5. Győrer Tribologie- und Effizienztagung, 19-20. June 2018

Friction Test Procedures in Engine Development

DI Wolfgang Hopfner
AVL List GmbH, Graz, Austria

Dr. Siegfried Lösch
AVL List GmbH, Graz, Austria

DI (FH) Stefan Satschen
AVL List GmbH, Graz, Austria

Dr. Ernst Winklhofer
AVL List GmbH, Graz, Austria

Lecturer: Dr. Ernst Winklhofer

Abstract

The paper discusses the application of routine engine strip down tests for the assessment of an engine's friction behavior and the contribution of individual engine components. Cylinder pressure effects are frequently tested with the boost / motored test procedure. Some results are presented together with a discussion of the tests applicability. The main part of the paper describes measurement of friction losses arising between piston and liner. A test engine with a "floating liner" design is applied to evaluate piston ring variants. The focus in these tests is given to the repeatability and accuracy of friction force and friction power measurements with a consequent discussion of FMEP results. Such discussion also includes design aspects and operation requirements for the FRISC floating liner engine.

Abstract (in German)

Eine umfassende Reibungsanalyse von Verbrennungsmotoren nimmt ihren Ausgang am sogenannten „strip down“ Test: Schritt für Schritt werden Baugruppen aus dem Motorantrieb entfernt, aus dem Drehzahl – Drehmomentverlauf wird der entsprechende Reibungsbeitrag ermittelt. Der Motor wird dazu geschleppt, in wenigen Testkonfigurationen auch gefeuert, Testergebnisse werden im Beitrag kurz beschrieben. Durch Aufladung des geschleppten Motors gelingt auch eine Abschätzung des Reibungsverlaufs unter erhöhtem Zylinderdruck, die Genauigkeitsgrenzen dieses

Verfahrens der „Schleppaufladung“ werden diskutiert. Den zentralen Teil des Artikels bildet die Beschreibung eines Motors, der nach dem „floating liner“ Prinzip aufgebaut ist. In dieser Motorvariante gelingt die Messung der Reibungsverluste, die zwischen Kolben und Zylinderlaufbahn entstehen. Diese Testmethode wird den Messanforderungen gerecht, die zur Bewertung von Bauteilen der Kolbengruppe erforderlich sind. Der Motor wird sowohl geschleppt als auch gefeuert betrieben. Die Messergebnisse zeigen, dass eine Differenzierung der Reibungseigenschaften oft erst im Arbeitstakt des Verbrennungsmotors erkennbar wird. Entsprechend hoch sind hier die Anforderungen an Messgenauigkeit und Wiederholbarkeit. Ergebnisse werden anhand eines Vergleichs von Kolbenringvarianten vorgestellt.

1. Introduction

Testing and improvement of the friction status is part of each combustion engine’s development program. Friction test procedures include motored and fired engine operation, with each method providing results for specific engine components at an accuracy level given by the specific method’s boundary conditions.

We report on the benefits and efforts of standard procedures such as strip down and pressurized motoring tests. As the big advantage of such tests is their applicability to normal engines, a large database has become available to evaluate test results for any given component. The exception, however, are friction losses arising between piston and liner.

Piston – liner friction losses may account for more than 30% of overall losses, by far exceeding any other component’s contribution to friction mean effective pressure (FMEP). Consequently, solutions have been developed to experimentally measure and evaluate these losses. Various designs of such “floating liner” engine configurations have been published. They all share the concept of separating the liner from the cylinder head by means of a friction force sensing device which also needs to maintain liner position. The design requires specific sealing between liner and cylinder head and it furthermore must ensure normal fired engine operation for a representative range of operating conditions.

The design of such floating liner engine suitable for routine tests of piston – liner friction losses has been presented in past years. It was reported that precision of measurement as well as the accurate setting of boundary conditions are essential to differentiate between test variants. At least as important is the simple handling of the test engine: engine components such as piston, liner, piston rings need to be routinely changed for comparison of their specific friction effects. Hence, their mounting and dismounting must not interfere with the measurement system’s accuracy and repeatability. It is furthermore essential to provide and maintain precisely defined boundary conditions for the engine and the test bed environment.

Result examples from such floating liner tests on the effect of piston – liner clearance and piston ring parameters are presented.

