Engineering at the interface revisited

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Abstract: Three publications from Part C which strongly influenced the development of the field of lubrication in human joints are revisited and their impact on the field is outlined. Furthermore, the impact of the *Journal of Mechanical Engineering Science* on the field of lubrication and wear in living and artificial human joints is analysed.

'Analysis of "boosted lubrication" in human joints' by Duncan Dowson, Anthony Unsworth, and Verna Wright appeared in 1970, 'The lubrication of porous elastic solids with reference to the functioning of human joints' by Gordon R. Higginson and Roger Norman was published in 1974, and 'Engineering at the interface' by Duncan Dowson addressed the audience in 1992.

Keywords: lubrication, biotribology, human joints, key publications

1 SYNOPSIS OF THE THREE ARTICLES

1.1 'Analysis of "boosted lubrication" in human joints' by D. Dowson, A. Unsworth, and V. Wright. *Proc. Instn Mech. Engrs, Part C: J. Mechanical Engineering Science*, 1970, 12, 364–369

In 1970, Duncan Dowson had already been a Professor at the University of Leeds for four years, Anthony Unsworth was still a graduate student, and Verna Wright was head of the Rheumatism Research Unit in the medical faculty of the University of Leeds.

This work [**1**], reproduced as Appendix 1, provides a basic analysis of boosted lubrication and was frequently referenced between 1985 and 2007. The publication starts with a description of the human load-bearing joint in engineering terms:

> 'The load-bearing human joint is a self-acting dynamically loaded bearing which employs a porous and elastic bearing material (articular cartilage) and a highly non-Newtonian lubricant (synovial fluid)'.

The concept of 'boosted lubrication' was proposed by Walker *et al.* in 1968 [**2**] as a new mode of lubrication, based on squeeze-film action with porous bearing surfaces, capable of playing a significant part in the successful operation of load bearing human joints. This concept is still valid, 131 scientific publications (as found on scholar.google.com) dealt with 'boosted lubrication' between 1968 and 2007. In short, the squeeze-film action leads to concentration of hyaluronic acid-protein complex in the lubricant as a result of diffusion of water and low molecular weight substances through the porous cartilage and the restricted gap between the approaching cartilage surfaces. The increased concentration of hyaluronic acid thereby gives rise to an increase in the viscosity of the synovial fluid.

In their theoretical analysis of squeeze-film action under conditions of boosted lubrication, Dowson, Unsworth, and Wright assumed that the viscosity of the lubricant increases as the surfaces approach each other. Three cases were investigated: a cylinder near a plane, parallel plane surfaces, and parallel circular plates. They concluded that the ratio of boosted to normal squeeze-film times is determined by a factor of the form $(1 + k(F/h_2))$. The initial film thickness h_1 was assumed to be 100 μm, the final film thickness h_2 to be 10 μm, and F amounted to (3/160) cm. For the three cases considered the ratios of the (boosted/normal squeeze-film) times were found to be 32, 126, and 126. Thereby, this work demonstrated that any process that leads to an increase in concentration of hyaluronic acid and hence, the viscosity of the synovial fluid as the squeeze-film action takes place leads to an increase in the squeeze-film time. The boosted squeeze-film time is more than two orders of magnitude greater than the normal one. The authors also speculated about the relative importance of the filtration action provided by the porous cartilage and the surface undulations in the boosted lubrication mechanism. As opposed to early suggestions, Dowson, Unsworth, and Wright considered that the restriction to side-leakage of the large molecules was the most important factor in boosting lubrication. They compared pore and film thickness dimensions and concluded that the permeability of the space between opposing rough cartilage surfaces was much lower than that of the cartilage.

One year later, the trio – Dowson, Unsworth, and Wright – solved the medical mystery why knuckles crack, and not only published their insights in a scientific journal [**3**], but also made it to *Time Magazine* on 16 August 1971. They based their findings on observations and X-ray photographs of 17 patients who volunteered to have their finger joints stretched on a specially designed machine. The tests showed that stretching increased the space between the finger bones, thus reducing pressure in the clear, viscous synovial fluid that lubricates the joints. This causes cavitation within the fluid and when these bubbles burst they release their energy as noise. As the joint returns to normal position, the gas is reabsorbed into the synovial fluid over a period of 15–25 min. This explains why most knuckle crackers must wait a while for the satisfaction of performing an encore.

1.2 'The lubrication of porous elastic solids with reference to the functioning of human joints' by G.R. Higginson and R. Norman. *Proc. Instn Mech. Engrs, Part C: J. Mechanical Engineering Science*, 1974, 16, 250–257

In the second publication [**4**] revisited in this mini-review and reproduced as Appendix 2, Gordon R. Higginson and Roger Norman theoretically and experimentally investigated the lubrication of porous elastic solids in a very simple model and related this to the functioning of human joints. The simple model dealt with the normal approach of a porous elastic solid and a rigid impervious solid, separated by a viscous fluid.

The two main rival theories at that time concerning lubrication in human joints were the 'boosted lubrication' theory put forward by Dowson *et al.* and the 'weeping lubrication' theory by McCutchen. The latter envisaged the load to be carried by the fluid in a regime described as 'self-pressurized hydrostatic lubrication'. McCutchen proposed that the fluid between the opposing solids was there by virtue of wringing out, and that whatever fluid film was active it was hydrostatic and not hydrodynamic.

The work by Higginson and Norman is devoted to those conditions where the entraining velocity is small or zero. At such points in the human walking cycle, the load is high, namely at 'heel strike' and 'toe off'. At these points the relative velocity between the two mating solids is normal approach and any hydrodynamic lubrication must therefore rely on the squeeze-film effect.

Their experiments used only isoviscous lubricants, but the calculations were extended to include the effect of solute concentration on viscosity.

The authors assumed that the phenomenon as a whole would not be materially altered by having a porous elastic layer on only one of the rigid solids. The normal approach was achieved by allowing the upper solid to fall under gravity onto the lower one. The upper solid surface was spherical polished steel with a radius of 0.3 m. The initial clearance was 0.25 mm. The mass of the upper surface was 4, 6, and 8 kg and the soft layers on the lower surface were all 5 mm thick, mounted on a steel backing plate. Measurements were made of the displacement of the upper surface, and of the mean pressure over a small area at the centre of the upper surface. This pressure was measured with the help of a small stiff diaphragm in the spherical surface, on the centre line. At the centre of the back was mounted a semiconductor strain gauge with a gauge factor of about 100. Pressure and displacement were recorded simultaneously. Three mineral oils with viscosities between 0.21 and 6.3 Ns/m^2 were used.

Their computations with constant viscosity suggested that the lubricating effects of permeability were not as beneficial as had generally been hoped. They concluded that if further progress was to be made in understanding the true mechanism, it must next be sought in the effects of variable viscosity, particularly in the enrichment mechanisms.

> 'If the filtration is completely effective, the additive cannot flow in the radial direction, and the concentration is therefore inversely proportional to the film thickness. For property values of human joints, the calculated closure time to a tenth of the initial separation is increased by about an order of magnitude, and that to a hundredth of the initial separation by about two orders. If a mechanism on these lines does operate, it would be very effective'.

They concluded that the permeability of cartilage was much too low to play an important role in lubrication.

The publication describes a beautiful basic mechanical experiment, and the theory accompanying it starts from basic equations. The authors gave errors of all instruments. This publication is of such high quality that it is proposed to serve as basic reading for mechanics students.

1.3 'Engineering at the interface' by D. Dowson. *Proc. Instn Mech. Engrs, Part C: J. Mechanical Engineering Science*, 1992, 206, 149–165

From 1992 to 1993, Duncan Dowson was the 106th President of the Institution of Mechanical Engineers.

In his presidential address [**5**] entitled 'Engineering at the interface' reproduced as Appendix 3, he states that many of the challenging problems in engineering and life seem to occur at interfaces between the established disciplines or experiences. Sound solutions to current problems in engineering must be established on the twin pillars of respect for engineering education and research and an ever increasing collaboration between industry and higher education in relation to education and training and the solution of the technical problems of the future.

The publication starts with describing the author's family background. His mother's respect for education strongly influenced the guidance and advice offered to him at critical stages in his school career. His father was a talented blacksmith producing beautiful wrought iron work such as the Nelson memorial gates at Duncombe Park.

The main part of the Presidential Address deals with research in lubrication and bioengineering. Dowson states the importance of knowledge about interfaces:

> 'The level of confidence drops markedly when we consider the behaviour of surfaces, or even worse, of interfaces between machine elements'.

Today, in the age of nanotechnology, where surfaces are of ever more importance, knowledge in this area continuously increases. Still, interfaces continue to pose a challenge,

> 'not only in the relation to real behaviour of physical interfaces and their engineering significance but also in relation to the educational barriers and interfaces between established disciplines in engineering and science'.

The main section starts with historical remarks on tribology. In the second half of the nineteenth century, there was growing confusion about the nature of friction in lubricated machinery, and the Council of the Institution of Mechanical Engineers (founded in 1847) adopted in 1878 a proposal to sponsor research on the subject. Beauchamp Tower investigated friction in bearings and pivots and found out that

> '. . . the brass was actually floating on a film of oil . . .'.

Osborne Reynolds of the University of Manchester recognized that the behaviour of the lubricating film detected by Tower could be determined from the laws of fluid mechanics. The Reynolds equation of fluid film lubrication was published, and provided the foundation of twentieth century bearing analysis and design.

Dowson continued to illustrate some of the features of 'his first love, cavitation' and his major field of endeavour – elasthydrodynamic lubrication. He showed beautiful cavitation patterns of accumulated air and vapour phase lubricants in clearance spaces in machinery.

In 1956, Duncan Dowson and Gordon Higginson started their work on elastohydrodynamic lubrication. The reason for developing a new theory was the fact that all the solutions to the Reynolds equations predicted film thicknesses much inferior to the surface roughness of the devices. It was found that the influence of very high pressures upon lubricant viscosity and the elastic deformation of the solids in the vicinity of the stressed conjunction were remarkably supportive of film formation.

Their initial publication appeared in the first issue of the Institution's distinguished *Journal of Mechanical Engineering Science* (*JMES*) in 1959 [**6**].

The calculations were at that time performed by hand, and it took weeks of work to solve equations that can now be solved by computers in a matter of seconds.

Dowson and Higginson provided a formula that could be applied to predict the lubricant film thickness in a wide range of highly stressed machine elements.

The film thicknesses were about 40 times larger than those predicted by conventional hydrodynamic theory and ranged between 0.1 and 1 μm.

There is still no clear understanding of the mechanism, neither of lubrication in healthy human synovial joints nor of the factors responsible for the deterioration of some of them in osteoarthritis. In a long-standing cooperative research approach, research at this interface between engineering and medicine yielded quite remarkable results.

> '...sustained cooperation between engineers, physicians and surgeons at this difficult interface provides the best foundation for progress in bioengineering research'.

The load in the human synovial joint is dynamic, reaching peaks of three to six times body weight with every step he takes, while the motion is oscillatory rather than steady. The bearing is self-contained, subjected to a few million cycles of loading each year. The problem has been that hydrodynamic and even elastohydrodynamic theory predicted film thicknesses that were much too small compared with the known roughness of cartilage surfaces (typically 2 to 5 μm). Dowson and co-workers found that the undulations on the rough cartilage surfaces could be effectively smoothened out by self-generated perturbations to the hydrodynamic pressure during articulation.

Like many dynamically loaded engineering bearing systems the joint probably experiences fluid-film, mixed and boundary lubrication during normal operation.

The hip joint replacement is widely regarded as the major advance in orthopaedic surgery during the last century. Tribologists and material scientists have worked closely in association with orthopaedic surgeons to provide a sound engineering and medical base for the developments. A challenging task for the twenty-first century is to develop total replacement joints that enjoy the benefits of fluid-film lubrication, similar to natural joints.

In his presidential address, Dowson then touches upon the education of engineers and the academic-industrial interface:

> 'The main challenge is to establish the foundations of sound engineering principles and to develop skills in their application to the exciting range of problems encountered in our subject, while at the same time ensuring that the undergraduate develops an understanding of the human, social, political, and economic interactions affecting responsible professional engineering activity';

and

> '… the engineers of the future are stimulated to seek careers in industry. Likewise, the research carried out in universities provides that longer term fundamental knowledge base which underpins more immediate industrial developments. Neither teaching nor research thrive within a framework of short-term decisions, but I am not yet convinced that the value of long-term research in selected fields which can underpin our industrial base is fully recognized by society'.

2 IMPACT ON THE FIELD

2.1 Impact of these articles and the authors

The impact of Duncan Dowson's work on science and engineering is evident. One example is the high number of citations in the scientific literature.

The 1970 publication [**1**] was one of the initial publications by the author in this field. In the years around that date (1968, 1969, 1970 (2), 1972, 1973, 1974 (2), 1975 (3)), and also recently, in 2001, he published altogether 12 articles with 'human joint' in the title (source: ISI Web of Knowledge). The 2001 article appeared in a journal of the IMechE, in *Proc. Instn Mech. Engrs, Part J: J. Engineering Tribology* [**7**].

Verna Wright (1928–1998) was a rheumatologist at Leeds University. His research in rheumatology was characterized by a multi-disciplinary approach, including engineering and pharmacology. He wrote or co-authored hundreds of scientific articles and 21 books. Between 1968 and 1976 Dowson and Wright published seven articles together.

Higginson and Dowson have been publishing together for nearly half a century. Their first joint publication was in 1959 [**6**]: In the first issue of the first volume of the *JMES*, Duncan Dowson and Gordon Higginson, then lecturers in Mechanical Engineering at the University of Leeds, published the numerical solution to the elasto-hydrodynamic problem of highly loaded cylinders under isothermal conditions. They solved the simplified problem of two circular cylinders that were steadily rolling and/or sliding, being separated by a lubricating film. The lubricant film shape required to produce a given pressure curve can be determined completely by inverse hydrodynamics from the pressure curve. Therefore, the shape of the elastically deformed surface can be compared with the hydrodynamic film shape by equating the thickness of the oil films at the point of maximum pressure by solving the Reynolds equation. This fundamental publication has been cited 85 times between 1961 and 2007 (source: scholar.google.com).

47 years later Dowson and Higginson were still publishing together [**8**].

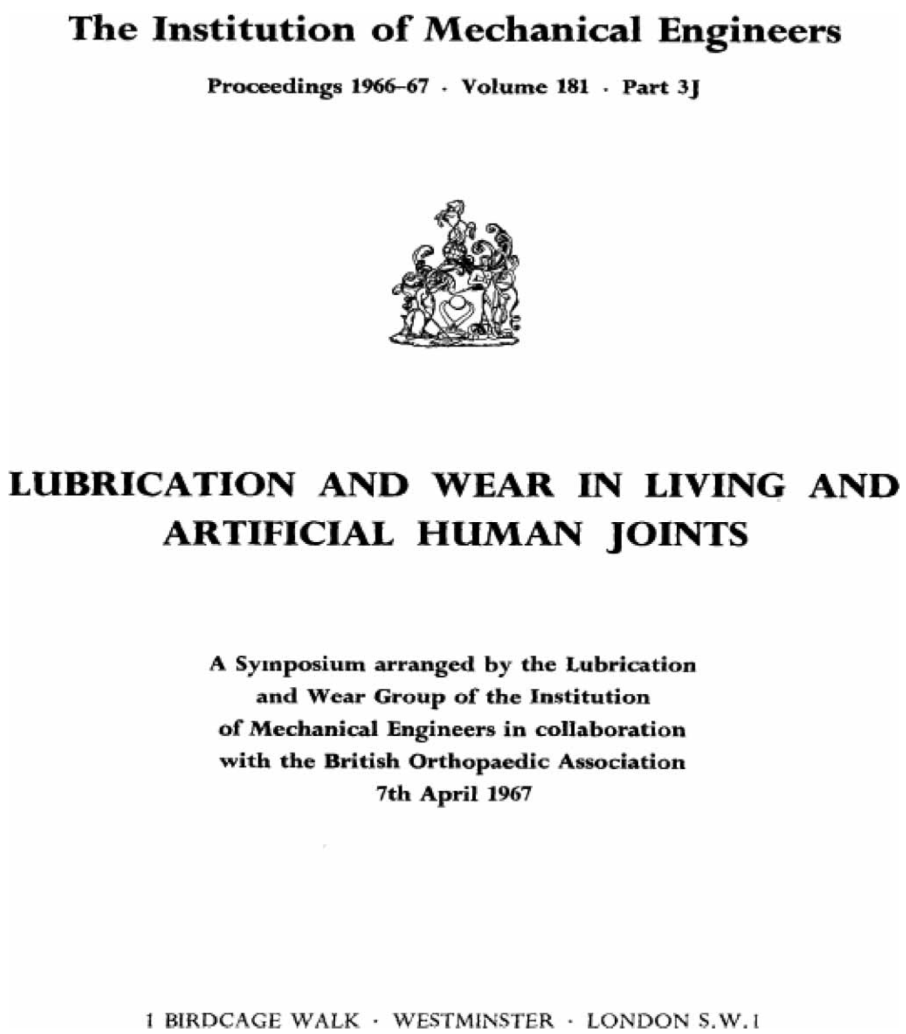
Higginson's first scientific publication dealt with the strength of short cylinders under internal pressure 1954 [**9**]. Starting from 1974, when he was dealing with a model investigation of squeeze-film lubrication in animal joints he included biological systems in his investigations [**10**]. Ever since then his work has focused on articular cartilage and hip joints.

