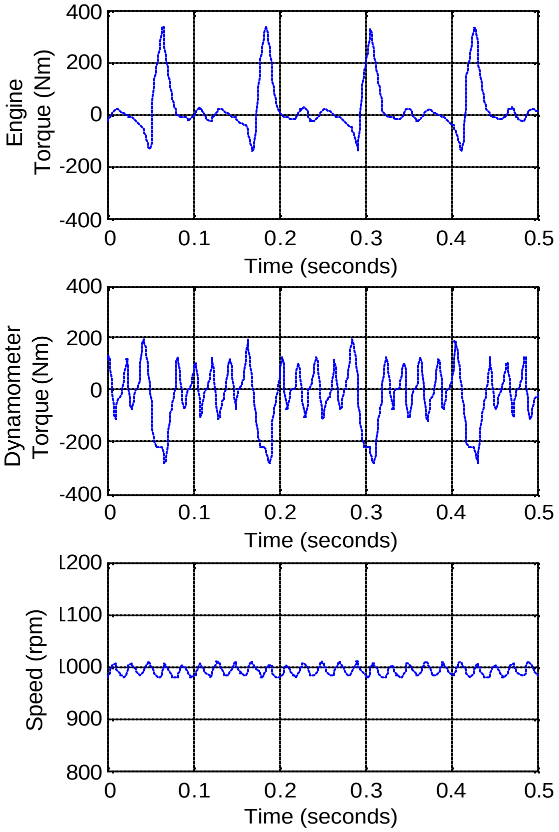

Figure 10: Simulation of a single-cylinder engine and dynamometer operating with a speed trajectory matching that of a multi-cylinder engine.

Simulation showed the control strategy to work very well at low speeds where it is most critical. As the engine speed approaches 3000 rpm the response time of the servovalve is not fast enough to accurately generate the torque rise that matches that of the combustion process. The bandwidth of the servovalve used in this simulation was 120 Hz, a very fast servovalve for the size required in this application.

In terms of reproducing the multi-cylinder speed trajectory the new dynamometer will perform best at low speeds where this operating mode is most beneficial. The elimination of flywheel inertia made possible by this design has the most significant benefit. It enables transient speed testing with a single cylinder engine.

5. CONCLUSIONS

The single-cylinder dynamometer system described here has stable low speed operation, is capable of simulating a multi-cylinder engine speed profile, and has transient test capability. The system improves test data accuracy by eliminating the large speed fluctuation that typically occurs with a single cylinder engine without using a large flywheel. This may well open up many new areas of research in the transient operational regime, while maintaining the open accessibility and attractive attributes of the single-cylinder engine.

6. ACKNOLEDGEMENTS

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