2. The “strip down” test

The purpose of strip down tests is to gain data on friction trends of individual engine components. Tests are mainly performed under motored conditions. Friction data are given as friction mean effective pressure (FMEP) as per equ. 1:

$$FMEP = IMEP - BMEP \qquad \text{equ. 1}$$

With BMEP (brake mean effective pressure) and IMEP (indicated mean effective pressure) derived from torque and cylinder pressure measurements.

The schematic of a test bed configuration suitable for such FMEP measurements is given in Fig. 1. Test procedures need a careful adjustment of boundary conditions including the “break in run” of the engine in order to stabilize friction behavior. Typical break in run time may extend for over 50 hours of engine operation.

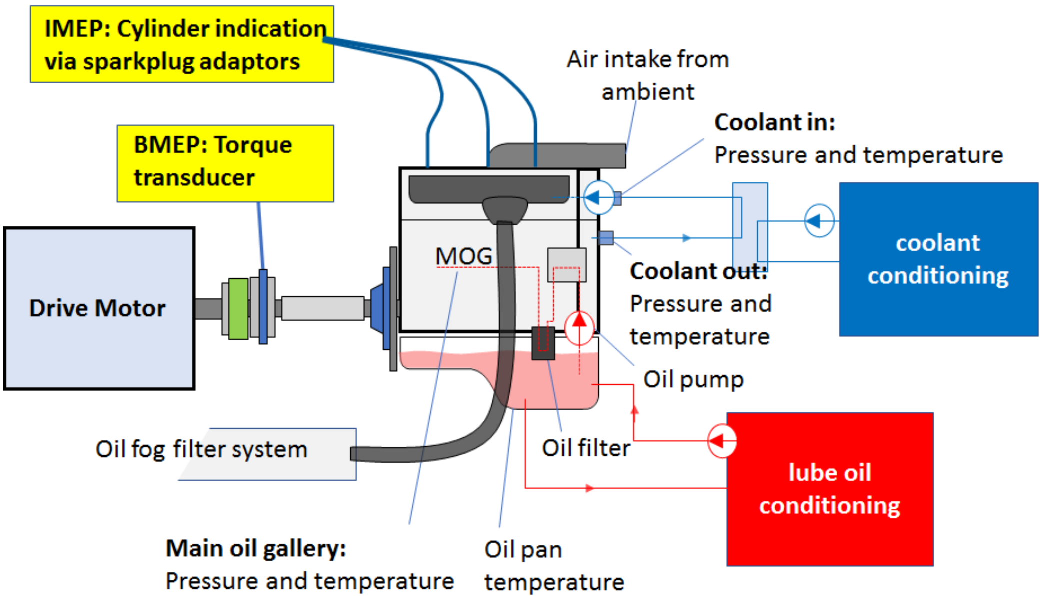


Figure 1: The strip down test bed configuration

Results of such tests are given in Fig. 2 for an engine speed range of up to 5500 rpm and engine temperatures kept constant at 40, 90 and 120°C respectively. The example in Fig. 2 also includes an insert with the engine stripped down to provide friction data for the crankshaft rotation only.