Higginson and Norman published three articles together in 1974: they were dealing with lubrication of porous elastic solids with reference to the functioning of human joints [**11**], a model investigation of squeeze-film lubrication in animal joints [**10**], and fluid entrapment by a soft surface-layer [**12**]. These publications are still widely cited.

Tony Unsworth, now a Professor in the School of Engineering and Applied Science at the University of Durham, has 112 peer reviewed scientific articles listed in the ISI Web of Knowledge. He has contributed to hip implant research over several decades, and just recently published an article on soft layer lubrication of artificial hip joints [**13**]. He has been the director of the Centre for Biomedical Engineering since 1989 and is the editor of the *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*.

3 IMPACT OF THE JOURNAL

In 1967, the Institution of Mechanical Engineers published the Proceedings of a Symposium on human joints. These Proceedings were called 'Lubrication and wear in living and artificial human joints' (for title page, Fig. 1) [**14**]. The contributions and authors read like a 'who-is-who' in the field: 'Basic anatomy of weight-bearing joints' by M. A. MacConaill, 'Forces transmitted by joints in the human body' by J. P. Paul (cited 166 times, scholar.google.com), 'Physical characteristics of articular cartilage' by J. Edwards (cited 16 times, scholar.google.com), 'Properties of synovial fluid' by D. V. Davies, 'Materials and the design of artificial weight-bearing joints' by M. J. Neale, 'Friction and wear, detection and measurement' by F. T. Barwell, 'Modes of lubrication in human joints'



The Institution of Mechanical Engineers

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LUBRICATION AND WEAR IN LIVING AND ARTIFICIAL HUMAN JOINTS

A Symposium arranged by the Lubrication
and Wear Group of the Institution
of Mechanical Engineers in collaboration
with the British Orthopaedic Association
7th April 1967

1 BIRDCAGE WALK · WESTMINSTER · LONDON S.W.1

Fig. 1 Title page of the proceedings volume of the symposium on 'Lubrication and Wear in Living and Artificial Human Joints' [**14**]

by D. Dowson (cited 35 times, scholar.google.com), 'Physiological lubrication' by C. W. McCutchen (cited twice, scholar.google.com), 'Arthroplasty of the hip using foreign materials: a history' by J. T. Scales (cited eight times, scholar.google.com), 'Developments in total hip joint replacement' by G. K. McKee, 'Total human hip joint prostheses – a laboratory study of friction and wear' by I. Duff-Barclay and D. T. Spillman (cited five times, scholar.google.com), 'Factors in the design of an artificial hip joint' by J. Charnley, 'Problems of acetabular fixation in total hip replacement' by J. N. Wilson, 'Complex movements at the knee joint' by C. D. Shute, 'Hyaluronic acid films' by Alice Maroudas (cited 14 times, scholar.google.com), 'Are synovial joints squeeze-film lubricated?' by R. S. Fein (cited nine times, scholar.google.com), 'Patterns of ageing in human joints' by J. W. Goodfellow and P. G. Bullough, 'Friction and wear of artifical joint materials' by P. S. Walker, D. Dowson, M. D. Longfield, and V. Wright, 'Influence of carbide distribution on the wear and friction of "vitallium"' by S. J. H. Ahier and K. M. Ginsburg (cited ten times, scholar.google.com), 'A laboratory experiment on total hip prosthesis' by A. Poli, 'Current status of joint lubrication' by L. Dintenfass (cited twice, scholar.google.com), and 'A theoretical analysis of hip joint lubrication' by P. Marnell.

This volume of proceedings [**14**] established the state of knowledge and provided the springboard for much of the work to follow.

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APPENDIX 1

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ANALYSIS OF 'BOOSTED LUBRICATION' IN HUMAN JOINTS

By D. Dowson*, A. Unsworth† and V. Wright‡

The load-bearing human joint is a self-acting dynamically loaded bearing which employs a porous and elastic bearing material (articular cartilage) and a highly non-Newtonian lubricant (synovial fluid).

The authors' understanding is that the human joint experiences fluid-film (including elastohydrodynamic), mixed and boundary lubrication in its various operating conditions. It has been recognized that squeeze-film action is capable of providing considerable protection to the cartilage surface once a fluid film is generated (6) (8)§. Furthermore, the possibility of an increasing concentration of hyaluronic acid in synovial fluid during the squeeze-film action due to the porous nature of the cartilage and its surface topography and the known relationship between this concentration and the effective viscosity (7) has led to the concept of 'boosted lubrication' as an important feature of joint behaviour (10).

A mathematical analysis of the concept of boosted lubrication of human joints is presented in this paper. The predictions of the analysis are shown to be in good agreement with experimental findings (12).

INTRODUCTION

In engineering terms the human joint is a self-acting dynamically loaded bearing which uses a porous and elastic bearing material (articular cartilage) and a highly non-Newtonian lubricant (synovial fluid). The analysis of such a bearing in normal engineering situations would not be easy and in the biological environment it is even more difficult.

Serious study of the lubrication mechanism in human joints has extended over the past 40 years but it is only very recently that a fairly clear picture of the process has emerged. Much effort has been expended in trying to describe the operation of load bearing human joints in terms of a single mode of lubrication familiar to the engineer. However, when the operating conditions outlined in the first paragraph are recalled and quantified it soon becomes clear that such efforts are unlikely to succeed. The understanding of the present authors is that the human joint experiences fluid-film (including elastohydrodynamic), mixed and boundary lubrication situations in its varied operating conditions and a full appreciation of the exceptional characteristics of the human bearing requires a recognition of the role of each mode of lubrication.

MacConaill (1) suggested as early as 1932 that human joints probably utilized the hydrodynamic mode of lubrication but Charnley (2) challenged this view in 1959 when he concluded that experimental evidence supported a boundary lubrication action. McCutchen (3) introduced the porous nature of the cartilage into the lubrication concept when he proposed his 'weeping lubrication' ideas in 1959. The successful application of elastohydrodynamic concepts to engineering situations in the early 1960s was accompanied by the suggestion that the elasticity of cartilage might be important in human joint lubrication. Dintenfass (4) and Tanner (5) were associated with this suggestion and in 1967 Dowson (6) concluded that . . . 'the major lubrication mechanism would seem to be some form of elastohydrodynamic action determined by sliding or squeeze-film action between porous surfaces with boundary lubrication providing the surface protection in cases of severe loading and little movement.'

Three further observations of importance to the present understanding of human joint lubrication were reported between 1964 and 1967. Negami (7) found that the viscosity of synovial fluid was related to the concentration of hyaluronic acid in an approximately linear manner. Fein (8) drew attention to the importance of squeeze-film action in human joint lubrication in 1967 and at the same time Maroudas (9) reported that, under pressure, a gel of concentrated synovial fluid collected on the surface of the cartilage.

A study of the surface topography of cartilage specimens and a range of squeeze-film experiments on a reciprocating friction machine led Walker *et al.* (10) to propose in 1968

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§ *References are given in the Appendix.*

that a mode of lubrication previously unknown to tribologists probably played a significant part in the successful operation of load bearing human joints. According to this concept, known as 'boosted lubrication', squeeze-film action leads to a concentration of hyaluronic acid-protein complex in the lubricant as a result of diffusion of water and low molecular weight substances through the porous cartilage and the restricted gap between the approaching cartilage surfaces. The increased concentration of hyaluronic acid will give rise to an increase in viscosity of the synovial fluid in accordance with Negami's findings and the proposal is also consistent with the formation of gels on the cartilage surface (Maroudas). Scanning electron microscope studies of cartilage surface (11) subsequently provided evidence in support of this view in the form of trapped pools of concentrated synovial fluid in the surface depressions. This action, which appears to be without parallel in engineering situations, provides an 'enriched' lubricant of increasing viscosity as the cartilage surfaces approach each other, whilst the 'trapped pools' of hyaluronic acid-protein complex or gel in the surface depressions form reservoirs of a boundary lubricant ready to afford protection to the surfaces if sliding motion ensues. The efficacy of these surface gels as boundary lubricants is not fully known, but the unique performance characteristics of load-bearing human joints suggest that they are admirably suited to the biological situation.

The role of lubricant enrichment in delaying the approach of load carrying cartilage surfaces has not previously been the subject of mathematical analysis, and this was one of the main objects of the work described in this paper. It should be emphasized that this particular study is concerned with only one aspect of the wide spectrum of lubricating conditions which we believe are encountered in load-bearing human joints. However, the results confirm the importance of squeeze-film action and the extraordinary protection afforded to the cartilage surfaces by the mechanism of 'boosted' lubrication.

THEORETICAL ANALYSIS

In this analysis of squeeze-film action under conditions of boosted lubrication it will be assumed that the viscosity of the lubricant increases as the surfaces approach each other. This effect would follow from an increase in the concentration of hyaluronic acid which might occur as a result of filtration of the synovial fluid or by the restriction on the movement of relatively large hyaluronic acid molecules in the direction tangential to the surfaces at small film thicknesses.

Another possibility is that the hyaluronic acid acts as a boundary lubricant and that the molecules show an affinity for the surface of the cartilage. In all these cases the concentration of hyaluronic acid will increase as the surfaces approach each other and in this analysis an attempt will be made to determine the effect of this increased concentration upon squeeze-film times.

Negami (7) has shown that the viscosity of synovial fluid varies linearly with concentration of hyaluronic acid. It is widely believed that the viscosity of synovial fluid has a base value of 0·001 Ns/m^2 and since Negami records the viscosity of synovial fluid as about 0·05 Ns/m^2 for a concentration of hyaluronic acid of 8 mg/cm^3, a reasonable representation of viscosity as a function of concentration is,

$$\eta = \left(1+\frac{c}{0{\cdot}16}\right)\times 10^{-3}\ \mathrm{Ns/m^2} \quad . \quad . \quad (1)$$

If it is further assumed that in boosted lubrication the concentration of hyaluronic acid (c) is inversely proportional to film thickness (h), a general expression for viscosity can be written as,

$$\eta = \eta_0\left(1+\frac{F}{h}\right) \quad . \quad . \quad . \quad . \quad (2)$$

where F is determined from a knowledge of the concentration of some specified film thickness by the relationship,

$$F = \frac{ch}{0{\cdot}16} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and η_0 represents the base viscosity; normally 10^{-3} Ns/m^2.

In the subsequent analysis it will be assumed that the approaching surfaces retain their shape throughout the squeeze-film action.

(a) *A cylinder near a plane*

It has been noted by Dowson (6) that the knee joint can be represented with reasonable accuracy by a cylinder near a plane as shown in Fig. 1*a*. If two-dimensional flow is considered the governing Reynolds equation is

$$\frac{d}{dx}\left(\frac{h^3}{\eta}\frac{dp}{dx}\right) = -12W \quad . \quad . \quad . \quad (4)$$

This equation is presented with the assumption that all the fluid displaced by the approaching surfaces is squeezed out of the lubricating film into the surrounding space and that the volume flowing through the porous cartilage is negligible. The adequacy of this assumption can be tested as follows.

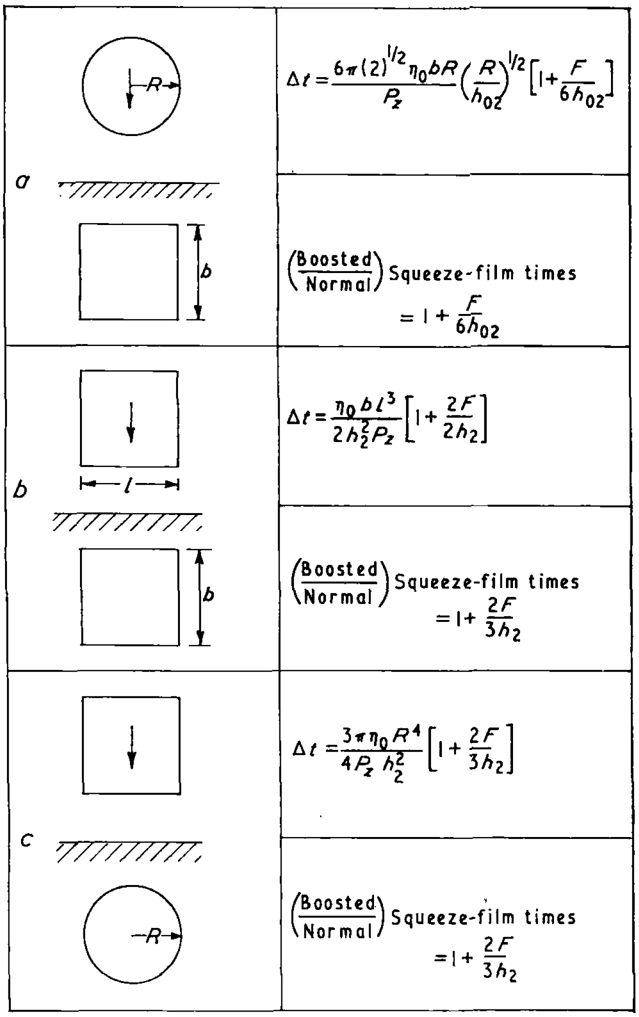
Edwards (12) has studied the porosity of the cartilage and he expressed the rate of flow Q through a thin section of cartilage of thickness X and cross-sectional area A under a pressure difference p by the equation

$$\frac{Q}{A} = k\frac{p}{X}$$

It is quite likely that the lack of homogeneity of the cartilage will lead to different values for k in directions normal and parallel to the free surface, but with the limited amount of information currently available on this point it will be adequate for the present calculation to adopt the value of k quoted by Edwards as a result of his experiments with cartilage and water.

If the thickness of the cartilage is t the flow parallel to the cartilage surface per unit width at any section is

$$Q = -kt\frac{dp}{dx}$$



Δt = boosted lubrication squeeze-film time.
a Rigid cylinder and plane.
b Parallel plane rectangular surface.
c Parallel circular plates.

Fig. 1. *Squeeze-film geometries*

The pressure gradient varies with x but if it is assumed that flow in the porous cartilage has little effect upon the normal squeeze-film pressure distribution and that the effective lubricating film between the cylindrical and plane surfaces terminates at a point where the surface separation is large compared with the minimum film thickness, the following expression can be employed

$$\frac{dp}{dx} = \frac{-12\eta Wx}{h_0^3}$$

Hence

$$Q = 12\eta W\, kt\, \frac{x}{h^3}$$

The corresponding rate at which fluid is being displaced from the clearance space is Wx per unit width and hence, when account is taken of lubricant flow through two layers of cartilage,

$$\frac{\text{flow through porous cartilage}}{\text{total squeeze film flow}} = \frac{24\eta kt}{h^3}$$

Typical values for the quantities in this expression are:

$\eta = 10^{-3}$ Ns/m²
$k = 10^{-16}$ m⁴/Ns (see reference (12))
$t = 2\times 10^{-3}$ m
$h = 10^{-6}-10^{-5}$ m (see reference (13))

The data suggest that the flow through the porous cartilage is less than one two-hundredth of the total volume of fluid displaced by the squeeze film action.

This approximate analysis suggests that flow through the cartilage can be neglected and that little error will be introduced by adopting equation (4).

