Introduction to Analytical Methods for Internal Combustion Engine Cam Mechanisms

A typical finger follower cam mechanism for a high performance engine

J. J. Williams

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To Wendy

Foreword

It is now over 40 years since the Cosworth DFV made its race winning debut in a Formula 1 event and surprisingly since then there has been a remarkable lack of good technical information relating to race engine design. It was, therefore, with great pleasure I received the first draft of this book that covers Jeff Williams's significant contribution to design and manufacture of race engine cam mechanisms.

During my career I have been very fortunate to have worked at Cosworth, Ferrari and Ilmor. I saw first-hand how the challenge of race engine design was approached at each of these successful companies.

The design-led approach at Cosworth was an inspiration. The clear thinking and directness of the late Keith Duckworth was unforgettable.

The development-led approach at Ferrari was in complete contrast. However, not until witnessing horse power increases that in a season were multiples of anything achieved at Cosworth did the value of a well-organised development activity become clear.

At Ilmor the leadership of the late Paul Morgan demonstrated very successfully an approach that was focused on gathering the input from all departments rather than biasing the activity towards any one of them. Few projects embodied this good working relationship between departments better than that of the F1 cylinder head design to incorporate a curved finger follower. All departments worked well together, design, simulation, metallurgy, rig test and manufacturing.

All strove to solve the not insignificant problems encountered on the way to the introduction of a very successful arrangement with measurable performance benefits. Such projects clearly require all departments to play their part, yet significant performance steps always seem to be preceded by one or more extraordinary contributions and for this project I can recall two. Finding a surface coating that allowed the steel finger follower to survive was one such contribution and the cam design software written by Jeff Williams the other.

The software, used by the designers, allowed them to quickly evaluate different arrangements viewing outputs such as pivot loads, entrainment velocity, pressure angles, cam profiles, etc., and allowed modification to inputs such as valve accelerations, finger follower geometry, spring loads, etc. The huge number of equations and manipulations required for the presentation of this information as a useable design and manufacturing aid, is in itself a significant achievement. However, achieving it within the very tight time frame imposed by the engine run date, along with the incorporation of features peculiar to each designer's preference was in my view key to the project's success and a clear indication that good information is crucial and particularly welcome when it arrives. So to now have this and a wealth of other good information in this one excellent publication will, I am sure, see its widespread use as a teaching aid as well as a great reference for the experienced engine design or development engineer.

Stuart Grove
Chief Engine Designer F1 (1994–2005)
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Preface

Not long after I graduated, I was involved in looking into a problem with one of the early nuclear power stations. What surprised me was that those who had designed it, together with those responsible for overseeing the commissioning, seemed to have very little relevant knowledge. Some years later I found that due to government policies, university teaching had ceased to provide attractive employment, and I would need to move back into industry. I remembered my experience with the power station, and sought a subject about which little seemed to be known to those involved. I found that automotive cam design and analysis seemed to be such a subject. I therefore studied the literature and then the current practice and managed to gain employment back in industry.

The literature did not address many of the problems which needed to be solved. It was helpful in presenting solutions to some problems, but many aspects were not covered. It was eventually decided that it would be worthwhile to try and produce new solutions from first principles. These were frequently based on diagrams which others had already produced in part or whole. Therefore the notation may, in places, have been copied from existing diagrams. Once a mechanism has been correctly represented by a diagram, and the relevant parameters have been identified, the analysis should follow fairly easily. Obtaining the correct diagram and establishing which quantities will be prescribed by the designer, and which need to be determined is an iterative process, which may not be apparent in the following chapters.

There are two schools of thought as to how design decisions should be made using digital computers. There are those who believe that the more complex the computer model is the better and having written a suitable program, they are more inclined to have implicit belief in the results. Unfortunately this has led to many engineering failures. The mathematical model will be no better than the accuracy of the boundary conditions, loads and material properties which are specified and frequently assumed to be linear. The results, which are obtained from computations involving complex computer models, are less likely to be questioned by the designer, because the software has been expensive to purchase or develop. Engineering judgement is needed and very often, nonlinear behaviour of components, material or boundary conditions, or failure to create the mathematical model correctly can lead to misleading results, which may be assumed to be correct by inexperienced designers.

An alternative approach is to create a model which is simple and relies on a linear model and boundary conditions, which if they are approximate, or time and wear dependent are understood to be so and allowed for empirically by the designer. The nonlinear behaviour of pneumatic valve springs and some steel springs with unevenly wound coils can however be included with simple but approximate models. This method allows a design decision to be made relatively quickly and if a more complex model is subsequently needed, this can be used together with rig testing and prototype development. I am a believer in this approach which also requires judgment experience and thought from the designer, but I have been very fortunate in having worked with experienced, talented and knowledgeable designers.

The lack of knowledge of the relevant tribology and the best materials and surface coatings together with financial constraints has resulted in many failures in cams and followers. The latter can fail due to excessive wear on surfaces which involve interaction between cam and follower, and the heel of finger followers and the valve stem. The same problem can occur with rockers which can also lead to wear of the end of the valve stem.