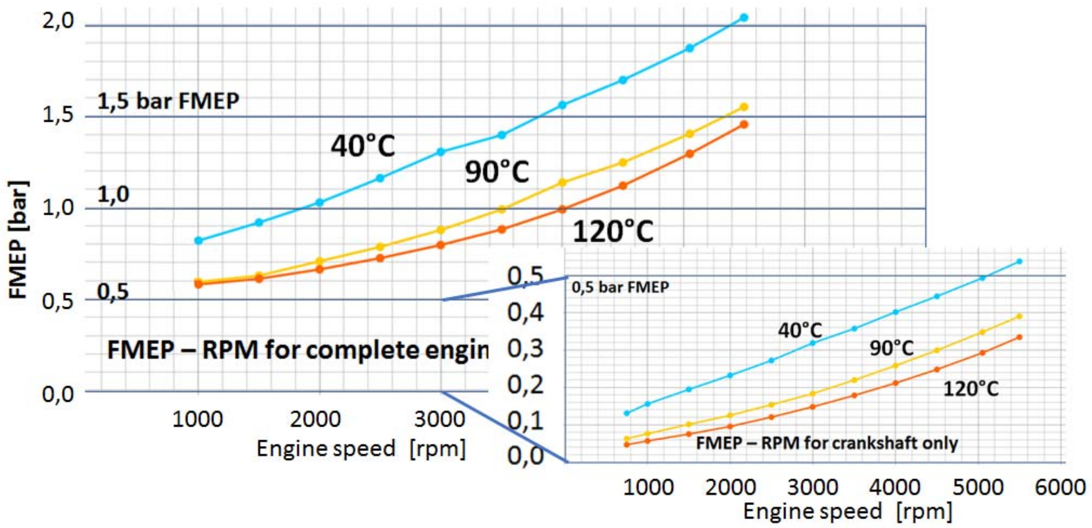


Figure 2: Strip down test result examples for total engine and for crankshaft only

The summary of a typical strip down test is given in Fig. 3, identifying individual components' or modules' contributions to the engine friction behavior. Main contributions to friction losses are seen to arise from the crankshaft, the piston group, the oil pump and auxiliaries driven by belt or chain drives.

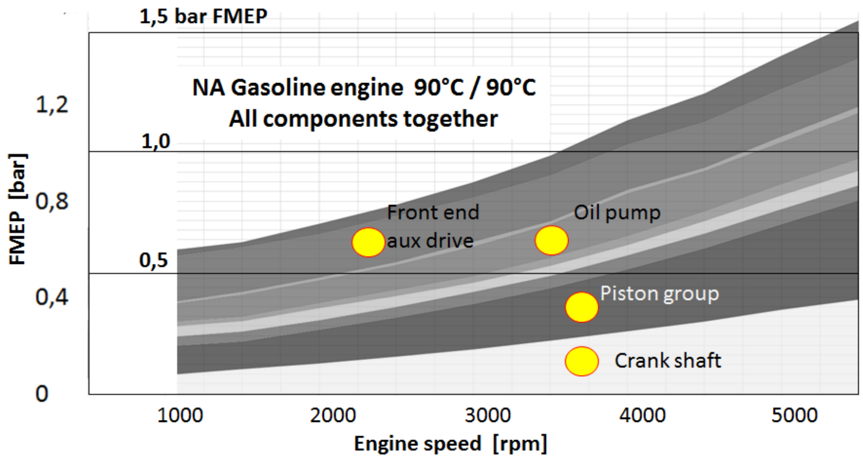


Figure 3: Strip down test results identify individual components' friction trends.

The strip down tests as presented above are routine activities in engine friction evaluation, test procedures are well established and with careful attention to boundary conditions and test variants, high quality results are achieved. Comparison with well established reference data and scatter bands furthermore support results evaluation.

However, there are inherent limitations of strip down tests: in motored operation, realistic cylinder pressure effects on piston side forces and thus piston – liner friction are ignored. This may be overcome with fired engine operation and the IMEP minus BMEP evaluation. Results accuracy for piston specific friction evaluation, however, is questionable.

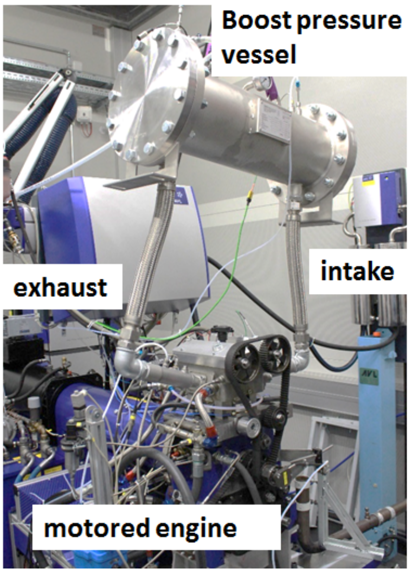
An alternative is presented with motored operation at boosted intake pressure. This avoids high IMEP operation but maintains high compression pressure levels, thus improving the IMEP minus BMEP evaluation.

3. The "boost / motored" friction test

Testing of piston – liner friction effects at cylinder pressure levels similar to fired engine operation is frequently done with operating the engine under boosted intake air conditions.

The test bed assembly follows the configuration as is shown in Fig. 4. Target cylinder pressure levels are adjusted by means of a pressure controller feeding air into the boost pressure vessel. The method is applicable to normal engines operated on an active dyno.

