

Mass Balancing Measures of a Linkage-Based Extended Expansion Engine

Patrick Pertl, Michael Lang, Stephan Schmidt, and Roland Kirchberger
Graz University of Technology

ABSTRACT

The enhancement of efficiency will play a more and more important role in the development of future (small) internal combustion engines. In recent years, the Atkinson (or Extended Expansion) cycle, realized over the crank drive, attracted increasing attention. Several OEMs have investigated this efficiency-increasing principle in the whole range from small engines up to automotive engines until now.

In prior publications, the authors outlined the remarkable efficiency potentials of an Extended Expansion (EE) cycle. However, for an internal combustion engine, a smooth running performance as well as low vibrations and noise emissions are relevant aspects. This is especially true for an Extended Expansion engine realized over the crank drive. Therefore, design measures concerning friction and NVH need to be taken to enable possible series production status. Basically, these measures strongly depend on the reduction of the free mass forces and moments. Hence, the focus of this publication is laid on mass balancing measures of an Extended Expansion engine based on a linkage system.

This paper first gives a brief overview of the specific 2-cylinder engine layout of the designed EE prototype engine. The second part deals with the determination of occurring free mass forces and moments. In the following, possible as well as performed mass balancing arrangements are presented and evaluated. Finally, a comparison between the EE prototype engine and other conventional 2-cylinder engines is performed.

The determination of free mass forces and moments is based on numerical calculations. They include a kinematic simulation of the crank drive and, derived from that, accelerations of each relevant engine part. The geometry data are determined via CAD and the appropriate masses are calculated according to the corresponding density of the applied materials. In addition, results based on a Fourier transformation are presented, whereas free mass forces and moments are mathematically split into harmonic orders, which are helpful to evaluate balancing measures.

CITATION: Pertl, P., Lang, M., Schmidt, S., and Kirchberger, R., "Mass Balancing Measures of a Linkage-Based Extended Expansion Engine," *SAE Int. J. Engines* 9(4):2016, doi:10.4271/2016-32-0096.

INTRODUCTION

The Extended Expansion (EE) in internal combustion engines gained increased interests since the 1980s [1, 2, 3, etc.]. This fact is also recognizable in a variety of publications regarding this topic up to several designed concepts [4, 5, 6, etc.]. Moreover, one EE engine for a cogeneration system is in series production [7]. The idea to improve the conversion of thermal energy to work, applying a strategy to expand the working gas to the lowest possible pressure by using a longer expansion than compression stroke, is not new. At the end of the 19th century the British inventor James Atkinson patented his engine based on a dedicated linkage system connected with the crank train.

The engine was originally designed to avoid infringing certain patents covering Otto cycle engines. However, this special crank train arrangement also enables, beside a piston motion with a longer expansion than compression stroke, 4-strokes in one crank shaft revolution. Other possible kinematic principles to generate an EE

piston motion use dedicated crank drive mechanisms. The majority is based on a superposition of two oscillations with different frequencies and phases. These crank drive arrangements mostly use linkage systems [6, 7 and 9] or planetary gear boxes [9, 10, 11].

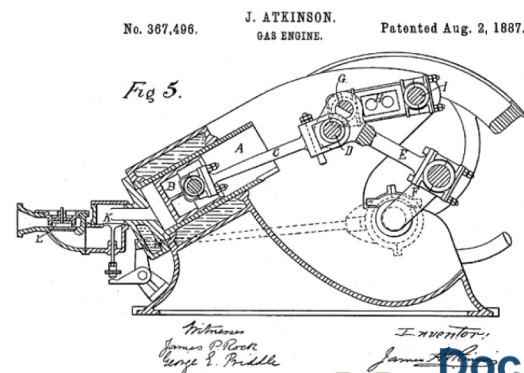


Figure 1. Atkinson engine patent [8]

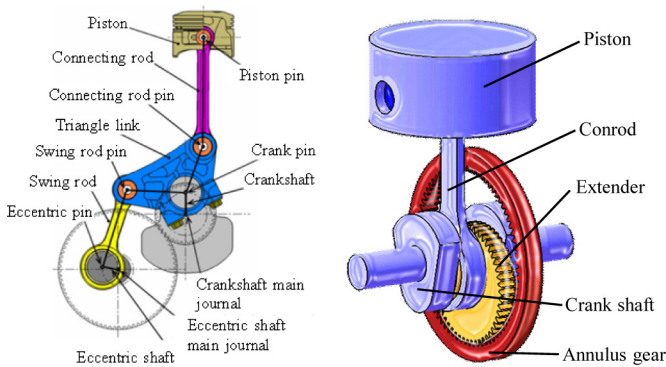


Figure 2. Possible EE crank drive concepts [7 and 9]

Beside beneficial characteristics concerning free mass forces and mass balancing, planetary gear concepts suffer from basic problems when realizing high ratios of expansion to compression volumes. These problems mainly concern the increasing diameter of the big end bearing and the increasing loads on the annulus gear. Based on previous concepts and thermodynamic studies the decision was made for an approximately two times higher expansion volume than compression volume [9 and 12]. Therefore, planetary EE concepts were excluded and the decision was made in favor of a linkage-based EE concept. Another reason for this decision is also the fact that a series application a similar crank train arrangement already exists [7]. The EXlink (Extended Expansion Linkage) engine from Honda Motor Co., Ltd. is part of a cogeneration system for private homes.