If the usual parabolic profile is assumed,

$$h = h_0 + \frac{x^2}{2R} \quad . \quad . \quad . \quad . \quad (5)$$

With the boundary condition that $p \to 0$ as $h \to \infty$ double integration of equation (4) and the introduction of the viscosity relationship (3) yields,

$$p = 6\eta_0\, WR\left[\frac{1}{h^2}+\frac{2F}{3h^3}\right] \quad . \quad . \quad . \quad (6)$$

The load carrying capacity per axial width b is given by

$$P_z = \frac{3\eta_0 WbR\pi(2Rh_0)^{1/2}}{h_0^2}\left[1+\frac{F}{2h_0}\right] \quad . \quad (7)$$

The time taken for the surfaces to approach each other from a given minimum separation h_{01} to a final separation h_{02} is obtained by noting that $W = -dh_0/dt$. Integration then gives

$$\Delta t = \frac{3\pi(2)^{1/2}\eta_0 bR}{P_z}\left[2\left(\frac{R}{h_0}\right)^{1/2}+\frac{F}{3h_0}\left(\frac{R}{h_0}\right)^{1/2}\right]_{h_{01}}^{h_{02}} \quad (8)$$

If $h_{02} \ll h_{01}$,

$$\Delta t = \frac{6\pi(2)^{1/2}\eta_0 bR}{P_z}\left(\frac{R}{h_{02}}\right)^{1/2}\left[1+\frac{F}{6h_{02}}\right] \quad . \quad (9)$$

This is the 'boosted' lubrication squeeze-film time. In the conventional case, where the viscosity of the lubricant is assumed to be constant, $F = 0$ and

$$\Delta t = \frac{6\pi(2)^{1/2}\eta_0 bR}{P_z}\left(\frac{R}{h_{02}}\right)^{1/2} \quad . \quad . \quad (10)$$

Hence,

$$\frac{\text{'boosted' squeeze-film time}}{\text{'normal' squeeze-film time}} = 1+\frac{F}{6h_{02}} \quad (11)$$

(*b*) *Parallel plane surfaces*

The cartilage is elastic and it seems quite likely that local elastic deformation will yield a lubricant film of almost constant thickness in the load bearing region (8). It is therefore of interest to consider the approach of two parallel rigid surfaces of width l as shown in Fig. 1*b* in which the flow is two dimensional. The analysis follows similar lines to that for a cylinder near a plane and the important results are given below.

$$p = \frac{3\eta W}{2h^3}(l^2-4x^2) \quad . \quad . \quad . \quad (12)$$

$$P_z = \frac{\eta W b l^3}{h^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

$$\Delta t = \frac{\eta_0 b l^3}{P_z}\left[\frac{1}{2h^2}+\frac{F}{3h^3}\right]_{h_1}^{h_2} \quad . \quad . \quad (14)$$

and if $h_2 \ll h_1$,

$$\Delta t = \frac{\eta_0 b l^3}{2h_2{}^2 P_z}\left[1+\frac{2F}{3h_2}\right] \quad . \quad . \quad . \quad (15)$$

Equation (15) gives the boosted lubrication squeeze-film time. If the viscosity remains constant at η_0 the squeeze-film time is

$$\Delta t = \frac{\eta_0 b l^3}{2h_2{}^2 P_z} \quad . \quad . \quad . \quad . \quad (16)$$

Hence,

$$\frac{\text{boosted squeeze-film time}}{\text{normal squeeze-film time}} = 1+\frac{2F}{3h_2} \quad . \quad (17)$$

(c) Parallel circular plates

Fein (**8**) has noted that a synovial joint with spherical surfaces is kinematically equivalent to a spherical surface on a flat plate. The resulting dry contact area would present a circular shape and it is useful to consider this geometry. Once again rigid plates will be considered and the geometry is shown in Fig. 1*c*. The important results are

$$p = \frac{3\eta W}{h^3}[R^2-r^2] \quad . \quad . \quad . \quad . \quad (18)$$

$$P_z = \frac{3\pi\eta W}{2h^3}R^4 \quad . \quad . \quad . \quad . \quad . \quad (19)$$

$$\Delta t = \frac{3\pi\eta_0 R^4}{2P_z}\left[\frac{1}{2h^2}+\frac{F}{3h^3}\right]_{h_1}^{h_2} \quad . \quad . \quad (20)$$

and if $h_2 \ll h_1$,

$$\Delta t = \frac{3\pi\eta_0 R^4}{4P_z h_2{}^2}\left[1+\frac{2F}{3h_2}\right] \quad . \quad . \quad . \quad (21)$$

Equation (21) gives the boosted lubrication squeeze-film time. The normal squeeze-film time for constant viscosity is

$$\Delta t = \frac{3\pi\eta_0 R^4}{4P_z h_2{}^2} \quad . \quad . \quad . \quad . \quad (22)$$

Hence the ratio of boosted to normal squeeze-film times is identical with that for two dimensional flow between parallel plates considered in case 1(*b*) (see equation (17)).

A summary of the squeeze-film time expressions and the ratio of boosted to normal squeeze-film times is shown in Fig. 1.

THEORETICAL AND EXPERIMENTAL RESULTS

It is clear from the previous analysis that the ratio of boosted to normal squeeze-film times is determined by a factor of the form $[1+k(F/h_2)]$. The problem is to determine the magnitude of this factor for realistic situations.

Initial film thickness (h_1)

Dowson (**6**) has estimated the elastohydrodynamic film thickness in knee and hip joints to be in the range $10^{-4}-10^{-3}$ cm. It seems unlikely that films substantially greater than the latter figure will be generated in normal walking motion and hence for the present purpose it will be assumed that the initial film thickness at the beginning of squeeze-film action is 10^{-3} cm.

Final film thickness (h_2)

Studies of the surface roughness of articular cartilage by Walker *et al.* (**10**) have shown that the human bearing surface is much rougher than conventional engineering bearings. Specimens from younger subjects displayed an undulating surface with a c.l.a. of about $0{\cdot}8\times10^{-4}$ cm whilst some samples which showed evidence of osteoarthrosis had c.l.a. values of about 5×10^{-4} cm. Since we are primarily concerned with squeeze-film performance in healthy joints and there is some evidence of surface contact and transition from fluid-film to boundary lubrication conditions in engineering situations when the effective film thickness falls to a value comparable to the c.l.a. of the bearing surfaces it seems reasonable to evaluate the time required for the film thickness to fall to a minimum value of 10^{-4} cm.

Evaluation of F

The lowest concentration of hyaluronic acid in normal synovial fluid shown in the graphs recorded by Negami (**7**) is about 3 mg/cm³. If this concentration is assumed to apply to the fluid at the initial film thickness h_1 equation (3) shows that F has a value of 3/160 cm.

Calculation of the ratio of boosted to normal squeeze-film times

If a value of F of 3/160 cm is adopted equations (11) and (17) show that the ratios of boosted/normal squeeze-film times for a final film thickness of 10^{-4} cm and the three geometrical forms considered in the section dealing with theoretical analysis are:

(*a*) 32 (*b*) 126 (*c*) 126

Squeeze-film times

Typical values for the operating conditions in the load bearing human joints for squeeze-film situations are:

Load 50–150 kg ($0{\cdot}5-1{\cdot}5\times10^3$ N)
Effective radius of sphere near a plane (as defined in reference (**6**)), 2–100 cm
Effective modulus of elasticity 10^6–10^8 dyn/cm².

Table 1

Test	Time under load, seconds	Film thickness calculated from experimental values of frictional shear stress, m × 10⁶	Boosted lubrication film thickness based upon experimental squeeze-film times, m × 10⁶
1	3	8·8	8·5
2	2	7·9	10
3	5	6·7	7·3
4	30	4·7	4·0
5	60	4·1	3·0
6	600	1·1	1·5

The radius of the circular Hertzian contact zone for these conditions ranges from 0·01–0·3 cm. This range suggests that considerable local elastic flattening will occur and that the best squeeze-film models will be given by two parallel surfaces (cases (*b*) and (*c*)). Furthermore the concentration of 3 mg of hyaluronic acid per cm^3 of synovial fluid corresponds to an initial viscosity of 0·03 Ns/m^2.

If a load of 10^3 N is applied to two circular parallel plates of radius 1 cm and final separation 10^{-4} cm in the presence of synovial fluid of viscosity 0·02 Ns/m^2 the normal squeeze-film time given by equation (22) is 0·47 s.

The corresponding boosted squeeze-film time given by equation (21) is

$$0{\cdot}47\left[1+\frac{2F}{3h_2}\right] = 0{\cdot}47\times 126$$
$$= 59 \text{ s}$$

This period of approximately one minute is an exceedingly large interval in relation to the walking cycle time. It demonstrates the tremendous protective action provided by boosted lubrication.

Comparison with experimental evidence

Unsworth *et al.* (**13**) have described the results of a reciprocating friction experiment carried out by Walker in which the friction force was recorded as a specimen of cartilage sank through a film of synovial fluid towards a moving glass plate. The time under load varied from 2 to 600 seconds in the six experiments and the film thicknesses calculated from the measured shear force and speed and an assumed coefficient of viscosity of 0·001 Ns/m^2 consistent with the behaviour of synovial fluid at high shear rates are shown in Table 1. The boosted lubrication film thicknesses corresponding to the experimental squeeze-film times have been calculated from equation (21) and the values are recorded in Table 1.

DISCUSSION

The analysis has demonstrated that any process which leads to an increase in concentration of hyaluronic acid and hence in the viscosity of synovial fluid as the squeeze-film action takes place will lead to an increase in the squeeze-film time. When the available experimental evidence on the effect of concentration of hyaluronic acid upon viscosity is utilized it becomes apparent that the role of lubricant enrichment in the boosted lubrication mechanism is considerable. This point is demonstrated by the example quoted in the paper in which the boosted squeeze-film is found to be more than two orders of magnitude greater than the normal squeeze-film time.

The period of almost one minute which is calculated for the boosted squeeze-film time in the example demonstrates the tremendous facility of the human joint to preserve a fluid film. If significant films are developed during the lightly loaded swing phase of the walking cycle, and earlier studies (**6**) make it difficult to escape this conclusion, it seems unlikely that fully developed boundary lubrication will be encountered in healthy joints with reasonably good surface quality during the walking cycle. Prolonged periods of loading under near stationary conditions will inevitably introduce a boundary lubrication condition and it is likely that the enriched surface films or gels noted by Unsworth *et al.* (**10**) will play a dominant part in determining the friction and wear characteristics under these conditions.

One of the big difficulties with the interpretation of friction and lubrication studies of the human joint is the area of uncertainty which surrounds the quantitative statements referring to film thickness, surface roughness, lubricant viscosity, etc. The values selected for the examples quoted in this paper represent best estimates from the available experimental evidence. However, in this connection it is interesting to note that Maroudas (**14**) has suggested that the effective separation of the surfaces at which the fluid will cease to flow sideways is about 5000 Å (5×10^{-5} cm). This figure corresponds closely with the final film thickness adopted in the numerical work in this paper which was based upon measurements of surface quality of articular cartilage. Maroudas has also indicated that the gel noted on cartilage surface might become stable at a thickness of 100–250 Å ($1\text{–}2{\cdot}5\times 10^{-6}$ cm). This figure is most interesting in relation to the calculated final film thickness for boosted lubrication conditions and the values deduced from Walker's experiments which are both recorded in Table 1. The values fall within the range ($1\text{–}9\times 10^{-6}$ cm) and the results appear to be entirely in accord with the thicknesses suggested by Maroudas.

It is interesting to speculate on the relative importance of the filtration action provided by the porous cartilage and the surface undulations in the boosted lubrication mechanism. Early indications suggested that the effect was mainly associated with the difficulty which the large molecules of hyaluronic acid would have in entering the fine pore structure of the cartilage and that large scale fluid movements in the cartilage would be restricted to the dialysate. However, two factors have been recognized which support the view that the restriction to side-leakage of the large molecules may be most important. In the first place the effective diameter of the passage in the cartilage is extremely small. Secondly, the surface of cartilage has been shown to be relatively rough, and it has been noted in this paper that effective fluid films probably have to exceed 10^{-4} cm in thickness if substantial asperity contact is to be avoided. A comparison of the pore and film thickness dimensions suggests that the permeability of the space between opposing rough cartilage surfaces is much lower than that of the cartilage.

These observations suggest that the filtration of hyaluronic acid which leads to the concept of boosted lubrication in squeeze-film action is primarily related to the side-leakage action.

CONCLUSIONS

The analysis and calculations strongly support the view that a form of squeeze-film action peculiar to human joints and known as boosted lubrication is capable of providing a valuable mechanism for the preservation of effective fluid-film lubrication.

The results are in general accord with existing experimental evidence and they provide support for the view that squeeze-film action is an important aspect of the wide spectrum of lubrication régimes encountered in the human joint. This view, which has only recently (**9**) attracted the attention of research workers, was mentioned by Osborne Reynolds (**15**) in 1886 when he concluded his classical paper on the theory of fluid film lubrication with the words . . . 'The only other self-acting system of lubrication is that of reciprocating joints with alternate pressure on and separation (drawing the oil back or a fresh supply) of the surfaces. This plays an important part in certain machines, as in the steam engine, and is as fundamental to animal mechanics as the lubricating action of the journal is to mechanical contrivances'.

APPENDIX

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APPENDIX 2

THE LUBRICATION OF POROUS ELASTIC SOLIDS WITH REFERENCE TO THE FUNCTIONING OF HUMAN JOINTS

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The paper describes computational and experimental results for a simple mechanical model which has some features in common with load-bearing human joints. The normal approach of two rigid solids, one of which is covered by a layer of flexible porous material, is analysed; the gap between the bodies is filled with a viscous fluid. The rate of approach of the bodies is calculated and measured. Agreement between experiment and calculation is quite good, and some tentative conclusions are drawn about the lubrication of human joints, particularly in connection with the role played by the permeability of the cartilage layer.

1 INTRODUCTION

In engineering situations, the ideal role of a fluid lubricant is to separate completely two solid surfaces which are (usually) in relative motion. Such a regime is described as full-film lubrication. If the relative motion of the solids is normal approach, without rolling or sliding, the only deterrent to contact of the solids is the resistance provided by the viscous fluid as it is squeezed out sideways. This mechanism is called the 'squeeze film'.

This paper is concerned with a fairly straightforward physical situation: the normal approach of a porous elastic solid and a rigid impervious solid, separated by a viscous fluid; but the work was inspired by the vastly more complicated situation obtaining in living, human load-bearing joints. There, non-Newtonian thixotropic synovial fluid lubricates two layers of porous articular cartilage which have non-linear stress/strain/liquid-content relations.

A brief history of the theories of joint lubrication has already been given by Dowson, Unsworth and Wright (1)‡, whose understanding is that 'the human joint experiences fluid-film (including elastohydrodynamic), mixed and boundary lubrication situations in its varied operating conditions and a full appreciation of the exceptional characteristics of the human bearing requires a recognition of the role of each mode of lubrication'. In the critical situation of high normal load and low or zero sliding velocity, those authors propose a mechanism which they call 'boosted lubrication'. That mechanism depends on an increase in the viscosity of synovial fluid as the gap between the opposing cartilage surfaces closes, caused by the increasing concentration of hyaluronic acid, the solute which is largely responsible for the viscosity of the fluid. They argue that, because the hyaluronic acid molecules are too big to pass through the pores in the cartilage, the concentration in the gap increases as the base fluid (water) is driven away through the pores, and filtered parallel to the film through the aggregates on the surface of the cartilage. They give a simple and persuasive quantitative analysis in support of the proposal.

In a communication relating to the paper, McCutchen takes issue with the authors on fundamentals and on a number of details. Arguing qualitatively, McCutchen reasserts his often stated view (2) (3) that the porosity of the cartilage, coupled with the impervious nature of the bone backing, is responsible for the very low coefficients of sliding friction, but by a mechanism quite different from that of Dowson, Unsworth and Wright. He sees the load carried mainly by the fluid, in a regime which he describes as 'self-pressurized hydrostatic lubrication'. The coefficient of friction is very low when the load is first applied, but increases markedly as fluid is wrung from the cartilage, and the solid carries an increasing proportion of the load. Local solid-to-solid contact is a feature of McCutchen's proposed mechanism, and he emphasizes that the fluid between the opposing solids is there by virtue of wringing out, and that whatever fluid film is active it is hydrostatic and not hydrodynamic. He has given the mechanism the name 'weeping lubrication'.

From all that has been written about the functioning of human joints, no reliable description of their lubrication has emerged. One probable conclusion is that no single mechanism operates throughout the range of practical conditions, as has been noted by Dowson, Unsworth and Wright. However, it does seen quite likely, on the evidence available, that simple fluid film lubrication prevails in conditions where the entraining velocity is substantial and the loads are not abnormally high, in much of the walking cycle for example (4). No doubt even there the flexibility of the cartilage plays a dominant role in promoting full-film lubrication (as anyone who has observed the difference in the behaviour of a hard-boiled egg on a wet, smooth draining-board, before and after removal of its shell, will appreciate!). The simple experiments of Bennett and Higginson (5) in pure sliding lend support to this view; a thin surface layer of soft material sustains full-film, low-friction lubrication down to values of the parameter (speed × viscosity)/load more than an order of magnitude below that at which the film breaks down between rigid solids.