A comparison of total engine FMEP as derived from boost/motored operation versus fired operation is given in Fig. 5. Both methods evaluate FMEP with measurement of IMEP and BMEP.



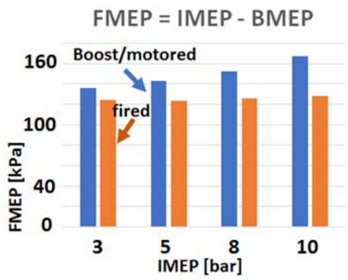
rpm	IMEP [bar] equivalent	Pmax [bar]	boost pressure absolute [bar]
1000	8	39	2
1200	6,5	33	1,8
1750	3	21	1,05
1750	5	31	1,53
1750	8	41	1,96
1750	10	51	2,4
2500	8	38	1,77

Figure 4: test assembly for the boosted – motored friction test with examples of boost pressure levels adjusted to achieve target compression pressure.

In the boost/motored test variant, IMEP only comprises of gas exchange losses. Cycle to cycle variability due to combustion fluctuations does not compromise the IMEP part in this test variant. Thus, the boost/motored test in itself provides significant advantages for signal accuracy.

The test itself, however, is compromised by the fact that it introduces piston to liner contact forces during the compression stroke which in normal engine operation would be significantly smaller. In normal engine operation, furthermore, friction during the expansion stroke is under influence of a pressure – deg CA profile which enhances piston side forces throughout later phases of the expansion stroke than is simulated by the boost / motored test variant.

Apart from above arguments on pressure profile discrepancies, arguments on temperature effects under fired operation furthermore add to the necessity for careful and critical considerations in concluding on test results gained with the boost/motored method.



SI engine 1750 rpm		
IMEP [bar] equivalent	Pmax [bar]	boost pressure absolute [bar]
3	21	1,05
5	31	1,53
8	41	1,96
10	51	2,4

Figure 5: Friction data gained under realistic cylinder pressure levels

4. The "floating liner" friction test

Today's requirements for friction measurement and analysis must address any individual components' effects on friction losses as well as potential improvements achievable with component modifications. Component suppliers are interested to understand their products' effects on friction losses. Engine manufacturers need data on engine operation behavior under real test conditions. A specific challenge arises for the evaluation of the piston – liner friction behavior. This "power cell" may contribute up to 30% of total engine friction losses. Any reduction of these losses needs to address a complex balance of design details, materials, surfaces, clearances as well as lube oil features, all of which are under the influence of temperature and pressure variations.

The means to study and measure piston-liner friction effects have become available with the design of so called "floating liner" engines. Numerous research variants of such engines have been published (see e.g. [1,2,3]). Emphasis on these research engines is given to the design concepts with cylinder liners separated from their usual contact with the cylinder head whilst maintaining fired engine operability.

For industrial test applications, any floating liner engine configuration must aim at

- Measurement accuracy and test repeatability
- Realistic operation of the test engine
- Recording and documentation of test boundary conditions
- Data analysis and data reduction / comparison procedures supporting test evaluations
- Effective handling of all modules to ensure test productivity

Meeting these requirements has been accomplished with the design of a so called FRISC (friction single cylinder) engine. Design details and typical test results have been published in [4,5,6].

Operation of such FRISC engine requires similar test bed facilities as for strip down or boost/motored testing. Emphasis however is given to engine operation in fired conditions with recording of crank angle resolved combustion and force signals. These data are processed to yield piston to liner friction data per degree crank angle which are then directly related to cylinder pressure signals.

Engine design concept, signal recording and processing as well as handling the engine for the exchange of test components has been described in detail in [5,6].

5. FRISC engine tests – some analysis examples

Piston ring comparison

Selection of a piston ring package as is shown in Fig. 6 takes influence on friction, blow by, oil consumption as well as particle emissions. How to design a test which provides realistic combustion conditions and yields data at an accuracy level sufficient to understand a ring package's specific friction behavior?

