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Development and Performance Evaluation of a Cam-Driven Stirling Engine with Optimised Piston Motion

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INTRODUCTION:

Global energy demand rises, while power generation depends highly on fossil fuels, raising concerns of sustainability, cost, and environmental. Renewable technologies mature but face intermittency, high costs, and complex material requirements, causing a renew interest in thermal energy conversion systems.

The Stirling engine presents a promising solution. This external combustion, closed-cycle heat engine converts heat from various sources into mechanical power. First patented by Robert Stirling in 1816, early implementations faced material constraints and sealing challenges. With modern advancements in heat exchangers, working gases, and manufacturing, performance had improved. Today, Stirling engines apply in micro-CHP systems, cryogenic cooling, waste heat recovery, and space power. Notably, free-piston Stirling engines demonstrate long-term reliability (Slaby, 1987; Sukel, 2025).

The ideal Stirling cycle achieves Carnot efficiency but in practice, small-scale engines achieve thermal efficiencies of only 5–10%. This is due to irreversibilities such as imperfect heat transfer, fluid friction, regenerator inefficiencies, and mechanical losses (Romanelli, 2020; Yu & Cheng, 2010), highlighting much opportunities for optimisation.

Performance depends on the motion and phase relationship between the displacer and working piston. Conventional kinematic designs employ sinusoidal motion, but non-sinusoidal motion profiles enhance performance by improving heat transfer and synchronising pressure–volume interactions. Implementing such motion remains challenging.

Cam-driven mechanisms offer a solution by enabling precise control of displacement, velocity, and acceleration profiles, allowing systematic exploration of motion optimisation. This paper presents the development and experimental evaluation of a novel cam-driven Stirling engine, focusing on motion to improve efficiency.

LITERATURE REVIEW:

The thermodynamic performance of a Stirling engine is intrinsically linked to the synchromised motion of the displacer and working piston. These motions determine

instantaneous pressure variation, working gas mass flow, and the timing of heat addition and rejection processes. Classical analyses show that phase angle and volume modulation directly influence indicated work and thermal efficiency (Walker & Senft, 1980; Senft, 1998).

The coordinated motion of the displacer and working piston fundamentally governs the cyclic variation of the expansion and compression volumes (V_e and V_c). This relationship is most effectively illustrated through the Schmidt analysis, a seminal isothermal model that remains a cornerstone for initial engine sizing and performance estimation due to its analytical simplicity (Dobre et al., 2021; Rochelle & Grosu, 2011). The schematics of a gamma configured Stirling engine, shown in Figure 1 illustrates the instantaneous pressure, $P(\theta)$, is a function of these shifting volumes and the fixed volumes of the heat exchangers, derives equation (1).

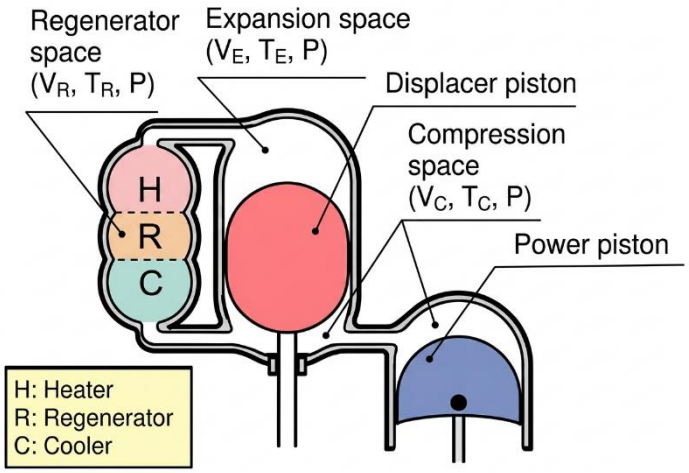


Figure 1: Gamma Stirling engine (Hirata, 2005)

$$P(\theta) = \frac{m\,\mathrm{R}}{\frac{V_c(\theta)}{T_c} + \frac{V_r}{T_r} + \frac{V_e(\theta)}{T_e}} \tag{1}$$

From equation (1), T_c, T_r, and T_e represent the absolute temperatures of the compression space, regenerator, and expansion space, respectively, while V_r accounts for the dead volume within the regenerator (Auñón et al., 2023). According to Hirata (2005), for gamma Stirling engines, the volume created in the power cylinder by the power piston is combined into V_c. By coupling kinematic piston movement to this pressure equation, the Schmidt analysis reveals how volume modulation shapes the pressure-volume (P-V) work loop, influencing the indicated power and thermal efficiency (Dobre et al., 2021). Despite its idealised assumptions, this framework demonstrates how mechanical phase shifts and swept volume ratios translate into the pressure variations that ultimately determine engine output (Auñón et al., 2023; Rochelle & Grosu, 2011).