In terms of the mass balancing, linkage-based crank drive designs pose demanding challenges. Basically, free mass forces and moments induce deflections of the frame, in case of a vehicle of the chassis. For an ICE operation, a smooth running performance as well as low vibrations and noise emissions are relevant aspects beside efficiency (fuel consumption), reliability, cost-effective maintenance, etc. Consequently, mass balancing, in particular for an EE engine, requires special attention. As mentioned before, the EE prototype engine design is based on a linkage system. Basically, this design offers a complex kinematic interaction between all relevant crank drive parts and further leads to a complex determination of free mass forces and moments. Considering the separation into harmonic orders [13], which is helpful to determine mass balancing measures, this special crank drive causes also orders of free mass forces and moments which are a multiple of the frequency ratio between the different oscillations in the linkage. To generate a cyclic piston motion over 720°CA (4-stroke principle), these ratios can basically be a natural number plus 0.5 with a phase shift of $\pm 90^\circ$ between both oscillations [9 and 12]:

$$\text{frequency ratio} = i + 0.5 \text{ (for: } i \in \mathbb{N})$$

However, the practical relevance is only given for the ratios 0.5 and 1.5. Higher ratios lead, on the one hand, to higher engine speeds (and accelerations) and, on the other hand, to an increased number of inflection points in the piston motion, which cause alternations of the acceleration during the stroke (see Figure 3).

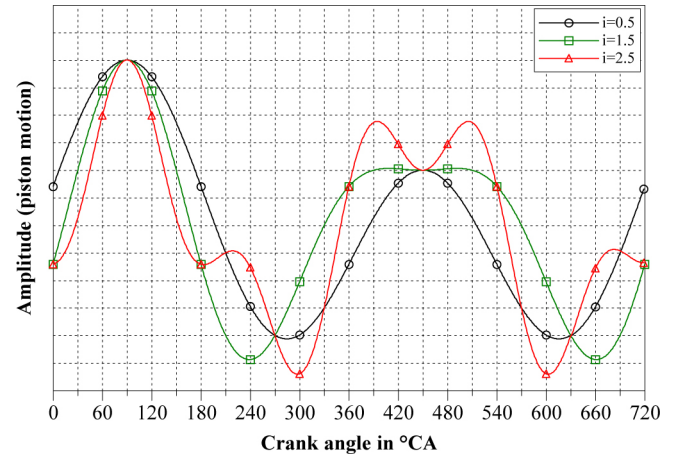


Figure 3. Influence of the frequency ratio on the superposition

Another reason for the special importance of mass balancing for an EE engine realized over a linkage system is the higher part number compared to conventional engine crank drives. Linkage systems use connecting elements to transfer the movement. In case of this publication the connection element will be further denoted as trigonal link (cf. also Figure 2 and Figure 4). However, the trigonal link integrates three bearing points which leads to a defined geometry based on engine size, generated loads, materials, stiffness, etc. Consequently, these properties influence the trigonal link part mass and hence the mass forces. However, the mass of the trigonal link plays a decisive role in terms of the amount of free mass forces and moments. Moreover, additional parts like a second conrod, a second crankshaft and other smaller engine parts like bearings, screws, etc. further increase the free mass forces and moments in comparison to a conventional crank drive arrangement.

First, this paper gives an introduction concerning the basic design of the Extended Expansion prototype engine which was designed, prototyped and experimentally tested at IVT. The subsequent chapter deals with the determination of the free mass forces and moments of the EE prototype engine via simulation. After that, the balancing measures will be presented. Finally, an evaluation of the balanced EE prototype engine compared with 2-cylinder engines with conventional crank drive arrangements is carried out.

DESIGN OF THE EXTENDED EXPANSION PROTOTYPE ENGINE

The crank drive design of the EE prototype engine is based on a linkage system which is quite similar to the EXlink engine from Honda Motor Co., Ltd. [4, 7 and 14]. Beside the twin-cylinder arrangement, the main differences lie in the compression to expansion ratio (CER), the intake volume and the compression ratio. CER is a decisive factor for attainable efficiencies and engine sizes. It is defined as the quotient of the compression ratio to the expansion ratio:

$$\text{CER} = \frac{\varepsilon_C}{\varepsilon_E}$$

ε_C ... compression ratio

ε_E ... expansion ratio

The compression ratio is based on the swept volume at compression stroke $V_{H,C}$ and the dead volume V_C . The expansion ratio is based on the swept volume at expansion stroke $V_{H,E}$ and the dead volume V_C .