The most commonly used heel is cylindrical as it is easy to machine. This leads to movement of the line of contact across the end of the valve stem together with a relative rotation by the follower heel. The movement across the valve stem causes a bending moment in the valve stem, and it is unlikely the combined motion will generate much of an oil film. The use of a suitable involute heel can ensure that a centrally positioned line of contact will remain central, which obviates the bending moment in the valve stem due to axial loads, but there is still relative motion between the two components due to follower rotation, and again there is little prospect of a substantial oil film being entrained. A good surface coating and finish, and a material which permits a hard substrate, are essential to ensure these poorly lubricated contact areas do not fail, due to avoidable wear.

The premature failure of some finger followers and the associated cams was explained by A. Dyson in a seminal paper, published in 1980. He showed that for some cam shapes and finger follower curvatures insufficient oil was entrained between the contacting surfaces and that this could be avoided by decreasing the follower radius. This has the effect of increasing the contact stress and to avoid surface pitting superior, but more expensive materials are required which have a higher yield stress. At this time this form of failure was prevalent in cars manufactured in large numbers by two multinational motor companies, and resulted in a large after-market in third party replacement camshafts and followers.

During the Second World War some cams and followers made for the Rolls Royce Merlin engine suffered from the same problem. This was not so much a problem in war time as many engines were destroyed due to enemy action. However these engines are still used in the Spitfire, Hurricane and Lancaster of the Battle of Britain flight, and in Spitfires, Hurricanes and P51 Mustangs used for recreational flying, where this problem is often apparent. It would now be very easy to design new cams and followers with good oil entrainment. Other cam mechanisms can suffer from the same problem, but failures due to poor entrainment are less common than with finger followers. In this book the method for computing the entrainment velocity is given for all the cam mechanisms considered.

Algorithms are now available for computing the oil film thickness between cam and follower, but these require considerable knowledge of the many properties of the oil and these are frequently highly nonlinearly dependent on the temperature and pressure of the oil at and in the immediate vicinity of the line of contact. In the writer's opinion, for an initial design, ensuring good entrainment velocity should normally suffice.

The advent of the digital computer and related software and in particular the widespread use of personal computers which are relatively cheap and powerful now permits every designer to have his own machine. This has transformed methods of analysis, but there is always the problem that designers, who lack sufficient experience and knowledge will still produce poor designs which they consider acceptable because a computer has been used. This is in many ways similar and as equally dangerous as the belief that if something has been published in a book or a technical paper it is necessarily correct.

The completed analysis can be initially checked by writing a computer program and looking at the results. Most designers will have their own preferences and ideas on how they want the design data input, especially the units, which may not be those used for the calculations. For example, valve mass may be input in g, but the calculations will be easier if masses are in kg. There will also be preferences as to what is output both graphically and numerically and how the user interface is arranged. If the designer finds the program easy to use, fatigue and mistakes should be reduced. The final design of the user interface and establishing what the designer requires is often also an iterative process.

The engine designer has to consider many parts of the engine before finalising his design. A few years ago there was a V10 racing engine with a wide V-angle to achieve a lower centre of gravity. Unfortunately this engine suffered from vibration problems and the V-angle was eventually reduced by about 35 %. Although the valve timing was not known exactly, a good guess could be made, and as the V-angle was known, a calculation similar to those described in Chap. 9 showed that there would be significant interaction between the camshaft torques, which was likely to induce torsional vibration. If designing a V engine the valve timing and the V-angle should be considered and the total camshaft torque checked, before designing the cylinder block.

There is no point in designing something, if it cannot be manufactured, or if it is unlikely to work reliably. Interaction with those involved in manufacturing, assembling and developing the engines can be very worthwhile, not only for the designer, but also for the analyst. Those on the shop floor may have problems whose solution result in improved design, performance or reliability. Their experience in their particular part of the whole production process is frequently considerable, and suggestions and criticism are often very valuable.

This text is intended as an introduction to a large subject, and where possible the mathematics used is elementary and should be familiar to most Engineers. Cubic Spline Interpolation and the Fast Fourier Transform do not need to be completely understood for the reader to use them, as the relevant algorithms are well documented. Some parts of the text, in particular, Chap. 3, is not easy to read, and although the contents of Chap. 10 is well documented elsewhere, this work has been included as some of the subject matter may be hard to access, as the best book on this subject is out of print.

I have been very fortunate in having had many colleagues, who have been talented, knowledgeable and helpful, and to whom I give sincere thanks for the help, advice and information they have given me. Amongst these were: H. Alten, K. P. Baglin, T. Brightwell, A. J. Cook, M. Dhaens, the late A. Dyson, S. B. Grove, M. J. Illien, G. Langham, the late P. J. Morgan, the late C. J. Morrison, H. Tsuda, and I. Watson.

However all errors and omissions in this book are mine.

Great Oxendon, November 2011 J. J. Williams

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