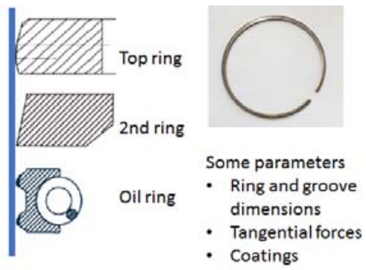


Figure 6: piston ring combinations for a friction test in a FRISC engine

The piston ring test procedure comprises of

1. Break in run for each piston ring package
2. Measurement of friction force signals and signal evaluation for FMEP
3. Measurement of cylinder pressure
4. Measurement of blowby, oil consumption and further combustion and media related parameters

The break in run has the purpose of stabilizing a test variant's friction behavior at operating conditions which are later also selected for the measurements. Such break in is done in about 7 hours of engine operation. Test automation ensures precise repetition of this procedure per each hardware variant.

Some results of such piston ring comparison tests are shown in Fig. 7-9. Prerequisite to any results comparison is test repeatability which finally shows up in the overlay of force signals recorded for the individual ring packages. The signal traces in Fig. 7 show identical friction force traces for most part of the engine compression and power stroke, including the force oscillations introduced by the piston slap against the liner. A small differentiation between piston ring packages arises at high pressure conditions at around 30 deg CA before and after TDC. These piston ring effects give rise to an FMEP difference of 0,025 bar against an overall piston – liner FMEP of around 0,397 bar. Measurement accuracy, which is essentially dependent on stability of boundary conditions, is estimated to be better than +/-0,005 bar FMEP.

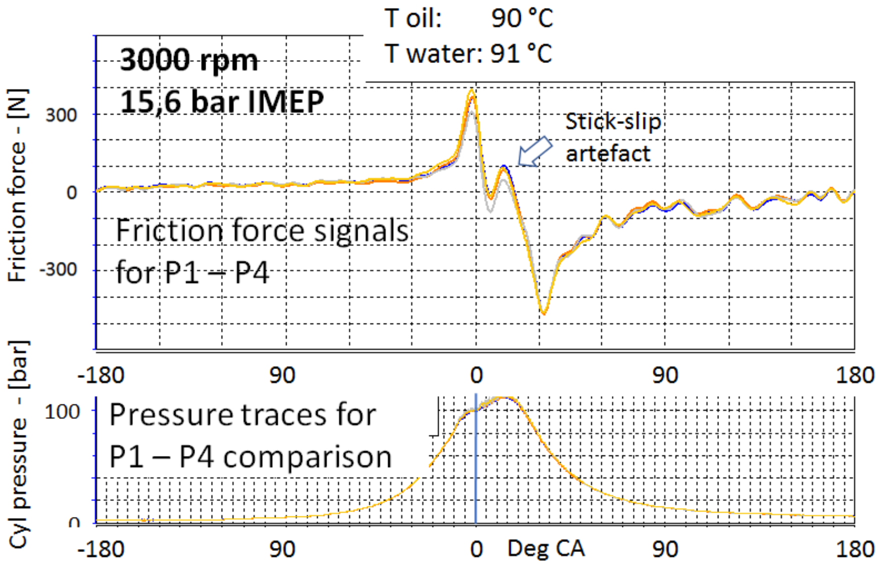


Figure 7: Ring package comparison with friction force signals for given pressure traces. Small differences become evident in the power stroke.

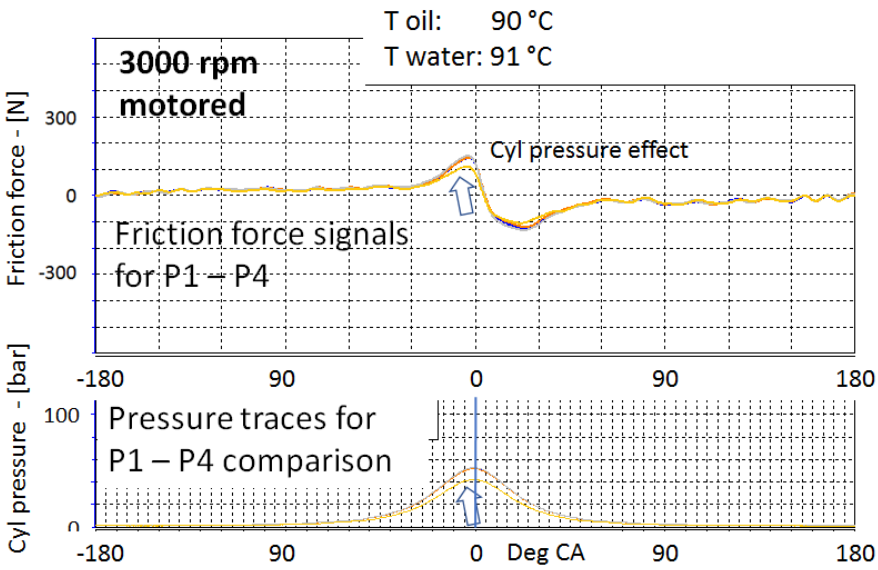


Figure 8: Ring package comparison in motored operation. The only difference arises when cylinder pressure is reduced.

