

An Advanced and Comprehensive CAE Approach of Piston Dynamics Studies for Piston Optimal and Robust Design

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ABSTRACT

A successful piston design requires eliminate the following failure modes: structure failure, skirt scuffing and piston unusual noise. It also needs to deliver least friction to improve engine fuel economy and performance. Traditional approach of using hardware tests to validate piston design is technically difficult, costly and time consuming. This paper presents an up-front CAE tool and an analytical process that can systematically address these issues in a timely and cost-effectively way.

This paper first describes this newly developed CAE process, the 3D virtual modeling and simulation tools used in Ford Motor Company, as well as the piston design factors and boundary conditions. Furthermore, following the definition of the piston design assessment criteria, several piston design studies and applications are discussed, which were used to eliminate skirt scuffing, reduce piston structure dynamic stresses, minimize skirt friction and piston slapping noise. A multi-objective optimal study on piston design is also presented in the end of this paper. In summary, the presented CAE process and tools can be used to identify piston failure modes and optimize piston design parameters so that the best design decisions can be made in early design stage to ensures a durable piston with lowest friction energy loss and sustainable radiate noise level.

INTRODUCTION

With increase of fuel price and the demand to reduce carbon dioxide (CO₂) emission from the governments world wide, the automotive industry is being asked by customers to provide more fuel efficient vehicles without any compromise of performance. To meet these requirements is great

challenging work. Direct injection (DI) and boost engine technologies give the combination of vehicle performance and fuel economy improvement through downsizing the engine displacement. As a result, the power density of modern engines continuously rises, and the power conversion system, which consists of piston, connecting rod, pin and cranktrain, is being pushed to the design limits. Designing a durable and reliable power conversion system with low friction energy loss becomes a key task to meet the requirements.

It is well known that the piston, a critical component of engine power conversion system, works mostly under the conditions of high combustion pressure, high temperature and various high loads (thermal and inertial). In addition, the piston material properties can significantly change with the temperature variation in different engine operations. All of these create a lot of durability concerns such as piston dome fracture, skirt cracking and scuffing. On the other hand, if the piston is not designed well, the piston might be rattling and slapping due to the piston secondary motion when engine is running at cold condition with a light load. A successful piston design not only requires the elimination of these failure modes, but also needs to deliver least friction to improve the engine fuel economy and performance as well.

For more than two decades, various piston computational models have been developed in the world to study piston's dynamic behavior by automotive OEMs, engine manufactures, piston suppliers, engineering consulting companies and universities. Many of them studied the effect of piston structure and design parameters on lubrication and friction; some of them studied piston radiate noise or piston slapping and rattling. A few of them were reported to investigate the piston skirt scuffing, top and ring land contact