$$\varepsilon_C = \frac{V_{H,C} + V_C}{V_C}$$

$$\varepsilon_E = \frac{V_{H,E} + V_C}{V_C}$$

$V_{H,C}$... swept volume at compression stroke

$V_{H,E}$... swept volume at expansion stroke

V_C ... dead volume

At a CER value of 1 the expansion and compression stroke are the same. Hence, the layout is similar to the conventional reciprocating piston engines. In related literature the volume ratio γ is also used to calculate the thermal efficiency potential of Atkinson cycles. This volume ratio is defined as quotient between the swept volume at expansion stroke and the swept volume at compression stroke:

$$\gamma = \frac{V_{H,E}}{V_{H,C}}$$

γ ... volume ratio

A CER of 0.5 at a compression ratio of e.g. 12.5 corresponds to a γ of 2.09 and therefore to an approximately two-times higher expansion than compression stroke for this engine. In comparison, the single-cylinder Honda EXlink has a CER of approx. 0.7 and a compression ratio of 12.2 [7]. This results in kinematics more similar to a conventional crank drive. Therefore, taking into account its application as a stationary device, it seems that even without the use of balancer shafts, no critical NVH issues, especially vibrations, occur.

In case of the EE prototype engine of IVT balancer shafts are indispensable: CER is significantly lower and an automotive usage is considered. Furthermore, for test bench investigations low vibrations favour the entire measuring equipment. The main technical specifications of the EE prototype engine are listed in Table 1.

Table 1. Technical specifications of the EE prototype engine

Cylinder number		2
Intake displacement / cylinder	$V_{H,C}$	320 cm ³
Expansion displacement / cylinder	$V_{H,E}$	660 cm ³
Expansion / intake displacement ratio	γ	2.09
Compression ratio	ε_C	12.5
Expansion ratio	ε_E	25
Compression (to) expansion ratio	CER	0.5
Intake stroke / bore		0.74
Expansion stroke / bore		1.52

The cylinder head, including intake and exhaust port geometries and the valve train design, is based on a conventional 2-cylinder SI 4-stroke motorcycle engine. The main technical specifications are listed in Table 2.

Table 2. Technical specifications of the base engine

Cylinder number	2
Operating principle	4-stroke
Fuel	Gasoline
Fuel supply	Multi-point fuel injection (MPFI)
Total displacement	800 cm ³
Stroke / bore ratio	0.92
Compression ratio	12.5
Specific power	80 kW/l

The EE prototype engine (Figure 4) mainly consists of the pistons (1), the conrods (2), the trigonal links (3), the crankshaft (4), the Atkinson crankshaft (5), the Atkinson conrods (6), the balance shafts (7), the Atkinson gear wheel (8) and the cylinder head (9). The gear ratio is 2 and, hence, the Atkinson crankshaft rotates with half the crankshaft speed.

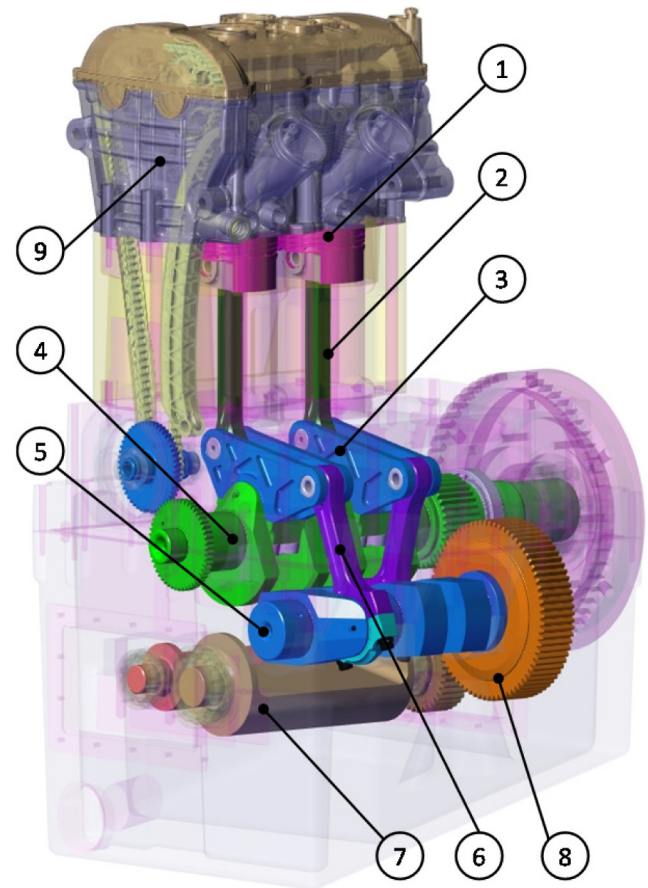


Figure 4. EE prototype engine layout [12]

The piston motion is based on a linkage system crank train arrangement. This specific engine layout results in a characteristic piston motion based on the superposition of two oscillations with different amplitudes, frequencies and phases. The phase shift between