While conventional engines typically employ sinusoidal motion for mechanical simplicity; such trajectories are thermodynamically optimal. Research studies have shown that deviations from sinusoidal motion can enhance cycle effectiveness by improving heat transfer during near-isothermal processes and reducing losses associated with imperfect regeneration (Urieli & Berchowitz, 1984). For instance, by decoupling the volume changes at the expansion and compression ends, Gopal (2012) improved engine performance through the strategic inclusion of "dwells" in the displacer motion.

Advanced modelling further demonstrates that tailored motion profiles can increase gas residence time within heat exchangers and improve synchronisation between pressure and temperature oscillations, leading to higher efficiency (Craun, 2015). However, these benefits depend entirely on the ability to precisely control and reproduce the prescribed motion.

Various mechanical approaches have been explored to achieve this control. Free-piston Stirling engines utilise dynamic balancing and gas springs to regulate motion, offering high efficiency but limited controllability (Walker & Senft, 1980; Briggs, 2015). In contrast, cam-driven mechanisms provide explicit control over kinematic behaviour, enabling independent design of displacement, velocity, and acceleration profiles. Building on this advantage, Wong (2024) introduced a cam-drive approach that enables the application of highly specific motion profiles, opening new avenues for experimental optimisation and enhanced engine performance.

METHODOLOGY:

This study adopts an experimental approach to investigate the effects of displacer and working piston motion on Stirling engine performance. While prior studies have established theoretical benefits of non-sinusoidal motion, experimental validation remains limited. The research therefore focuses on the design, construction, and testing of a dedicated Stirling engine test rig.

The engine is based on a gamma-type configuration, selected for its simplicity and ease of implementation, as shown in Figure 2. It operates under atmospheric pressure and is designed for moderate temperature differences (Wong & Goh, 2020). The test rig is equipped with a high-resolution data acquisition system capable of measuring pressure, temperature, cam angle, and component displacement, as indicated in Figure 3.

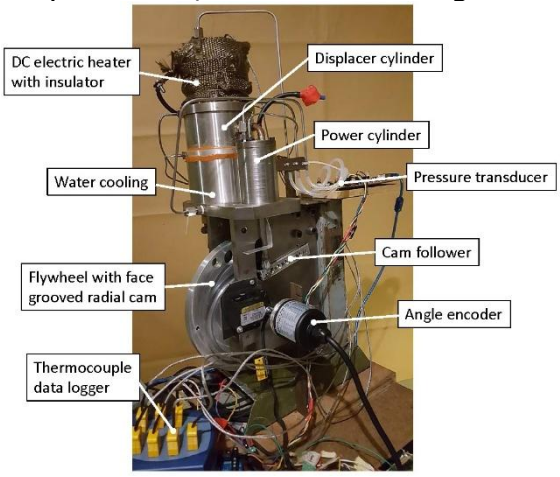


Figure 2: Stirling engine test rig (Wong & Goh, 2020)

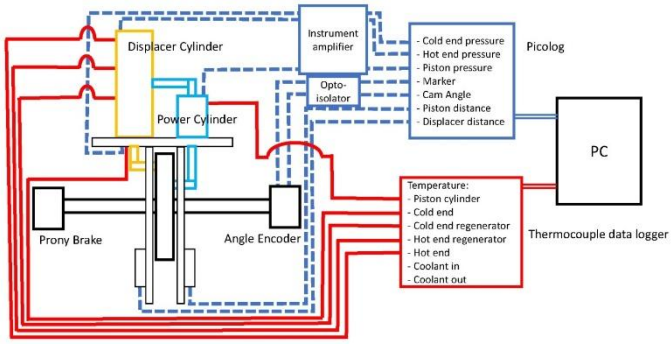


Figure 3: Data-acquisition system for the test rig (Wong & Goh, 2020)

Central to the study is the cam-driven mechanism used to control the motion of the displacer and working piston. The system employs a face-grooved cam integrated into the flywheel, with oscillating cam followers assigned to each component (Wong, 2024). Figure 4 shows the examples of these flywheel cam. By varying cam profiles, distinct motion trajectories can be generated, enabling systematic evaluation of their effects on performance.



Figure 4: Cams used for different motions of displacer and working piston (Wong, 2024)

Multiple cam profiles were fabricated, including theoretical motion, conventional sinusoidal motion, Rise-Dwell_Fall-Dwell motion, and hybrid motions (Wong, 2025). These profiles can be seen in Figure 5. The modular design allows repeatable testing under consistent conditions.