The simple elastohydrodynamic mechanism appears

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‡References are given in the Appendix.

to be adequate during the relatively straightforward phase of the operation, with no need to enlist the help of the various complications. The work described here is devoted to those conditions where the entraining velocity is small or zero; at such points in the walking cycle the load is high, viz. at 'heel-strike' and 'toe-off' (6). At these points the relative velocity between the mating solids is normal approach, and hydrodynamic lubrication must rely on the squeeze film effect.

As will be seen below, the model used in the investigation is *very* much simpler than the real thing. While clearly inspired by human joints, it lays no claim to describe them adequately, let alone accurately. Furthermore, the experiments use only isoviscous lubricants, but the calculations are extended to include the effect of solute concentration on viscosity. The values of the parameters employed in the experimental model are very different from those of human joints, but the object of the experiments is to confirm the approximate validity of the theory, which can then be applied with some confidence to values more appropriate to joints.

1.1 Notation

A	Flexibility of surface layer ($= \delta/p$)
A^*	AL/R^2T
c	Concentration of solute
c_i	Initial concentration
D	Initial separation on centre-line
F	Hydrostatic force
h	Film thickness
h_0	Centre-line film thickness
h^*	h/D
L	Load
M	Mass of falling solid
p	Pressure
p_0	Centre-line pressure in film
p^*	p_0R^2/L
r, θ, z	Cylindrical co-ordinates, origin on centre-line at surface of soft layer
R	Radius of curvature of upper solid
t	Time
t^*	$tL/\eta R^2$
T	Thickness of surface layer
u, w	Radial and axial rates of fluid flow per unit area
V	Void ratio
w_1	Velocity of lower surface
w_2	Flow rate per unit area of fluid out of porous solid
x	Centre-line displacement of upper solid
δ	Elastic displacement of surface layer
ε	Axial compressive strain in surface layer
η	Viscosity
η_0	Viscosity of base fluid
η_1	Initial value of η
η_2	Notional value of η when $c = 1$
φ	Permeability
φ_r, φ_z	Permeabilities in radial and axial directions
φ^*	φ/T^2

2 GEOMETRY OF THE MODEL

It was thought that the phenomenon as a whole would not be materially altered by having a porous elastic layer on only one of the rigid solids. The layer is therefore mounted on a flat rigid surface, which is stationary; the approaching, spherical surface is also rigid. The simplicity of the arrangement, shown in Fig. 1*a*, is obvious. The normal approach is achieved by allowing the upper solid to fall under gravity onto the lower one.

2.1 Apparatus

The experimental rig is essentially as shown in Fig. 1. The spherical surface is of polished steel with a radius of 0.3 m. It falls under gravity from an initial clearance of

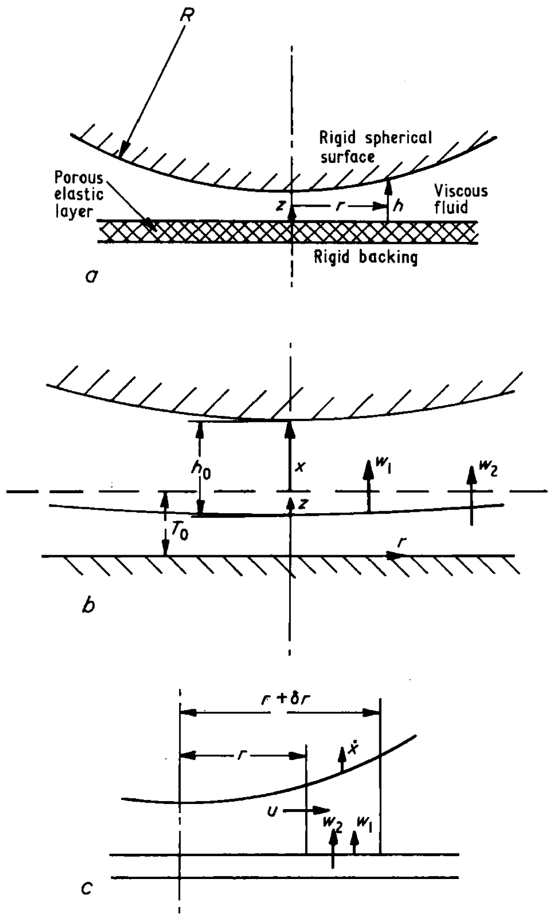

Fig. 1. *Geometry and notation*

0.25 mm, with a mass of approximately 4, 6 or 8 kg. The soft layers on the lower surface are all 5 mm thick, mounted on a steel backing-plate. The surface layers used in the experiments are:

(1) elastic porous (two materials, one with a much higher permeability than the other)
(2) elastic 'perforated' (silicone rubber with small axial holes, but no radial porosity)

The upper solid is retained by an electromagnet before dropping, and its axis is constrained to remain vertical during the fall. Measurements are made of the displacement of the upper surface, and of the mean pressure over a small area at the centre of the upper surface. An inductive displacement transducer mounted vertically on the support of the lower surface reads directly the displacement of the upper solid; the signal is recorded on an ultraviolet oscillograph. Because a fairly flat-topped pressure distribution is to be expected, the pressure is measured by the simple device of a small, stiff diaphragm in the spherical surface, on the centre-line. Machined out of the solid upper surface, the diaphragm is 0.75 mm thick and 10 mm in diameter; at the centre of the back is mounted a semiconductor strain gauge with a gauge factor of about 100. This simple pressure gauge was calibrated by applying hydrostatic pressure to the spherical surface. In the normal-approach experiments, the pressure signal is recorded simultaneously with the displacement on the same u.v. recorder.

The properties of the soft surface layers are defined in Section 3, and their values are given in Table 1. Three mineral oils were used as lubricants: their viscosities were 0.21, 1.28 and 6.3 Ns/m^2.

Table 1

Material	Flexibility, A (m^3/N)	Permeabilities, φ_r, φ_z (m^2)
Perforated rubber	0.5×10^{-9}	
Porous plastics	0.15×10^{-10}	
Low-permeability plastics	—	$\varphi_r = 0.9 \times 10^{-12}$, $\varphi_z = 2.1 \times 10^{-12}$
High-permeability plastics	—	$\varphi_r = 1.3 \times 10^{-11}$, $\varphi_z = 2.9 \times 10^{-11}$

3 ALGEBRA

The equation of motion of the upper body falling under gravity is

$$F - Mg = M\ddot{x} \qquad (1)$$

where M is the mass of the falling body and F is the force exerted by the fluid

$$F = \int p\,\mathrm{d}\,(\text{area})$$

integrated over the whole active area of the fluid film. It will be seen in the calculations that follow that $M\ddot{x}$ is very small compared with the other terms in the important closing stages of the squeeze film action.

The physical effects to be considered are the development of pressure in the fluid between the solids, the flow of fluid between the solids and through the porous layer, and the deformation of the elastic porous solid layer. It will be assumed that the local deformation of the thin elastic layer is given by

$$\delta = Ap \qquad (2)$$

where p is the local pressure in the fluid and A is a flexibility coefficient. The adequacy of this expression has been examined by Hooke, Brighton and O'Donoghue (7) in computations on the effects of distortion on the performance of a journal bearing with a thin elastic liner. They concluded that for thin layers with Poisson's ratios of 0.28 and 0.4, the results of equation (2) will not differ significantly from the exact solution, but for materials with Poisson's ratio near to 0.5 (such as rubber), the results will be inaccurate. The soft layers considered all have some sort of porosity, which it would seem, intuitively, would guarantee that Poisson's ratio is nowhere near to 0.5, a figure which implies incompressibility. The shape of the oil film is

$$h = x + \frac{r^2}{2R} + Ap \qquad (3)$$

This employs the parabolic approximation to the circular profile of the upper surface, involving negligible error over the effective area of the film.

The equations governing the flow and development of pressure in the fluid will now be derived. In the gap between the solids the Reynolds equation will be used. In the elastic porous solid, some assumptions not usually encountered in lubrication theory will be necessary, so they will be examined first.

3.1 Flow in the porous solid

The modern extension of Darcy's law for the flow of water through a sand filter will be applied. Darcy's empirical result for the vertical flow of water through sand is

$$q = -K(h_2 - h_1)/l$$

where q is the volume of water crossing unit area in unit time, $(h_2 - h_1)$ is the head of water driving the flow, l is the thickness of the sand filter, and K is a factor of proportionality. This law has been extended (in soil mechanics, for example) to

$$w = -\frac{\varphi}{\eta}\frac{\partial p}{\partial z}$$

where w is the rate of flow per unit area in the z-direction, η is the fluid viscosity, and φ is a characteristic of the porous solid or aggregate of particles, called the permeability, and having units of area. The law is said to hold for flows with Reynolds numbers up to about 10 (8), which is much greater than the values prevailing in the present investigation.

The permeability is a function of porosity and the size and tortuosity of the pores or passages. It is determined experimentally by the application of Darcy's law to a measured flow. Now it might well be that the permeability of articular cartilage and other solids will not be the same 'along' as 'through' the thickness; for the plastic layers used in the experiments, the two values differed substantially. The theoretical model must therefore include this difference, and it will be embodied in the form of two coefficients, φ_z through the thickness and φ_r radially, thereby retaining axial symmetry. The form of Darcy's law we shall use is

$$u = -\frac{\varphi_r}{\eta}\frac{\partial p}{\partial r}$$

$$w = -\frac{\varphi_z}{\eta}\frac{\partial p}{\partial z} \qquad (4)$$

There remains the additional effect of deformation of the solid on the coefficients of permeability. There is as yet no information on this point, but a reasonable and simple assumption is that the permeability is proportional to the void ratio. In addition we assume that the deformation of the porous layer is accomplished entirely by closure of the voids (i.e. the volume of the solid material is not reduced), and that the radial and axial permeabilities are equally affected by the deformation.

The flow rates per unit area, u and w, are subject to the condition of continuity of flow; if we treat the fluid as incompressible, this is

$$\frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial w}{\partial z} - \frac{1}{(1-\varepsilon)}\frac{\partial \varepsilon}{\partial t} = 0 \quad . \quad . \quad . \quad . \qquad (5)$$

where ε is the axial compressive strain. The first three terms give the usual continuity of flow in an element of constant volume, and the fourth represents the variation of the volume of the element. Substituting for u and w, we obtain for an elastic porous solid

$$\frac{\partial^2 p}{\partial r^2} + \frac{\partial p}{\partial r}\left[\frac{1}{r} + \frac{1}{\varphi_r}\frac{\partial \varphi_r}{\partial r}\right] + \frac{\varphi_z}{\varphi_r}\frac{\partial^2 p}{\partial z^2} + \frac{\eta\dot{\varepsilon}}{\varphi_r(1-\varepsilon)} = 0 \quad (6)$$

3.2 Flow in the film between the solids—Reynolds equation

If fluid inertia is neglected, the condition of radial equilibrium of an element of fluid in the film is (8)

$$\frac{\partial^2 u}{\partial z^2} = \frac{1}{\eta}\frac{\partial p}{\partial r}$$

The variation of p across the film is negligible, so $\partial p/\partial r$ can be treated as independent of z. Integrating twice with respect to z, and putting $u = 0$ at $z = 0$ and $z = h$, gives

$$u = \frac{1}{2\eta}\frac{\partial p}{\partial r}z(z-h)$$

It should be noted that putting $u = 0$ at $z = 0$ (the lower surface) is not strictly consistent with the solution of the equation governing the flow in a solid with radial permeability.

If we now apply the condition of continuity of volume flow to the annulus in the film between r and $r + \delta r$, as in Fig. 1*c*, we obtain

$$\frac{\partial}{\partial r}(rq_r) = -(\dot{x} - w_1 - w_2)r$$

where

$$q_r = \int_0^h u\,\mathrm{d}z = -\frac{h^3}{12\eta}\frac{\partial p}{\partial r}$$

and hence the Reynolds equation

$$\frac{\partial}{\partial r}\left(r\frac{h^3}{\eta}\frac{\partial p}{\partial r}\right) = 12r(\dot{x} - w_1 - w_2) \quad . \quad . \quad . \quad . \qquad (7)$$

$\dot{x}$ is independent of r, but w_1, the velocity of the lower surface, and w_2, the flow rate per unit area out of the porous solid, are functions of r and t. The problem of the variation of w_1 across the width of the film has been tackled by Christensen (9) (10) and Herrebrugh (11) by taking an 'average velocity for the surface as a whole', in other words, neglecting the variation of w_1 in comparison with $\dot{x}$. In the present work we treat $(\dot{x} - w_1 - w_2)$ as independent of r for the *first integration only* of Reynolds equation, and allow w_1 and w_2 to vary with r subsequently. An examination of the calculations lends support *a posteriori* to this step.

Integrating (7), and noting that $\partial p/\partial r = 0$ at $r = 0$ for all values of t, gives

$$\frac{\partial p}{\partial r} = \frac{6\eta r}{h^3}(\dot{x} - w_1 - w_2) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (8)$$

This is the form of Reynolds equation used in the calculations. The equations to be solved are therefore (6) and (8). Continuity of pressure and axial flow must be maintained at the boundary, but as has already been noted, the solution involves a discontinuity in radial flow there.

3.3 Elastic perforated layer—a simple special case

It seemed to the authors, at the outset of this work, that the mechanism of McCutchen's 'weeping lubrication' would probably be most effective in a situation where $\varphi_z \gg \varphi_r$, that is, the resistance to fluid flow 'along' the thin cartilage layer is much greater than that 'through' the thickness. That would appear likely to promote 'self-pressurized hydrostatic lubrication', by providing an easier escape route into the *loaded* region of the film than into the unloaded region.

Some calculations on these lines are included in the full computations, but the limiting case of $\varphi_z > \varphi_r$, viz. $\varphi_r = 0$, leads to a simple model, and in particular a very simple, and accurate, version of Reynolds equation. Physically, the situation is represented by an elastic layer which contains a large number of small holes through the thickness, but with no connections parallel to the layer; fluid can enter or leave the holes only by way of the film between the solids (see Fig. 2).

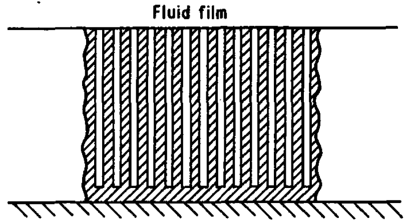

Fig. 2. *Elastic perforated layer*

The full Reynolds equation (7) is

$$\frac{\partial}{\partial r}\left(r\frac{h^3}{\eta}\frac{\partial p}{\partial r}\right) = 12r(\dot{x} - w_1 - w_2)$$

If we regard both the fluid and the material of the layer as incompressible, then $w_1 + w_2$ must equal zero everywhere, because flow per unit area w_2 out of the solid can only be engendered by a (downward) velocity $w_1 = -w_2$ of the solid surface (see Fig. 1*b*). So Reynolds equation becomes

$$\frac{\partial}{\partial r}\left(r\frac{h^3}{\eta}\frac{\partial p}{\partial r}\right) = 12r\dot{x}$$

which can be integrated to

$$\frac{\partial p}{\partial r} = \frac{6\eta r\dot{x}}{h^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (9)$$

4 ARITHMETIC

4.1 Dimensional analysis

The film thickness and pressure on the axis of symmetry at any time can be described in terms of ten variables.

$$h_0, p_0 = f_{1,2}[t, L, \eta, D, R, T, A, \varphi_r, \varphi_z, V]$$

The technique of dimensional analysis described by Morrison (12), which employs more than one length dimension—in the present case a radial length and an axial length—reduces the ten variables in the bracket to six dimensionless groups.

$$\frac{h_0}{D}, \frac{p_0 R^2}{L} = F_{1,2}\left[\frac{tL}{\eta R^2}, \frac{AL}{R^2 T}, \frac{D}{T}, \frac{\varphi_r}{T^2}, \frac{\varphi_z}{T^2}, V\right]$$

The first group in the bracket is a dimensionless time, the second a dimensionless load, and the third represents the initial gap from which the normal approach proceeds; the other three groups are properties of the surface layer. The model, and the dimensionless groups, will be modified later to incorporate the variable viscosity involved in the 'enrichment' mechanisms, but for the present the viscosity is treated as constant throughout.

4.2 Computing

Even the simple physical model adopted, and described by a grossly oversimplified theory, presents some computing problems. Briefly, the numerical procedure involves the simultaneous solution of Reynolds equation (8) in the film, and of the Laplace-like equation (6) in the porous layer. The flow equation in the porous solid is replaced by a finite-difference approximation and solved by iteration, using the method of successive corrections. The Reynolds equation is integrated first by a fourth-order Runge–Kutta method, and for a second time by Simpson's rule to give F, the total hydrostatic force on the moving solid. That is substituted into the equation of motion to give $\ddot{x}$ at that instant. New values of x and $\dot{x}$ can then be found for the next time increment, and so on until the whole trajectory is determined.