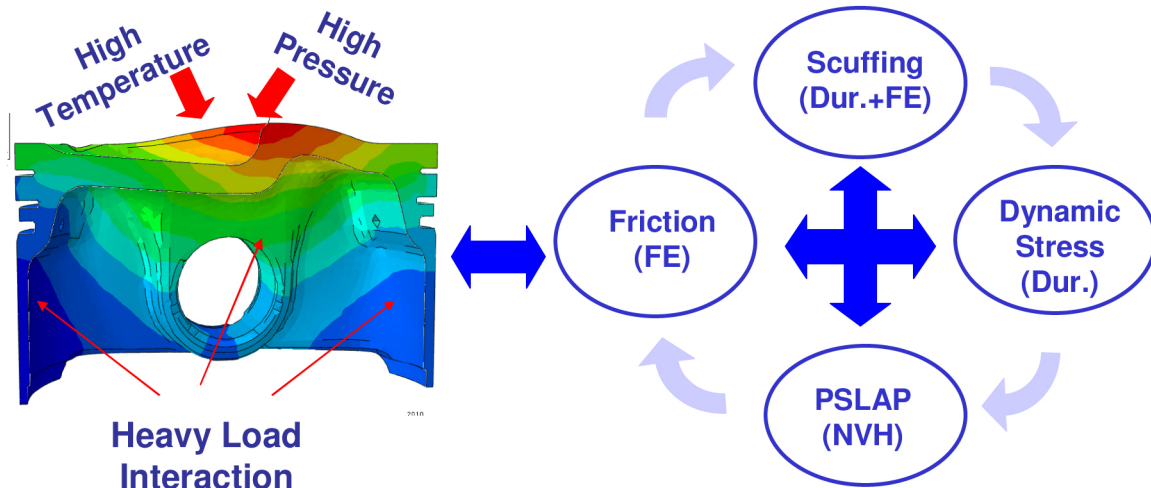


Figure 1. The Piston Design Issues and Interaction

issues [1], [2], [3], [4], [5] and [6], etc.. Historically, independent and incompatible piston solutions that have been identified to solve each of these failure modes separately, and the actions that were taken to counteract one of the problems might cause another issue. As shown in Figure 1, these issues interact with each other and a trade-off design must be found for piston design. Due to the limited capability of analytical process and the lack of up-front CAE analysis tools in the past in Ford Motor Company, piston designs have to heavily rely on dyno tests for verification without optimization. It is technically difficult, costly, and time consuming to identify those failure modes and to evaluate various piston designs. An up-front CAE tool and an analytical process, which can be used to address these issues systematically, cost effectively and time efficiently, are highly needed. Obviously, as discussed above, developing such a comprehensive piston design analysis process with high fidelity is a great challenging task.

An advanced and comprehensive CAE process, and simulation tools have been developed internally in Ford Motor Company to provide optimal trade-off piston designs, which are used to support various piston design level iterations with reduced hardware tests, and to ensure durable pistons of lowest friction and low radiate noise without unusual engine noise.

It is worth to point out that, in the CAE process and tools, the elastohydrodynamic (EHD) lubrication model and flexible liner are not used in order to eliminate the intensive computational time, so that many iteration studies on piston design can be simulated in a much faster way. The disadvantage to do so is that oil film thickness can not be calculated and the phenomena of asperity contact can not be studied. However, because major factors that affect the piston dynamics have been included in the process and CAE tools, according to the author's experience, the piston dynamic

behaviors, especially at high speed and high load conditions, can be simulated without the loss of crucial information.

3D VIRTUAL MODELING AND SIMULATION TOOLS OF PISTON DYNAMICS

Multi-discipline methodologies are used in the CAE process and tools so that the physic properties of piston motion, deformation and dynamic loading can be fully captured. The piston's design control factors and boundary conditions provided by cross-function teams can be integrated into 3D virtual dynamic models, as shown in Figure 2, to simulate piston dynamic behavior for various engine fatigue design verification (DV) tests. The dynamic stress, skirt contact pressure, top land contact, skirt friction energy loss and radiated noise can be investigated in systematical interaction levels. An optimal trade-off piston design can be finally achieved by conducting DOE and AR&R studies. The piston designers can use the analytical results to drive piston robust design in order to meet design requirements in component and system levels.

The 3D virtual piston dynamic modeling and simulation tools are developed by Ford experts, using a commercial software platform MSC/ADAMS [7]. This software provides an excellent integrated environment to model and simulate piston dynamics with the flexible modal structures, flexible body contacts and free-floating pin mechanism. A free-floating pin can also be simulated with multiple contact forces in the 3D virtual model. The pin is allowed to have translative and rotational motions to piston and connecting rod, and the clearances between pin and piston, pin and connecting rod can be specified as inputs. The pin motions and deformations are constrained by the contact forces in the simulation. The calculation of pin bore contact pressure is simplified.

Boundary Conditions: MSC/ADAMS 3D Virtual Model

- cylinder pressure
- cylinder temperature
- bore distortion
- clearance

Design Factors:

- profile & ovality
- pin offset
- piston temperature
- piston structure

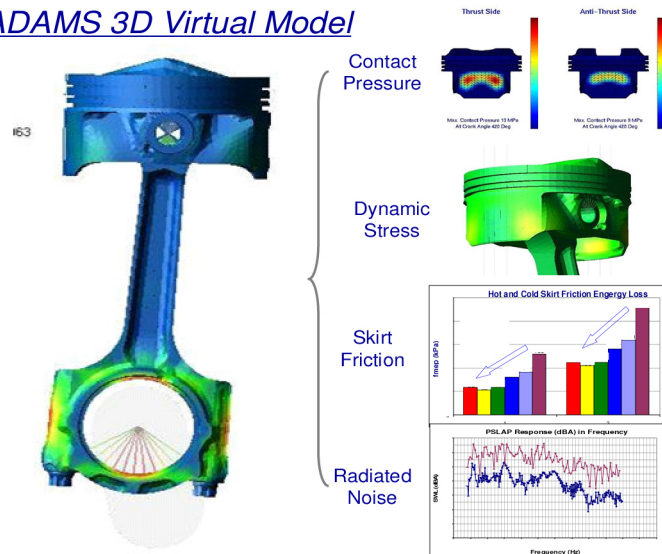


Figure 2. The Piston Design Analysis Process and CAE Tools

In addition, the strong 3D animation functions in MSC/AMDAMS allow design analysts to understand piston dynamic behavior clearly and easily. A single piston-rod-pin dynamic system with a rigid cylinder liner is simulated in consists of the following features:

- Flexible piston, rod and pin;
- Floating pin interaction with pin offset;
- Machined profile and ovality of piston;
- Rigid cylinder liner with assembly bore distortion;
- Thermal expansion due to piston and cylinder bore temperature;
- Cylinder combustion pressures;
- Clearances between piston and cylinder bore, piston and pin, pin and connecting rod;
- Experimental lubrication coefficient for friction at all contact area.

THE FLEXIBLE BODIES OF PISTON, ROD AND PIN, PISTON PROFILE AND OVALITY

The flexible bodies of piston, rod and pin can be integrated into the piston system model by using MSC/Adams flexible body modal models, which can be generated through the Craig-Bampton component mode synthesis method [7]. [Figure 3](#) shows finite element models of piston, rod and pin as examples.

Four key design factors are generally considered in piston CAE analysis: pin offset, clearance between piston and

cylinder bore, piston profile and ovality cut. An example of piston asymmetric profile and ovality curves can be seen in [Figure 3](#).

CYLINDER BORE ASSEMBLY DISTORTION, CYLINDER LINER AND PISTON THERMAL EXPANSION

The temperatures of piston and cylinder bore increase greatly when engine is in operation. Due to the combustion, cooling, heat transferring and material properties, piston's temperature is much higher than cylinder liner. Piston skirt expansion resulting from the higher temperature can exceed cylinder liner's growth so much that a significant additional thermal load can be added to piston skirt. As the result, plus the heavy forces from cylinder combustion pressure, rod and inertial loads, piston could experience skirt scuffing with high friction energy loss. At severe situation, piston might even have durability failure of dome and skirt if it is not designed well to counteract these dynamic loads.

Cylinder bore assembly distortion is also a big contributor to skirt load, contact pressure, top land contact and piston radiated noise. It is required to control the cylinder bore distortion in engine design and to consider it in piston dynamic simulations. A cylinder bore assembly distortion, a piston and a cylinder bore temperature, and the relative thermal expansion of a gasoline GTDI engine are shown in [Figure 4](#). The engine is running at a high speed with a wide open throttle (WOT) load.

All of the above analytical data are externally calculated by using CFD CAE software tools and ABQUAS [8]. These