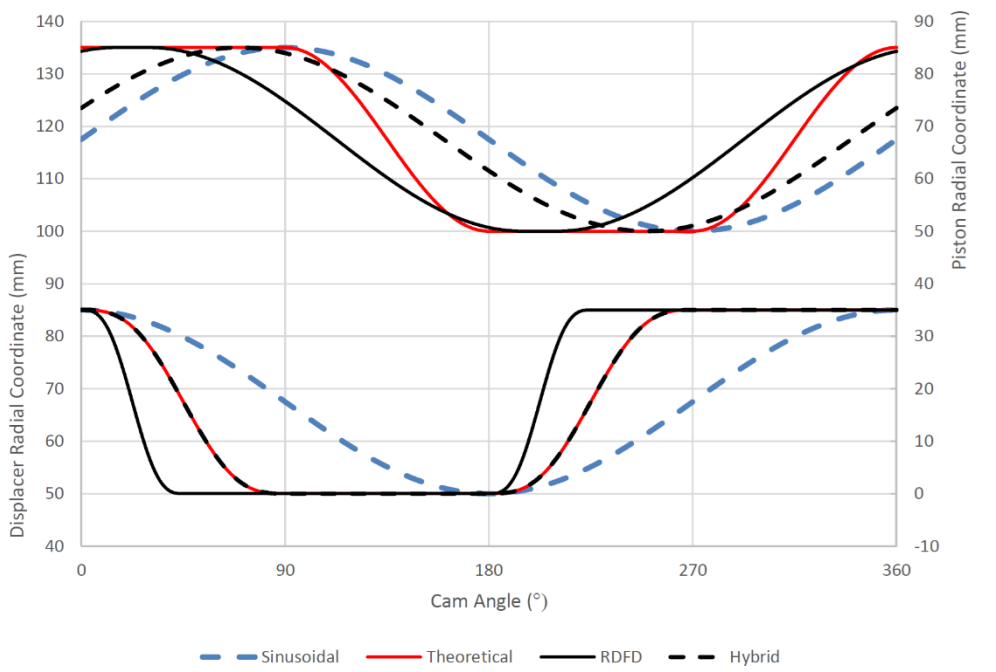


Figure 5: Cam profiles for displacer and working piston (Wong, 2025)

During experiment, the engine is supplied with a 350 W heat input, while the cold side is maintained at 40 °C. Speed is controlled using a prony brake dynamometer. Once steady-state is achieved, data for pressure, cam angle, and displacement are recorded.

The collected data are analysed to determine indicated work, power, and thermal efficiency. Instantaneous pressure–volume relationships are examined to evaluate performance and identify inefficiencies.

FINDINGS AND DISCUSSION:

Four cam profiles were evaluated in this study (Wong, 2025) with the resulting performance data summarised in Table 1. The results demonstrate that engine performance is heavily dependent on the volume variations, V_e and V_c, which are controlled by the specific motion characteristics of each cam. These findings align with the relationship defined in equation (1).

Table 1: Indicated power and efficiencies of each cam motions (Wong, 2025)

Cam motion	Indicated power(W)	Indicated thermal efficiency (x 10^{-2}%)
Hybrid	0.655	18.66
RDFD	0.613	17.43
Sinusoidal	0.448	12.81
Theoretical	0.224	6.38

The theoretical motion profile yielded the lowest performance. Although derived from ideal assumptions, it faltered under practical conditions. Analysis revealed inefficient energy conversion, as significant portions of the cycle contribute little net work.

Compression volume (V_c) experiences brief changes because the power piston dwells half the cycle. Consequently, insufficient volume change under pressure generates little work. With mechanical and thermal losses, net output degrades further.

Conventional sinusoidal motion showed marked improvement, nearly doubling the output of the theoretical case. Because the change in V_c spans the entire cycle, the engine achieves more consistent, efficient work extraction.

The RDFD motion profile performed second best. While generating high instantaneous work, it required substantial work input during other phases, reducing total net output. This highlights the necessity of balancing V_c and V_e variations.

The hybrid motion profile achieved the highest performance. The displacer motion remains identical to the theoretical case, while the working piston remains sinusoidal. This synergy resulted in a nearly threefold performance increase, exhibiting a similar work pattern to the sinusoidal case but with significantly greater magnitude, indicating enhanced energy conversion.

CONCLUSION AND RECOMMENDATIONS:

This study demonstrates a new cam-drive Stirling engine. The engine performed as intended, facilitating multiple motion profiles for the displacer and working piston. The successful implementation of cam-drive mechanisms confirms their importance for motion optimisation. Furthermore, the mechanism performed superbly smooth under load during testing with a prony brake dynamometer.

The experimental setup indicates performance can be significantly enhanced by optimising piston motion. Among configurations tested, the hybrid motion profile delivered superior performance, outperforming both theoretical and conventional sinusoidal motions.

These findings highlight the limitations of idealised theoretical motion under real-world conditions. Results emphasise the necessity of accounting for practical constraints and heat transfer dynamics relative to volume changes.

Despite performance gains, overall power output remains relatively low. This is primarily attributed to gas leakage, limited sealing, and atmospheric pressure operation. Future work should focus on manufacturing precision to minimise leakage, pressurising the working gas to increase power density, and improving regenerator design and materials.

In conclusion, this work demonstrates that the cam-drive system is a practical, effective solution for enhancing Stirling engine performance through precise motion control.

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