A problem which has not been overcome is an instability which arises in very flexible solids due to the term $\eta\dot{\varepsilon}/\varphi_r$ in equation (6). This has had the effect of limiting the range of values of A which could be covered in the calculations on porous elastic solids.

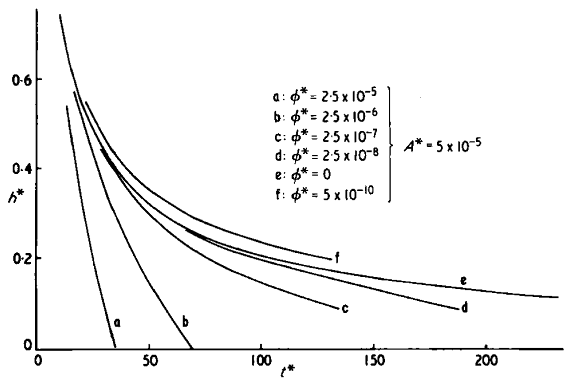

Fig. 3. *Theoretical variation of film thickness with time for porous elastic layers*

Fig. 3 shows the effect of permeability on the rate of film closure of an elastic layer, with curve 'a' the most permeable and curve 'e' impermeable. These graphs all speak for themselves, but it is worth noting that at the low value of $\varphi^* = 5 \times 10^{-10}$, the film closure is *slower* than with the impermeable layer. The maximum pressure is still on the axis of symmetry, but is now below the surface of the porous layer, and the material is 'weeping' fluid from its pores into the film.

The computed results for the perforated elastic layer are not very different from those for the impervious elastic layer *for the same value of* A^*. They are summarized over a wide range in Fig. 4 in the form of ratios of pressure and film thickness in the perforated and impervious cases plotted against A^*.

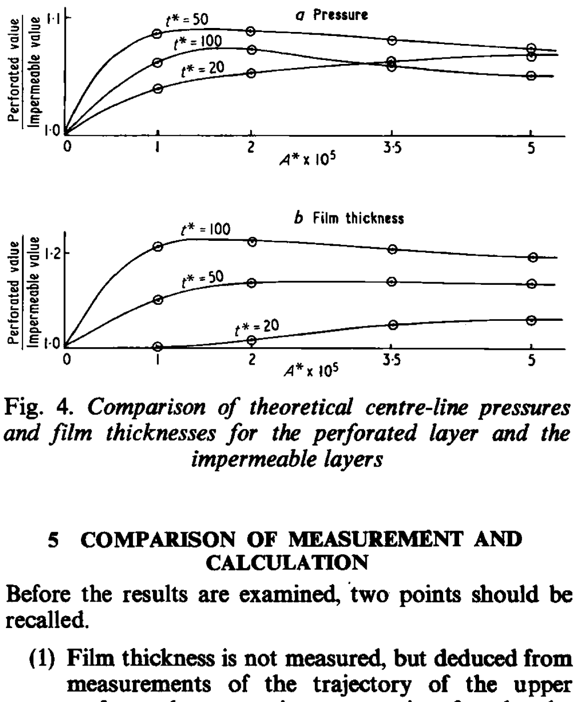

Fig. 4. *Comparison of theoretical centre-line pressures and film thicknesses for the perforated layer and the impermeable layers*

5 COMPARISON OF MEASUREMENT AND CALCULATION

Before the results are examined, two points should be recalled.

(1) Film thickness is not measured, but deduced from measurements of the trajectory of the upper surface: the correction accounting for the deformation of the lower surface is the same one used in the calculations, so strictly the comparisons shown below are between measured and calculated trajectories, but presented in the form of centre-line film thicknesses
(2) The pressure-detecting diaphragm is quite wide, so it must of necessity underestimate the centre-line pressures.

Concerning the accuracy of the readings themselves, all the experimental curves were taken as continuous traces on an ultraviolet recorder (so there are no 'points' on the curves), whose accuracy is quoted by the manufacturer to be ± 1 per cent; the traces could be measured to less than ± 1 per cent of full scale deflection. The bridges between the transducers and the recorder are quoted as being accurate to ± 1 per cent f.s.d. also. So the accuracy of recording is probably better than ± 3 per cent.

The displacement transducer is claimed to be better than ±1 per cent. The pressure diaphragm is calibrated statically and checked from time to time, so the average pressure measurements would show substantial error only due to temperature variation of the semiconductor gauge; the gauge factor variation is 5 per cent over a range of 50°C, and in the experiments the temperature varied by only a few degrees.

5.1 Elastic porous layer

Suitable flexible porous layers proved difficult to come by. The two used in the experiment were sintered polymeric layers supplied by Porvair Ltd. Their properties are given in Table 1. Unfortunately, the stiffnesses of both were much greater than that of the perforated rubber.

Figs 5 and 6 show typical pressure and film thickness curves for the low and high permeability layers respec-

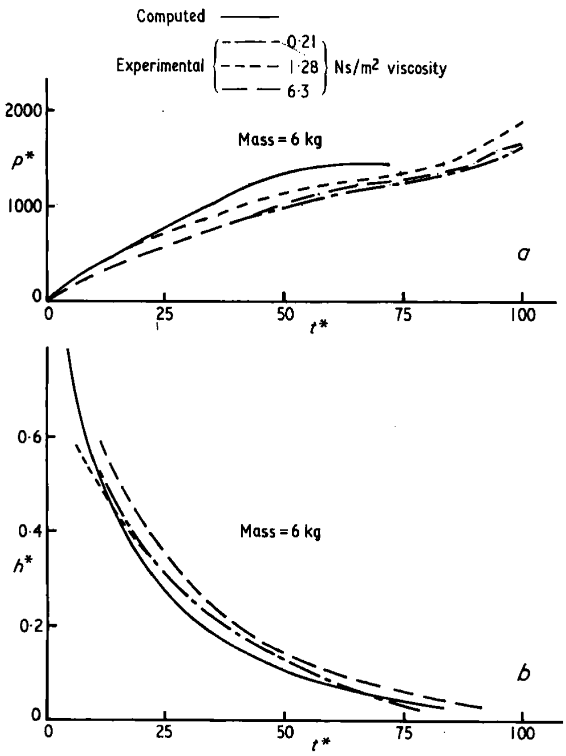

Fig. 5. *Experimental and theoretical pressure and film thickness/time characteristics for the low-permeability flexible layer*

tively. The pressure gauge fails to detect the finer points (if they exist), but the agreement is not bad. The agreement between theoretical and measured trajectories is good, up to the point of impact, which is as far as the calculation goes.

5.2 Elastic perforated layer

The perforated layer was made by punching a square grid of 0.6 mm diameter holes at 1 mm spacing in a silicone-rubber layer bonded onto a steel backing. Some

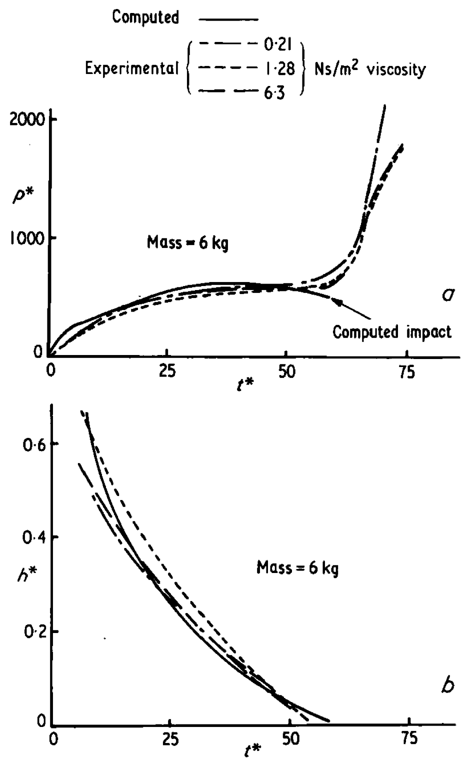

Fig. 6. *Experimental and theoretical pressure and film thickness/time characteristics for the high-permeability flexible layer*

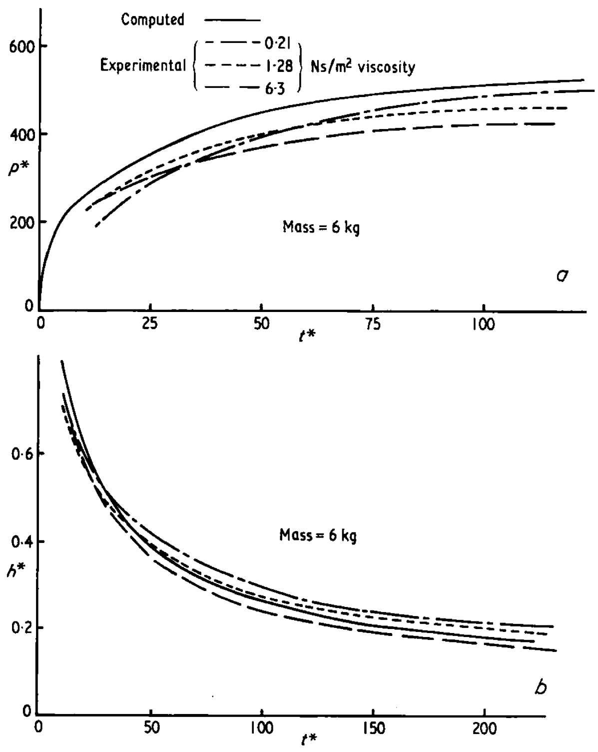

Fig. 7. *Experimental and theoretical pressure and film thickness/time characteristics for the perforated layer*

of the results are shown in Figs 7 and 8; the agreement is good, particularly in the film thickness, although even in those there appears to be a consistent effect of viscosity which is not forecast by the theory.

The reasonable agreement between the crude theory and experiments, which employ only constant viscosity fluids, allows the extension of the model to variable viscosity with some slight confidence. In the next section, the calculations are modified some way towards conditions more appropriate to human joints.

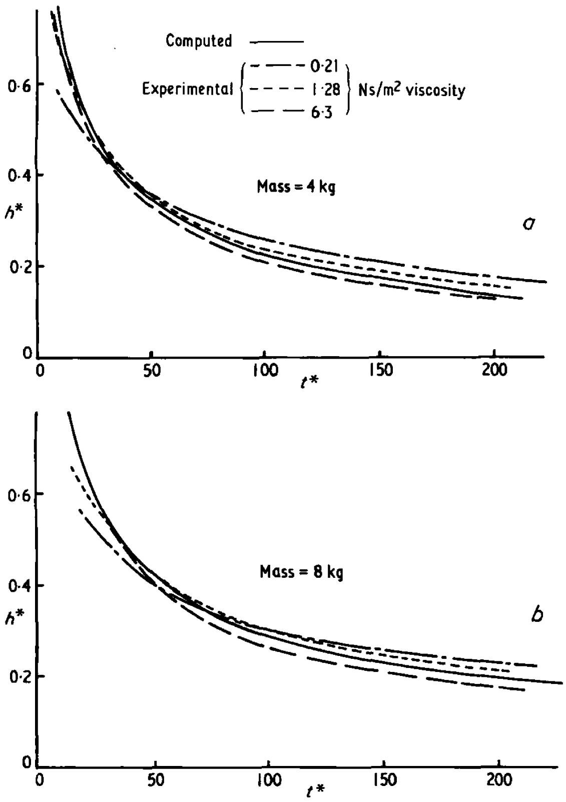

Fig. 8. *Experimental and theoretical film thickness/time characteristics for the perforated layer*

6 EXTENSION TO LIVING HUMAN JOINTS

Such terms as viscosity and Young's modulus or flexibility are inadequate to describe the mechanical properties of synovial fluid and cartilage, so the values given in Table 2 are order-of-magnitude values representing ranges which in some cases are quite wide.

The computations with constant viscosity suggest that the lubricating effects of permeability are not as beneficial as has generally been hoped, and sometimes asserted. Fig. 3 does show some indication of weeping from an isopermeable layer, but the performance of the layer is not substantially better than that of the impermeable layer. Even the limiting case of weeping, viz. the perforated layer, is only marginally better than the impermeable layer theoretically, and may not be any better at all in reality, because of the fluid entrapment which has been observed with impermeable layers. Further-

Table 2. *Orders of magnitude of variables*

	Animal joint	Model computing	Model experiments
T(mm)	5	5	5
R(mm)	300	300	300
A(m^3/N)	5×10^{-10} (3)	—	—
A^*(m^3/N)	10^{-4}	0–10^{-5} porous 10^{-4} perforated	10^{-5} porous 10^{-4} perforated
φ_z(m^2)	6×10^{-19} (15)	0–10^{-9}	$0, 2 \times 10^{-12}, 3 \times 10^{-11}$
φ_z^*(m^2)	2×10^{-14}	0–10^{-4}	$0, 10^{-7}, 10^{-6}$
φ_z/φ_r	?	$1, 100, 1000, \infty$	$2, \infty$
η_1(Ns/m^2)	0.02 (1)	—	0.2–6
η_0(Ns/m^2)	0.001 (1)	—	—
c	3×10^{-3} (13)	3×10^{-3}–0.3	—

more, it appears that the perforated layer mechanism is of academic interest only in connection with human joints; there is little data available on the relative values of the permeability through and along the thickness of the cartilage layer, but what there is suggests that the two values are not very different, and probably within a factor of two of each other (3).

If further progress is to be made in understanding the true mechanism, it must next be sought in the effects of variable viscosity, particularly in the enrichment mechanisms. The theoretical model can fairly easily be extended to take account of filtration by the cartilage, the ensuing increase in concentration of hyaluronic acid, and with it the increase in viscosity.

To the list of variables given earlier must now be added the concentration of solute in the lubricant film, c, and the different values of viscosity: the variable value η in the film (η_1 initially), the constant value η_0 in the porous solid (the value of the base fluid), and the notional value η_2 which the fluid would have at 100 per cent concentration of the additive. The dimensionless groups are modified to include

$$\frac{\varphi_r \eta_1}{T^2 \eta_0}, \; \frac{\varphi_z \eta_1}{T^2 \eta_0}, \; c, \; \frac{\eta_2}{\eta_1}$$

Computations have covered values of the permeability ranging over three orders of magnitude, and of the concentration over two orders. Of all the combinations, only the extreme case of highest permeability and highest

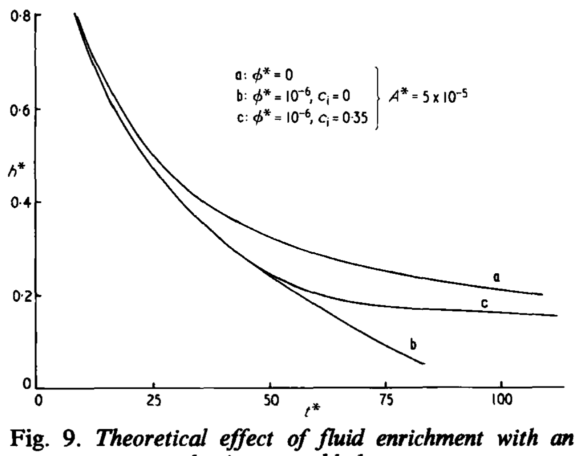

Fig. 9. *Theoretical effect of fluid enrichment with an elastic permeable layer*

concentration produced results discernibly different from those models with no additives. This result is shown in Fig. 9, and is at a much higher permeability than the value for cartilage, and at a much higher concentration than could possibly occur in practice, except at minute film thicknesses [even making an allowance for the probable difference between the gravimetric and volumetric concentrations of hyaluronic acid, in view of the nature of the molecule (13)].

With the property values for cartilage shown in Table 2, no effect of enrichment is noted before failure of the computation, which occurred at about $h^* = 0.1$ on all the computer runs. It is possible, therefore, that there might be some effect when the film is extremely thin.

The other enrichment process suggested by Dowson, Unsworth and Wright (1) depends on the restriction of movement of hyaluronic acid molecules *through the film*. Unsworth (14) amplifies this proposal by suggesting that aggregates of hyaluronate-protein complex on the surface of the cartilage are responsible for this filtration; he produces very impressive electron micrographs in support. The application of thin-film lubrication theory to such a situation is suspect, but insofar as it does apply, it can be used to evaluate the mechanism in quite a simple way. During the closing stages of the approach of two highly deformable bodies, the film is approximately parallel, and it is, therefore, in order to consider the approach of two rigid, flat surfaces. The simple analysis is given by Dowson, Unsworth and Wright.