Motored operation, see Fig. 8, does not show any noticeable difference arising from piston ring variants. Reduced boost pressure, however, results in smaller friction forces around TDC.

Selection of piston ring packages of course needs to include data on blowby, oil consumption and any further engine operation features under influence of piston ring packages. A typical set of FMEP data to support such decisions is shown in Fig. 9.

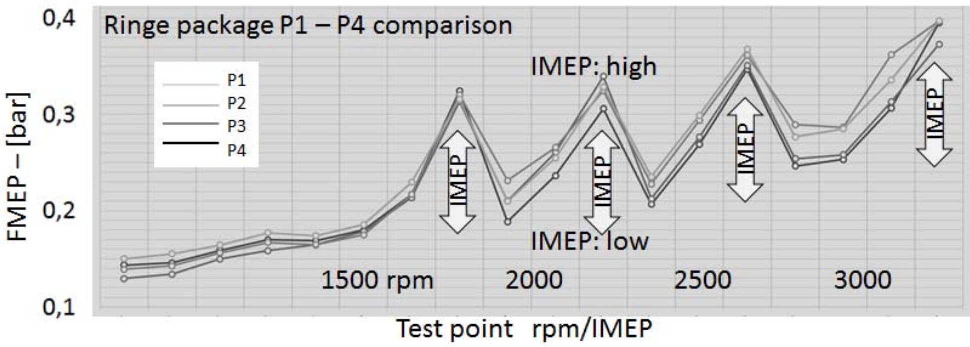


Figure 9: Ring package comparison for selected rpm – IMEP range. The 3000 rpm high load point is derived from signals shown in Fig 7.

6. FRISC versus normal engine – what is different?

Above test examples and signal traces have shown that a FRISC engine enables reliable and high precision measurement of piston – liner friction losses. Such friction losses, however, are under influence of thermomechanical parameters which are specific for each individual engine design. Thermal conditions are of course controlled with external media conditioning systems. But what about mechanical features such as liner distortion and the sealing between the floating liner and cylinder head?

1. Liner distortion: in normal engines, radial distortion of a nominally axisymmetric cylinder liner is introduced by the static force distribution between cylinder head and crankcase. In the FRISC engine, the liner is mounted in the liner housing, see Fig. 10, which is essentially different to any normal engine assembly.

In a first step, the liner housing is optimized to provide minimum liner distortion when mounted to its baseplate and to the crankcase. Ref. [7] reports on distortion amplitudes of around 15 µm. This assembly define the reference parameters for the FRISC liner.

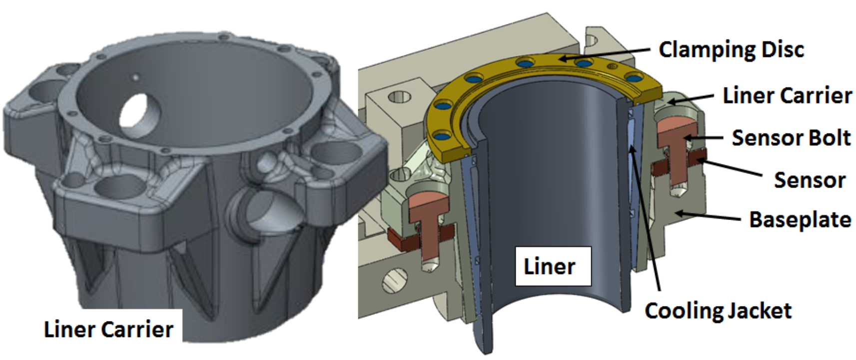


Figure 10: Liner carrier design for minimum liner distortion and liner assembly via carrier and force sensor package to the baseplate

In a second step, in order to duplicate the liner configuration of the target engine, the FRISC liner then is machined by means of the form honing process. Form honing parameters are taken from Incometer measurements of the target engine.