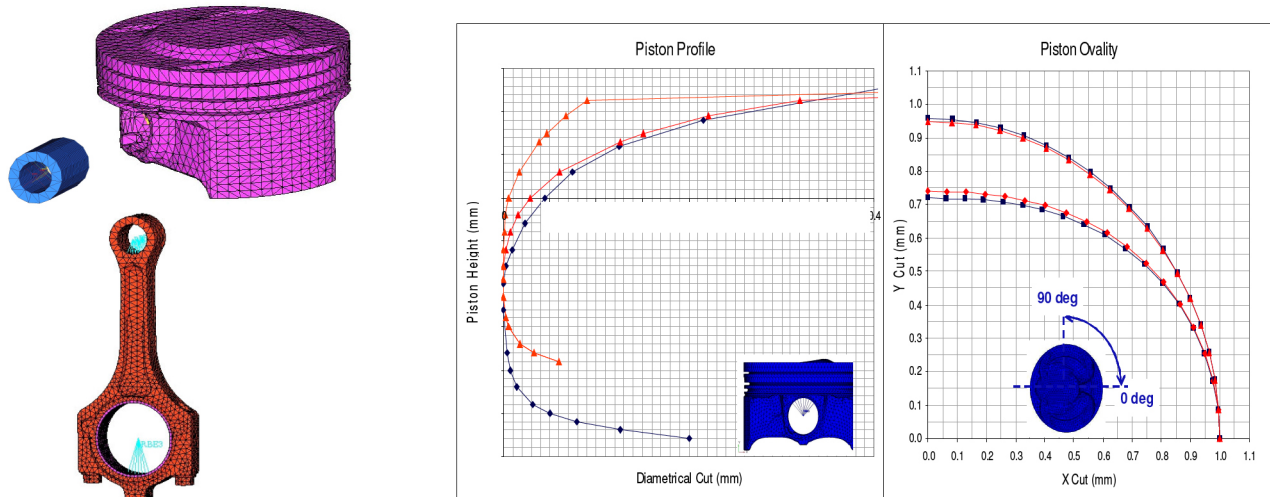


Figure 3. Piston, Rod and Pin FE Models with Asymmetric Profile and Ovality

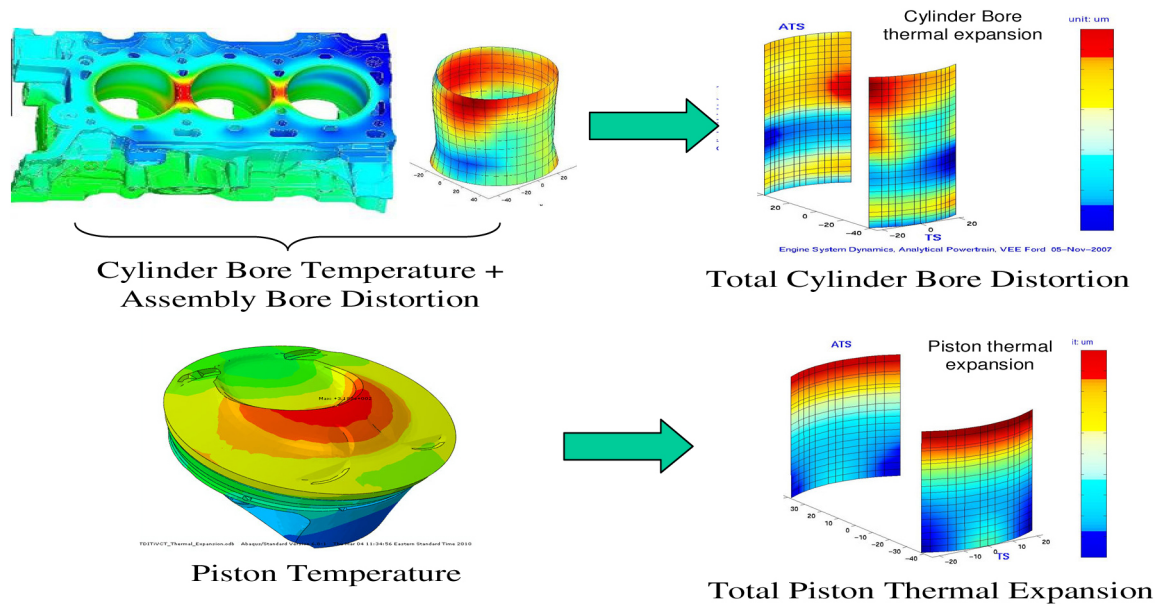


Figure 4. Piston and Cylinder Temperature and Thermal Effects

data also can be easily mapped into a 3D virtual piston model for simulation.

CYLINDER COMBUSTION PRESSURE

Cylinder combustion pressure can also be mapped on the piston dome surface according to different engine operation conditions in engine fatigue, piston slap noise, piston hot and cold scuffing DV tests. These pressure data can be obtained from engine dyno measurements, analytical studies or surrogate pressure trace. Typical cylinder combustion pressure data can be seen in [Figure 5](#).

LUBRICATION ASSUMPTION OF SKIRT, WRIST PIN AND CRANK PIN

As discussed in the previous sections, the equivalent friction coefficients are used with the help of simulation efficiency improvement. These experimental friction coefficients are the function of the sliding velocity v_i and the applied normal load F_i of contact nodes, which are expressed in the [equation \(1\)](#) and can be seen in [Figure 6](#). The friction force at each contact node can be calculated by simply multiplying the normal force F_i and the related friction coefficient f_{ij} together.