If the filtration is completely effective, the additive cannot flow in the radial direction, and the concentration is therefore inversely proportional to the film thickness. For property values of human joints, the calculated closure time to a tenth of the initial separation is increased by about an order of magnitude, and that to a hundredth of the initial separation by about two orders. If a mechanism on these lines does operate, it will be very effective.

7 CONCLUSIONS

Although the model used in this investigation is very different from a human joint, the results suggest some tentative conclusions.

The first is that the permeability of cartilage is much too low to play the important direct role in lubrication which has sometimes been suggested (it does of course affect the flexibility according to strain rate). That being so, the way in which a flexible, impermeable rubber layer holds a squeeze film by entrapment may well be relevant to cartilage layers, which are themselves very flexible, and which have been shown to have a surface roughness which would encourage entrapment.

It also follows that an enrichment mechanism relying on filtration through the cartilage layer is unlikely to be effective. On the other hand, filtration through the surface aggregates suggested by Unsworth will be very effective indeed if it operates.

APPENDIX

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APPENDIX 3

Presidential Address

Engineering at the interface

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Head of Department of Mechanical Engineering, University of Leeds

The President illustrates the challenges facing engineers at a number of interfaces between established disciplines, experiences and structures. An account of influences on his own early education and training are followed by descriptions of his fascination with the characteristics of thin films of lubricant at the interfaces between moving parts of machine components and body masses in the human frame. Developments in engineering education, particularly in relation to the promotion of interdisciplinary subjects and the opportunities for students to interface with overseas institutions in an international form of engineering education are outlined. The important interfaces between industry, the universities and the professional institutions in relation to education, training and research are identified as essential foundations for the promotion of a research and knowledge led competitive industrial base for the twenty-first century.

1 INTRODUCTION

It is my privilege to respond to the signal honour bestowed upon me by my fellow mechanical engineers by electing me as President of this great Institution, by presenting this Address at the very first opportunity in my period of office. Recent Presidents have adopted interesting autobiographical approaches to their Presidential Addresses and I suspect that the words 'customary' and 'traditional' in their opening paragraphs are intended to be beacons for their successors. I know that such approaches have been appreciated by members of our Institution, since they enable all to understand something of the background of their President, his professional interests and his personal philosophy. While following these pleasing and general guidelines, I would, however, like to focus attention on certain aspects of engineering education and research, to illustrate the excitements of both and to emphasize their importance to our industrial society.

There are weighty matters absorbing the minds and efforts of professional engineers in industry, higher education, the armed services and government departments at the present time, and I would not like this opportunity to pass without reference to some of them. The economic well-being of the United Kingdom depends upon its success as a manufacturing nation, interfacing with the international market, yet the portents are poor, since the positive trade balances of the 1970s have given way to substantial adverse balances in the 1980s. This decline in the standing of manufacturing industry in the United Kingdom's economy needs to be reversed, since service activities alone cannot be expected to balance the nation's books on a long-term basis. It also seems to me that external confidence in our ability to generate compensating earnings through the City, in banking, insurance and financial dealing, can best be upheld if our dedication to the development of a sound manufacturing base is clearly evident.

This backcloth gives rise to a host of problems for society and our profession, in relation to education at all levels, training arrangements and opportunities in industry, the interface between industry and the universities, the preservation and enhancement of professional standards, the structure of the engineering profession, the promotion of research and knowledge based industries and, perhaps most importantly of all, the development of dedicated, consistent, long-term perspectives on appropriate solutions to these issues. In subsequent sections I will illustrate how my own experience of certain aspects of teaching and research have led me to the view that sound solutions to the above problems must be established on the twin pillars of respect for engineering education and research and an ever increasing collaboration between industry and higher education in relation to education and training and the solution of the technical problems of the future.

2 PERSONAL BACKGROUND

I was born and brought up in Kirkbymoorside, a small market town in Ryedale, on the edge of the Yorkshire moors. My mother came from farming stock, but service as a nanny and nurse to a doctor's family developed a respect for education which, although I barely recognized it at the time, undoubtedly influenced the guidance and advice offered to me at critical stages in my school career. My father came from a long line of blacksmiths in a rural North Riding community, although my earliest recollection of his skills placed him in a local firm of agricultural engineers. He nevertheless found the opportunity to develop his passion and hobby in ornamental wrought ironwork, by undertaking commissions from local gentry and architects in his spare time. He had long since tired of shoeing horses in the family forge, but he seemed to be capable of repairing, or fashioning anew, items for the home, the church, vehicles of all kinds and a host of farm implements, as expected of their blacksmith by a village community. There was clear evidence of artistic talent alongside the craftsman's skills and I clearly remember his love of many features of Jean Tijou's seventeenth century school of English wrought ironwork. Tijou had come to England following the accession of William and Mary and his work with Sir Christopher Wren, HM Surveyor-General of Works appointed by Charles II, left a rich inheritance of elaboratre ironwork at sites which included Hampton Court and St Paul's Cathedral. My father studied, examined and marvelled at

This Address was presented at an Ordinary Meeting held in London on 27 May 1992. The MS was received on 3 April 1992.

Fig. 1 Wrought iron bed by W. Dowson, based upon sixteenth century German grille

Tijou's dexterity in creating certain motifs, repoussé panels and elaborate leafwork, and there is little doubt that the seventeenth century craftsman influenced much of his own more delicate creations.

As his skills in wrought ironwork developed during the 1920s and 1930s, my father's work attracted increasing attention. A set of fire steels, which was awarded first prize in open competitions in both Leeds and Northallerton in 1926, was supplied to Her Majesty Queen Mary, while an interesting reproduction of a fine sixteenth century German grille shown in Fig. 1 also demonstrates his artistry; but it was, perhaps, his design and execution of the Nelson memorial gates for Duncombe Park (Fig. 2), home of the Feversham family, that best represents his work in this period. The circular frame created by the juxtaposition of metal and stone is a familiar landmark in Ryedale to the present day. What is less well known is that much of the work was completed by candlelight, with my mother holding both the candle and the metal bars as they were fashioned on the anvil. It was during this time that my father developed a close friendship with the famous Kilburn wood carver Robert Thompson and he was to supply the wrought iron fittings on Mouseman furniture for many years.

In due course my father inherited my grandfather's forge and the Kirk forge was established for the manufacture of ornamental wrought ironwork in the difficult years of World War II. His skills and achievements were to attract national and international recognition and he was admitted to the Livery of the Worshipful Company of Blacksmiths and made a Freeman of the City of London. I played little role in the development of the forge, but I did have an excellent opportunity to

Fig. 2 Nelson memorial gates by W. Dowson, Duncombe Park

acquire simple practical skills of handling tools and forging metal by hand. Perhaps more importantly, I witnessed the practical dexterity and artistic skill of a craftsman and the creative process associated with his craft. It was hard work and the hours were long, but my father's evident satisfaction in creating a beautiful piece of decorative ironwork left a lasting impression on me. I was subsequently to learn that intellectual activity and problems in engineering science could be equally challenging and satisfying, even though it is difficult to equate the satisfaction derived from the two forms of activity.

I have indulged in this feature of family background since it was to lead to my first 'interface challenge' of any significance. My formal education commenced in the primary school in Kirkbymoorside and in the second year of World War II I was awarded a scholarship to enable me to attend a small grammar school at nearby Pickering. In those days the examination taken after five years was the School Certificate, and in my case that coincided with the end of the War. Sixth form studies brought me into contact with talented and enthusiastic teachers of mathematics and physics. They taught under very difficult circumstances, for many of the appropriate age group were still in the armed services or busily picking up the threads of interrupted education and training. There was no physics laboratory, the teacher of physics was a chemistry graduate, and practical work was restricted to occasional visits to another school 28 miles from home with Saturday morning visits to local enthusiasts in the village who built their own radios and who, in one case, had a cathode ray oscilloscope! The dedication of these teachers in the post-war years left a lasting impression on me, but in retrospect I also believe that the necessity to develop the skills of private study in those austere days was equally important. I also appreciated the opportunity to take two subsidiary subjects alongside my three main subjects in mathematics and physics in Higher School Certificate. This has no doubt contributed to the development of my sympathy for a broader based pre-university education.

At this stage my father's wrought iron business was developing, but the interfacial problem of choice between a practical/business career and higher education was resolved in favour of the latter. I attended the University of Leeds and graduated in mechanical engineering in 1950. During my final year I attended a course of lectures on lubrication by Professor D. G. Christopherson and subsequently completed a PhD under his supervision. I then worked for two years in the aircraft industry in the applied aerodynamics group of the Guided Weapons Division of the Sir W. G. Armstrong Whitworth Aircraft Company Limited, in Coventry. I was enjoying industry, but a chance encounter with my former professor while contemplating a move overseas to another company led to my return to the University of Leeds as a lecturer in mechanical engineering in the mid 1950s. I returned to Leeds on the understanding that it would be for two or three years, but I have been there ever since and it has been my experience as an educator at the interface between education and training and between fundamental research and industrial application and practice that has provided the basis for much of my Address.

3 RESEARCH IN LUBRICATION AND BIOENGINEERING

The theme of this Address springs from my experience that so many of the challenging problems in engineering and life seem to occur at interfaces between established disciplines or experiences. In engineering science this is clearly related to the fact that the properties of bulk materials, whether solid or fluid, are reasonably well understood and relatively easy to determine. The laws of continuum mechanics can be applied and the governing mathematical equations can be solved analytically or by efficient numerical procedures on ever more powerful computers, such that the response of the structure or machine to the operating requirements can be predicted with fair confidence. It may be necessary to throw in an occasional safety factor to cover any deficiencies in our slightly imperfect man-made materials of construction or to allow for our inadequate knowledge of the real operating circumstances to which our machines are exposed or our uncertainties about the environment in which the machine has to function, but by and large our design procedures and manufacturing methods succeed in meeting the specifications.

The level of confidence drops markedly when we consider the behaviour of surfaces, or even worse of interfaces, between machine elements. When engineering surfaces come close together and interact by transmitting load under specified kinematic conditions, we need to draw upon and integrate our knowledge of most aspects of engineering science, of physics, chemistry and mathematics if we are to understand the resulting behaviour. This presents a challenge, not only in relation to the real behaviour of physical interfaces and their engineering significance but also in relation to the educational barriers and interfaces between established disciplines in engineering and science. Behind each coefficient of friction, and certainly behind each wear factor, there still exists a world of inadequate knowledge of the controlling phenomena that determine these simply stated and widely used quantities in engineering analysis and design.

The best way to control the friction and wear of interacting surfaces is to separate them by a film of lubricant and this forms my first account of 'working at the interface'.

3.1 Lubrication

The theory of fluid film lubrication (**1**, **2**) represents a supreme example of the application of that branch of engineering science concerned with fluid mechanics to engineering systems.

Problems of friction and wear have opposed the development, construction and efficient operation of machinery and vehicles throughout history and I have greatly enjoyed the opportunity to study the history of tribology (**3**). There are some fascinating early examples of the ingenuity of man in overcoming some of these problems, ranging from the movement of large statues over logs (or rollers?) (Fig. 3) or lubricated planks (Fig. 4) in the Middle East some 2700–4400 years ago to the remarkable development of early forms of rolling element bearings in Roman times (Fig. 5).

The Industrial Revolution and the development of the railways focused attention upon the importance of

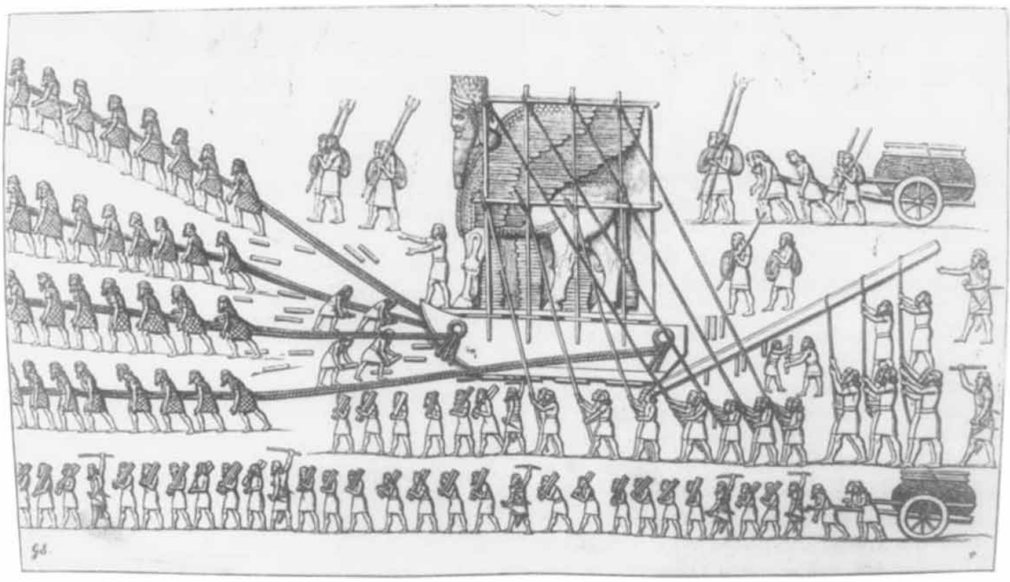


Fig. 3 Assyrians positioning a human-headed bull, from bas-relief, Kouyunjik (*ca.* 700 BC)

lubrication, since much machinery and many vehicles were incapacitated by excessive friction or debilitating wear. It was widely recognized that the application of animal fats and animal or vegetable oils to bearings generally relieved the severity of these problems, but there was no scientific understanding of the remarkable physical and chemical processes governing the behaviour of the interfaces between moving parts in machinery. Indeed, there was growing confusion about the nature of friction in lubricated machinery in the second half of the nineteenth century, until the Council of this Institution adopted a proposal from its Research Committee to sponsor research on the subject in 1878. A talented investigator by the name of Beauchamp Tower was appointed to investigate friction in bearings and pivots and the Council awarded grants of £100 in August 1882 and £200 in December of the same year to enable a testing machine to be constructed. Experiments were carried out in the Chapel Street Works of the Metropolitan Railway in London and Tower's chance detection of pressures far in excess of the average pressure on the bearing prompted him to conclude that:

> ... the brass was actually floating on a film of oil, ...

Tower also found (**4**) that, with bath lubrication and correct bearing proportions, coefficients of friction of 0.001 were possible.

This revelation of the separation of the rotating journal from the bearing by a coherent film of lubricant, independently and almost simultaneously confirmed in 1883 by Nikolai Petrov (**5**), Professor of Steam Engineering and Railway Vehicles in the Technological Institute of St Petersburg, was to initiate one of the most important advances in machine analysis and design ever recorded.