In FRISC engine test projects, step nr. 1 is applied for the analysis of any supplier's components or lube oil variants, whereas form honing is applied in view of actual engine configurations.

2. Cylinder liner to cylinder head sealing: The FRISC engine applies a radial seal ring which is mounted in a seal ring carrier, see e.g. [4,5]. This seal ring, by definition, should not transfer any force between liner and cylinder head. Such requirement, however, is contradictory to the functionality of any seal. The consequence of this ring to liner contact is a force component arising between compression TDC and the crank angle position of maximum cylinder pressure. This force component becomes evident in the "stick – slip" artefact shown in Fig. 7. The stick - slip amplitude is, among other parameters, under influence of cylinder head elasticity, combustion phasing and gas pressure. FRISC engine design and operation ensures that this signal artefact is highly repetitive when comparing test variants. Any difference in signal traces thus is assigned to the effect of a test variant with test validity being confirmed with repetitive reference measurements.

Summary

Three methods for IC engine friction tests have been presented with their installation and operation requirements summarized in table 1.

In normal engine testing the strip down method, occasionally combined with the boost / motored method, is routinely applied. Consequently, a large data base to compare various engines including their auxiliary components has become available for reference benchmarks. The method's accuracy depends on measurement of BMEP and IMEP. Here, motored operation has the advantage of small to negligible IMEP values, fired operation, however, requires very high precision IMEP evaluation in order to yield good quality FMEP results. As BMEP is usually not evaluated on degree crank angle resolution, FMEP results are available for cycle average operation only.

The requirements for high precision evaluation of piston – liner friction behavior has initiated various floating liner engine designs. A specific design variant suitable for the application in the routine development process of combustion systems has been introduced with the FRISC engine design. Some analysis examples for the evaluation of piston ring variants have shown the degree of repeatability and accuracy achievable with today's floating liner test systems. Access to crank angle resolved, high precision signals is a prerequisite for this method, and both, floating liner as well as strip down methods need a test bed environment providing precisely controlled thermal and load conditions.

	Strip down	Boost / motored	FRISC
Engine	normal	normal	FRISC
Test bed	Active dyno with automated operation		
Conditioning	Coolant, lube oil, intake air		
Fired operation	option	option	yes
Friction loss	All components		Piston - liner
Crank angle resolution	no	no	yes
FMEP evaluation	IMEP minus BMEP		Friction force * piston velocity
Main feature motored	FMEP near BMEP		Deg CA resolution
Main feature fired	Overall FMEP evaluation		Accuracy enables variant comparison

Table 1: Friction test methods for IC engines.

[1] Kwangsoo K., Paras, S., Takiguchi, M., Aoki, S.: "A study of friction and lubrication behavior for gasoline piston skirt profile concepts", SAE 09PFL-1163, 2009.

[2] Koch, F., Geiger, U., and Hermsen, F., "PIFFO - Piston Friction Force Measurements During Engine Operation," SAE Technical Paper 960306, 1996, doi:10.4271/960306.

[3] Merkle, A., Kunkel, S., Wachtmeister, G.,: "Analysis of the Mixed Friction in the Piston Assembly of a SI Engine," *SAE Int. J. Engines* 5(3):1487-1497, 2012, doi:10.4271/2012-01-1333.

[4] Winklhofer E., Loesch S., Satschen S.: „Kolben – Zylinderreibung – ein Prüfsystem für höchste Meßgenauigkeit", Vierte Györer Tribologie Tagung, Juni 2016

[5] Winklhofer E., Loesch S., Satschen S.: High precision piston to liner friction measurement, JSAE 2016, Yokohama.

[6] Winklhofer, E; Loesch, S; Satschen, S; Thonhauser, B.: Reduction of friction losses by means of cylinder liner offset; JSAE 2017, Yokohama .

[7] Tomaschko S. et al: „Stationäre und transiente Reibkraftmessung der Kolbengruppe bei unterschiedlichen Laufbahngeometrien mit einem eigens für diese Aufgabenstellung neu konstruierten Floating-Liner", 6. ATZ Fachtagung Reibungsminimierung im Antriebsstrang, Esslingen 2017.