Professor Osborne Reynolds of the University of Manchester, who had noted the distinction between laminar and turbulent flow in 1883, recognized at once that the behaviour of the lubricating film detected by Tower could be determined from the laws of fluid

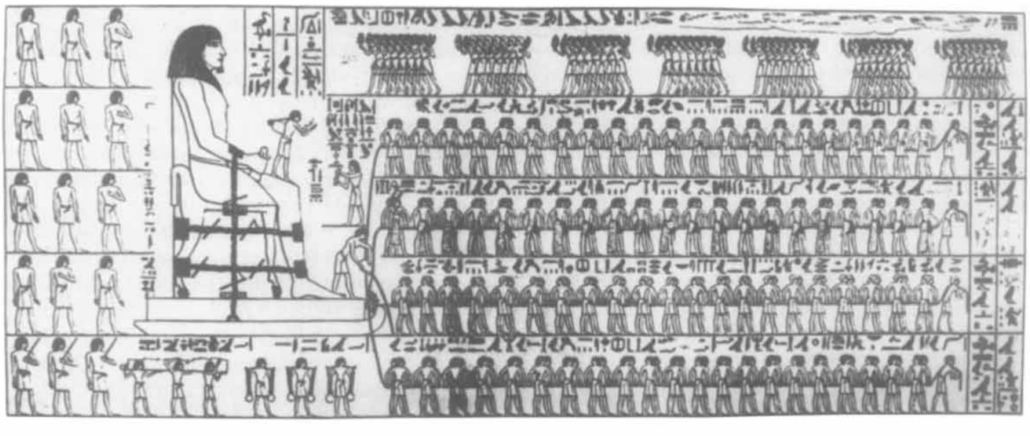
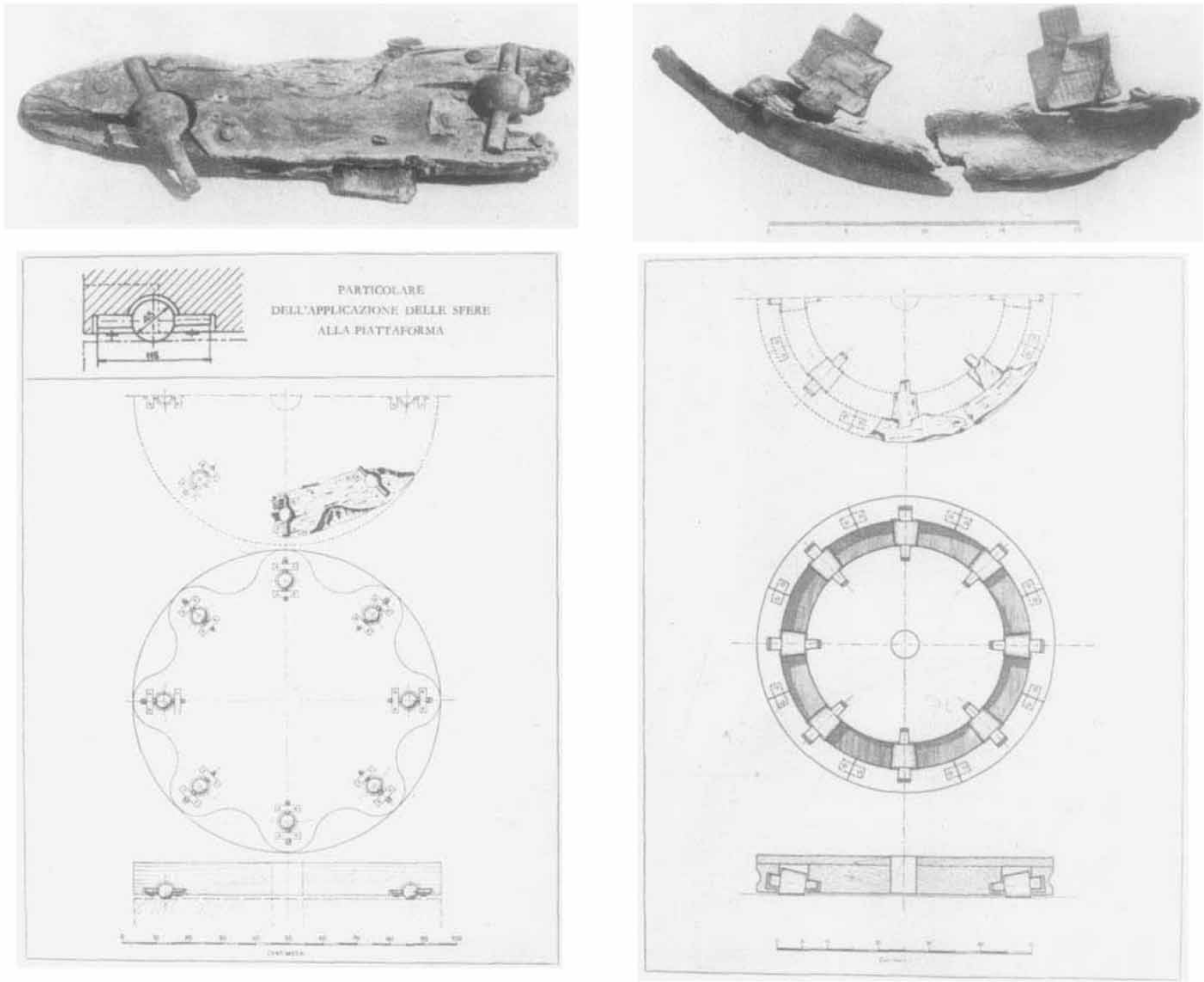


Fig. 4 Transporting an Egyptian colossus, from tomb of Tehuti-Hetep, El-Bersheh (*ca.* 1880 BC)



(a) Trunnion mounted bronze ball bearing (b) Wooden taper roller bearing

Fig. 5 Reconstruction of Roman bearings from Lake Nemi (*ca.* AD 44–54)

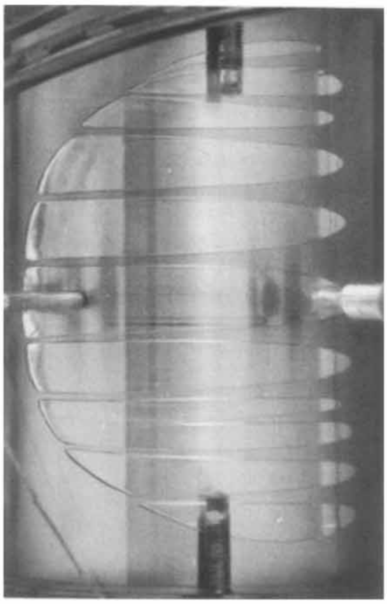
mechanics. His classical analysis of 1886 (**1**) led to a differential equation which related the pressure in a bearing of any form to the physical actions, such as entraining and normal approach or separation velocities, which generated the load supporting pressures. The Reynolds equation of fluid-film lubrication was to provide the foundation of all satisfactory twentieth century bearing analysis and design. Fluid-film lubrication is the ideal method of controlling friction and wear, since the opposing surfaces do not touch each other, but in due course other mechanisms of lubrication were revealed.

The thought that all successful modern machinery was floating on films of lubricant having an almost imperceptible thickness of about 5–25 μm (0.0002–0.001 in) excited my interest in the subject of lubrication about 40 years ago. It sometimes comes to mind, in a sobering way, when I reflect upon the stirring developments of the 1880s, that the period of my research on lubrication stretches back over some 40 per cent of the time that has elapsed since Osborne Reynolds published his classical paper!

Certain factors associated with the phenomenon of fluid-film lubrication, such as cavitation, thermal effects, fluid inertia, elastic distortion and lubricant rheology, had received relatively little attention and I have been fortunate to be able to pursue each of them to various extents at different stages in my research career. Furthermore, I have been concerned throughout with the process of integrating new knowledge into design procedures and in its application to the solution of industrial problems. I do not propose to review all the above topics, but I would like to illustrate some of the features of my first love, cavitation, and my major field of endeavour, elastohydrodynamic lubrication.

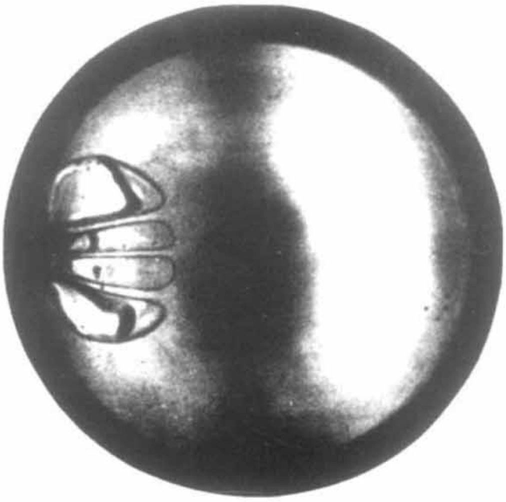
Cavitation in lubricating films

Hydrodynamic principles dictate that convergent–divergent bearing conjunctions, like those encountered

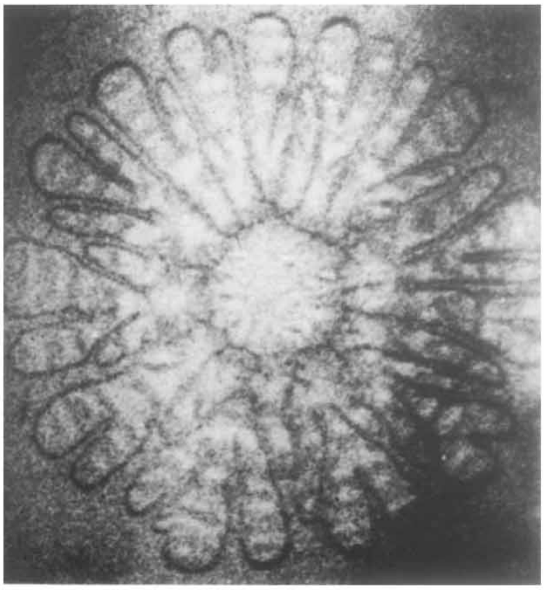


(a) Journal bearing (steadily loaded)

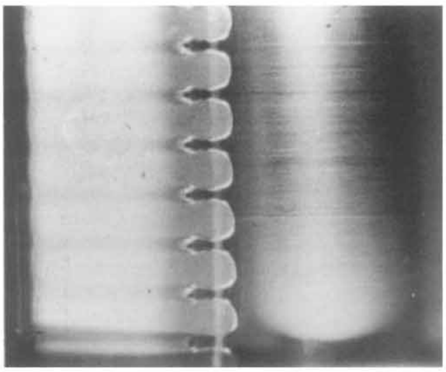
(b) Rotating cylinder near a plane (side view)



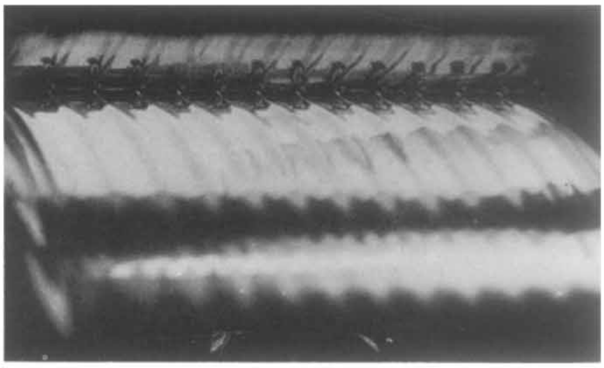
(c) Glass lens near a moving metal plate (steadily loaded)



(d) Separating surfaces



(e) Oil streamers penetrating into air bubbles in the cavitated zone between a rotating cylinder near a plane



(f) Rippled surface layer of oil emerging from cavitated region on rotating cylinder near a plane

Fig. 6 Cavitation patterns in lubricating films in most bearings in rotating machinery, lead to rupture of liquid lubricants and the accumulation of air, or lubricant in the vapour phase, in the divergent clearance space. It is easy to demonstrate theoretically that cavitation affects major bearing performance characteristics such as load carrying capacity, friction, lubricant flowrates and temperature rise, but it is the aesthetic features of the phenomenon, depicted in Fig. 6, that I call to your attention on this occasion. Bubbles in oils can exhibit beautiful shapes!

Elastohydrodynamic lubrication

Reynolds explained how lubricated, conforming thrust and journal bearings worked, but it was not until the second half of the twentieth century that the mechanism of lubrication of highly stressed machine components like gears and rolling element bearings was revealed. Operating experience indicated that gear teeth were often separated by films of lubricant, for the initial machining marks persisted for many hours of operation under load, yet all the solutions to the Reynolds equation predicted film thicknesses much inferior to the known surface roughness of the teeth. It was evident that something was missing in the modelling of contacts between gear teeth, and in due course it was recognized that the combined influence of very high pressures, of the order of GPa or, say, 100 ton/in^2, upon lubricant viscosity and the elastic deformation of the solids in the vicinity of the stressed conjunction was remarkably supportive of film formation.

A number of exploratory theoretical studies of the lubrication of elastic solids was reported in various European countries in the 20 years before work commenced in Leeds, but by far the most important contributions came from the Soviet Union. Ertel and Grubin (**6**) reported an elegant approximate analytical solution to the full problem, although the work was not to become known to us in the West for some years. Shortly afterwards, Petrusevich (**7**) presented a small number of numerical solutions to the problem which was to become known as 'elastohydrodynamic lubrication' (EHL), which not only confirmed the essential features of Grubin's predictions but also revealed a remarkably sharp pressure peak near the exit of the loaded conjunction, which became known as the Petrusevich pressure spike. The Soviet work percolated into the Western world late in the 1950s, about the time that Crook (**8**) was using electrical capacitance methods in disc machines in the Aldermaston Laboratories of Associated Electrical Industries to demonstrate experimentally the essential features of EHL.

The study of EHL at Leeds provides a good illustration of effective interaction between government research laboratories and universities. It arose from an initiative taken by the renowned Lubrication and Wear Group of the National Engineering Laboratory (NEL) at Thorntonhall, East Kilbride, directed by the late Professor F. T. Barwell. A letter was sent to the heads of a number of university engineering departments in 1956 drawing attention to the inadequate understanding of the nature of gear lubrication and pointing out that progress towards a solution of the problem might well be encouraged if the classical theory of hydrodynamic lubrication could be extended to take account of the influence of the high contact pressures upon both the lubricant viscosity and the local deformation of the elastic solids.

The letter to Leeds was directed to the late Professor D. C. Johnson whose expertise in vibrations was matched by a keen interest in mechanical transmissions. Johnson immediately recognized the significance of the NEL letter to studies of gearing and since I had returned to the University to develop lubrication research, I had no hesitation in pursuing the matter. Fortunately, Gordon Higginson, who was a fellow research student under Professor Christopherson at Leeds, returned to the department as a lecturer in the autumn of 1956 after working at Fort Halstead, and we began our theoretical studies of EHL together soon afterwards.

The generation of simultaneous solutions to the governing hydrodynamic and elasticity equations proved to be quite difficult. The analytical and numerical procedures for nominal line contacts, which were in place by October 1957, encountered all the problems of convergence experienced by subsequent generations of research workers in this field. An 'inverse hydrodynamic' procedure overcame this problem in 1958 and our initial publication on the subject appeared in the first issue of the Institution's distinguished *Journal of Mechanical Engineering Science* in 1959 (**9**). It is worth noting that our first satisfactory solution took us about 18 months to generate, although we also had substantial concurrent teaching responsibilities at the time. All the solutions obtained up to the end of 1958 were generated without the aid of a digital computer. The calculations were performed by hand, with the extensive use of tables of logarithms and, to speed things up, some access to mechanical desk calculators. The same calculations can be performed today on readily available digital computers in a matter of minutes.

We prepared computer programs to solve the EHL problem on the first major computer to be installed in the University in the early months of 1959. The University computer was housed in an old church just off the campus and the initial programs were written in Pegasus Autocode. Visits to church became more frequent as we investigated the influence of various parameters upon EHL solutions. We confirmed the essential features of elastohydrodynamic conjunctions (Fig. 7), appreciated the accord between our theoretical predictions and experimental measurements of film thickness and felt bold enough to produce a dimensionless film thickness formula which could be applied to any form of EHL line contact problem. The formula, reproduced here in its original form, was first published in the journal *Engineering* in 1961 with specific reference to roller bearings. Two years later the theory was amplified at the 1963 Lubrication and Wear Group Convention of this Institution (**10**).

$$H_{\min} = \frac{1.6G^{0.6}U^{0.7}}{W^{0.13}}$$

It attracted considerable attention, particularly from overseas, since it enabled the designer to predict, for the first time, the thickness of the all-important film of lubricant in a wide range of highly stressed machine elements.

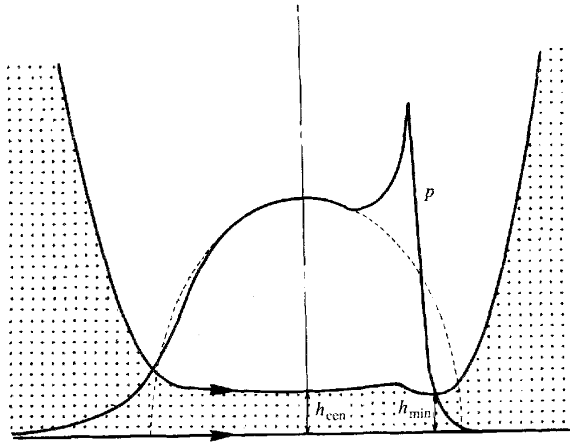


Fig. 7 Essential features of elastohydrodynamic line contacts

Perhaps the most important feature of the EHL film thickness equation developed in the early 1960s was that it predicted film thicknesses which were not only some 40 times greater than those predicted by conventional hydrodynamic theory but that the values revealed were at least as big as the composite surface roughness of the gear teeth or roller bearing tracks and rollers. It was found that a representative predicted range of EHL film thicknesses in common forms of highly stressed machine components was 0.1–1 μm. Theory and practice were in accord once more and EHL film thickness calculations are now integral features of many design procedures. Of particular importance is the ratio of EHL film thickness to composite surface roughness, since this ratio gives a good indication of the life of highly stressed, lubricated, machine components.

In 1962 we presented a short course on the basic features of EHL, long before the current recognition of the importance of technology transfer or continuing professional education (CPE) were in vogue. The first book on elastohydrodynamic lubrication (**11**) followed in 1966 and was based upon this course.

In due course elastohydrodynamic analysis was to be developed in various centres around the world to include thermal effects, normal approach, surface roughness, more complete rheological models and point (elliptical) contacts. Even today, the learned society journals on tribology devote a substantial proportion of their contents to the subject. Barwell (**12**) reviewed the subject and wrote:

> ... the elucidation of the mechanism of elastohydrodynamic lubrication may be regarded as the major event in the development of lubrication science since Reynolds' own paper ... .

The opportunity and privilege to have contributed to research in this field has been intellectually stimulating and professionally satisfying.

3.2 Biotribology

My research in this field has followed two main lines, both connected with synovial joints. The first has been directed towards the elucidation of the quite remarkable tribological performance of synovial joints and the second with the development of more satisfactory total joint replacements.

The former problem was brought to my attention by two routes in the 1960s, and the manner in which this arose demonstrates how knowledge and understanding of natural phenomena developed in one field might well find application in another. Our work on elastohydrodynamic lubrication had been undertaken in order to resolve the mystery of gear and roller bearing lubrication, but soon after the publication of our formula for film thickness I received a letter from the antipodes which suggested that it might shed light on quite a different, but perhaps equally important, problem. It appeared that the performance of highly prized serving bulls in Australia was being restricted by the premature onset of arthritis and the degeneration of the load bearing joints. The financial implications were substantial and my correspondent wondered whether our exposition of the principles of elastohydrodynamic lubrication might shed light on the problem.

The second approach came from Verna Wright, head of the Rheumatism Research Unit in the medical faculty of the University of Leeds, who called on me to suggest that, although my work on the lubrication of machine components was no doubt interesting, there was a much more challenging and important problem to be solved. It appeared that there was no clear understanding of the mechanism of lubrication of healthy human joints, nor of the factors responsible for the deterioration of some of them in that form of rheumatism known as osteoarthritis. This contact led to long-standing co-operative research, the establishment of a Bioengineering Research Group for the Study of Human Joints and, in due course, the foundation of a Centre for Studies in Bioengineering in the University.

Research on the tribological aspects of total replacement joints at Leeds also commenced early in the 1960s and was spurred on by the experiences of the late Sir John Charnley, as he pioneered the use of metal-on-polymer implants. Work on this topic continues to the present day.

Throughout this period of research in a truly multidisciplinary field, I have greatly enjoyed the opportunity to work at the interface between engineering and medicine. Engineers and physical scientists are generally ill equipped to tackle biological and medical problems, and the reverse is equally true, but I remain convinced that sustained co-operation between engineers, physicians and surgeons at this difficult interface provides the best foundation for progress in bioengineering research. I am very pleased to record my appreciation of the opportunity to work with my colleague at Leeds, the rheumatologist Professor Verna Wright, the late Professor Sir John Charnley and other orthopaedic surgeons in this field. It is also an opportunity to recall the responsiveness of the Institution of Mechanical Engineers to the developing interest in this subject. In 1967 the Lubrication and Wear Group of the Institution, the forerunner of the Tribology Group, arranged a symposium in association with the British Orthopaedic Association on the lubrication and wear of living and artificial human joints. John Charnley was a member of the planning panel for this 1967 conference. The volume of proceedings (**13**) not only established the current state of knowledge but also provided the springboard

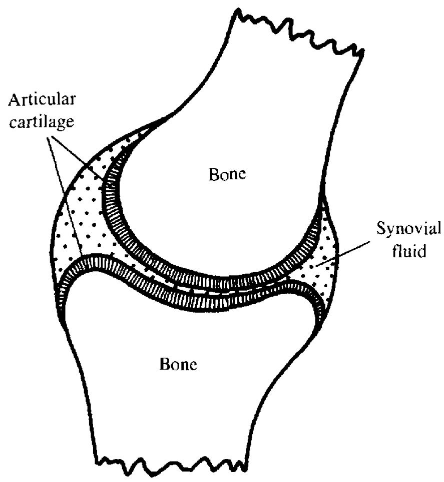


Fig. 8 Synovial joint

for much of the work to follow. I little imagined at the time that the title would describe most accurately one of my major research fields for the next 25 years! Since that time the Engineering in Medicine Group of the Institution has arranged numerous highly effective conferences and meetings, often in association with the British Orthopaedic Association and other bodies, in related fields, to the great credit and distinction of the Institution.

The lubrication of natural synovial joints

Synovial joints are quite remarkable plain bearings. They consist of an elastic, porous bearing material (articular cartilage) a few millimetres thick, on a relatively hard backing of bone, lubricated by a highly non-Newtonian fluid (synovial fluid) as shown in Fig. 8. The load is dynamic, reaching peaks of three to six times body weight with every step we take, while the motion is oscillatory rather than steady. The bearing is self-contained, subjected to a few million cycles of loading each year and yet it is expected to work for three score years and ten.

The general arrangement of the joint (see Fig. 8) suggests that it should operate as a fluid-film bearing, yet this is very difficult to prove theoretically. Whereas increasingly refined experimental approaches to the problem [see the work of Unsworth *et al.* (**14**)] have demonstrated fluid-film lubrication characteristics, analysis has generally failed to support the concept until recent times. The problem has been that hydrodynamic and even elastohydrodynamic lubrication theory for increasingly sophisticated models of the joint predicted film thicknesses which were much too small compared with the known roughness of cartilage surfaces (typically 2–5 μm) to engender any hope that the joint might indeed enjoy fluid-film lubrication. However, in the late 1980s we were able to show that the undulations on the rough cartilage surfaces would be effectively smoothed out by self-generated perturbations to the hydrodynamic pressures during articulation. The effectiveness of this micro-elastohydrodynamic action, illustrated in Fig. 9, is most impressive, and there is now a substantial measure of accord between experimental findings and quite sophisticated analysis. The engineering science concept of synovial joint lubrication is now quite well established, but like many dynamically loaded engineering bearing systems the joint probably experiences fluid-film, mixed and boundary lubrication during normal operation. There is still some work to be done to resolve the latter aspects of lubrication in synovial joints.

It now appears that an average coefficient of friction in healthy synovial joints is about 0.02 or less. Ambulation ensures that our self-acting bearings enable us to float along on lubricating films about 0.5 μm thick. The consequences of failure of this protective action are all too well known to an ageing arthritic population. It thus appears that much of our modern machinery and our remarkable synovial joints are dependent for their effective operation upon thin but coherent films of lubricant having a thickness about one-hundredth of a human hair.

Total joint replacements

There are many forms of rheumatic disorders and in severe conditions of pain and immobility the orthopaedic surgeon may consider the replacement of the natural joint by a man-made device.

The early history of joint replacement has been well told by Scales (**15**), another member of the planning panel of the celebrated 1967 symposium (**13**). Surgeons fashioned implants from a variety of materials prior to the 1960s, including wood, bone, ivory, gold foil, glass, celluloid, bakelite, Vitallium, platinum, acrylic, silicone rubber, nylon, polyacetyl resin, polytetrafluoroethylene (PTFE), polyethylene (PE) and, of course, surgical grade stainless steel and a chrome–cobalt–molybdenum alloy. In due course the combination of a metallic femoral stem and a polymeric acetabular cup, known as a low-friction hip arthroplasty, was pioneered by John Charnley. He had concluded that excessive friction had marred the performance of previous hip replacements and he even noted the squeaking of a French implant with an acrylic femoral head. The space age, low-friction polymer (PTFE) attracted his attention and in 1958 he introduced an implant with a stainless steel femoral stem having a small diameter (22 mm) femoral head and a PTFE acetabular cup. The initial results were spectacular, but the wear resistance of PTFE is very poor and this led to very rapid penetration of the femoral heads into the acetabular cups. Many of the cups were worn out in only two or three years (Fig. 10) and it became necessary and urgent to find an alternative polymer.

The material chosen was an ultra-high molecular weight version of polyethylene (UHMWPE). It proved to be a remarkable choice, since it has remained the preferred polymeric material in load bearing implants to the present day.

Total replacement joints in their present form do not enjoy fluid-film lubrication and it is therefore necessary to select materials that exhibit very low rates of wear under boundary lubrication conditions. Much of my interest in this field has been aroused by the need to understand the remarkable wear characteristics of UHMWPE when sliding against hard counterfaces and to ascertain how the wear can be minimized.

Long-term laboratory studies of the wear of UHMWPE (**16**) were to reveal the very important

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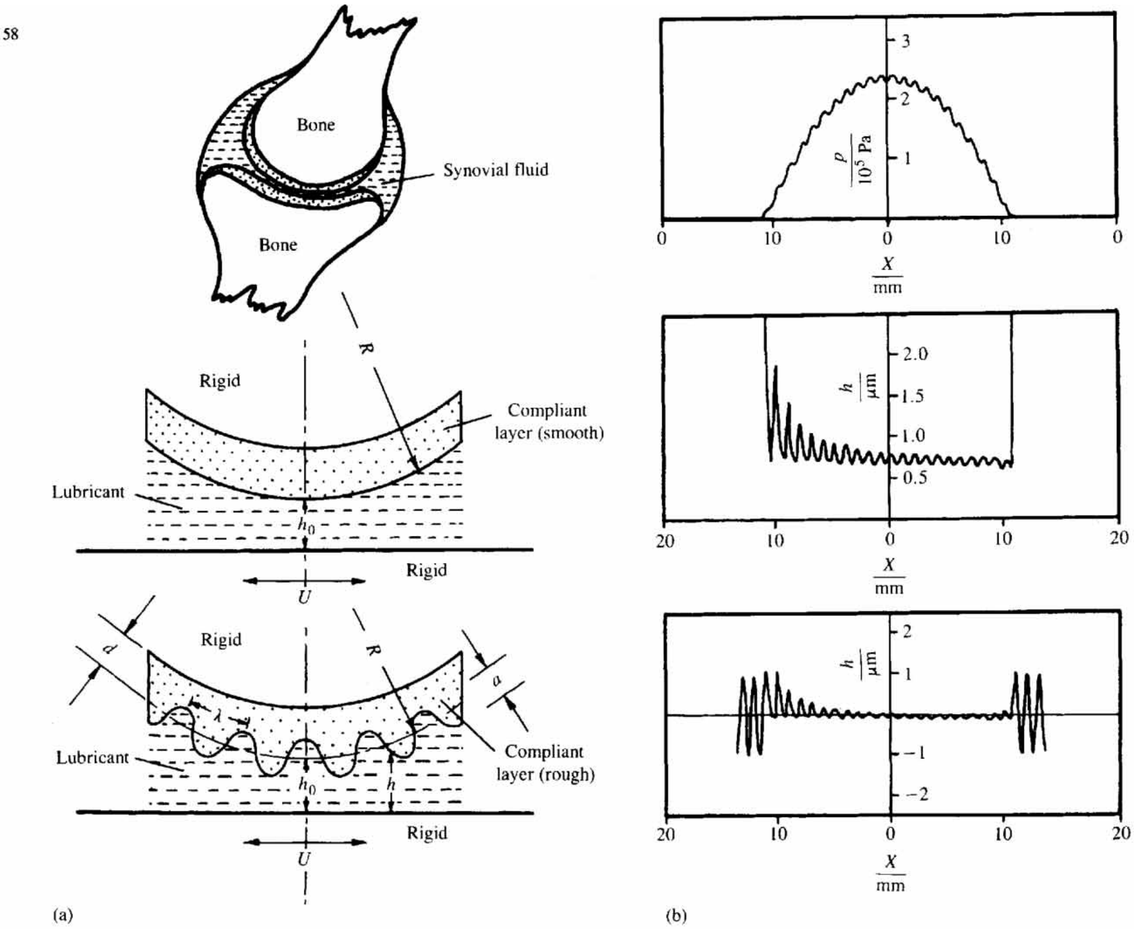
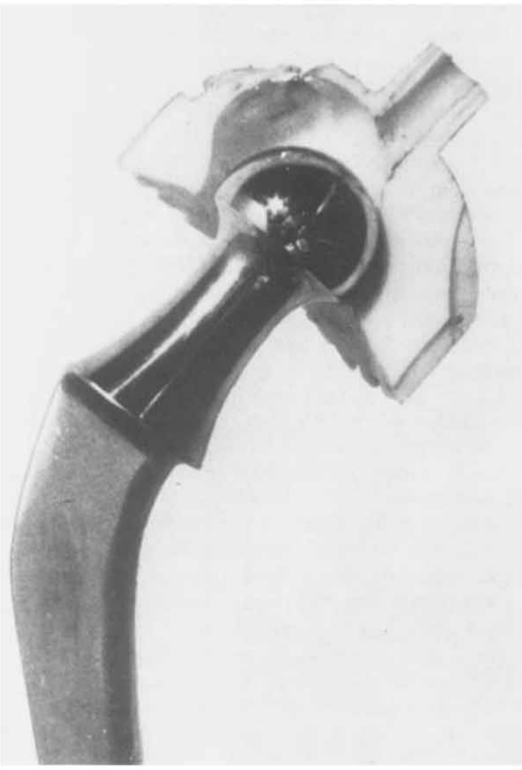


Fig. 9 Micro-elastohydrodynamic lubrication in synovial joints



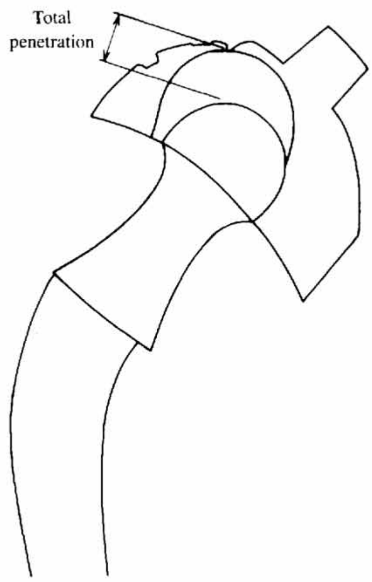


Fig. 10 Worn Charnley hip joint (PTFE)

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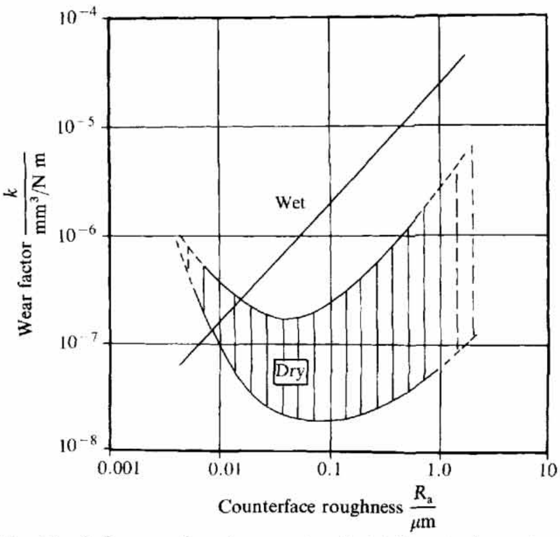


Fig. 11 Influence of environment and stainless steel counterface roughness on the wear of ultra-high molecular weight polyethylene (UHMWPE)

influences of the environment (wet or dry) and counterface roughness as shown in Fig. 11. It was also found early in the 1970s (**17**) that surface fatigue was an important feature of the long-term wear of UHMWPE. Further confirmation of this important feature of polyethylene wear has emerged recently from birefringence studies of thin sections taken perpendicular to the wear face of test pins and complete acetabular cups (**18**). It was also found that the UHMWPE wore at only about half the rate recorded against stainless steel when alumina ceramic counterfaces were introduced (**19**, **20**), a result that has interestingly been confirmed by recently reported (**21**) clinical appraisals of the *in vivo* performance of metallic–ceramic–polymeric total replacement hip joints. Illustrations of Charnley forms of low-friction arthroplasties based upon metallic and ceramic femoral heads are shown in Fig. 12.

Hip joint replacement is widely regarded as the major advance in orthopaedic surgery this century and in recent times tribologists and materials scientists have worked closely in association with orthopaedic surgeons to provide a sound engineering and medical base for the developments. There is still much to be done, particularly in relation to the development of satisfactory knee, ankle, shoulder, elbow and finger joints, but some 300 000 patients now benefit from hip joint replacement operations worldwide each year. Sophisticated joint simulators in the laboratory (Fig. 13) now provide valuable indications of the *in vivo* performance of new implant designs and materials. The rate of penetration of the femoral head into the acetabular cup in modern designs of total replacement hip joints is about 0.1–0.2 mm/year, and since most acetabular cups permit penetrations of 3 or 4 mm before their function and stability are impaired, their wear lives are in the range 15–40 years. This should be adequate for most cases, but implant function is often impaired before this limit is reached by loosening of the components in the bone. Encouraging progress is now being made in relation to the loosening problem, and it might therefore be thought that tribologists had completed their work in this field. However, this is not the case, since it appears that wear debris itself contributes to the loosening process. Furthermore, even though hip replacements are performing well, there is still a great need to solve the more demanding problems presented by the knee and other joints. Further improvements will undoubtedly be recorded as analysis, design, materials, manufacture and

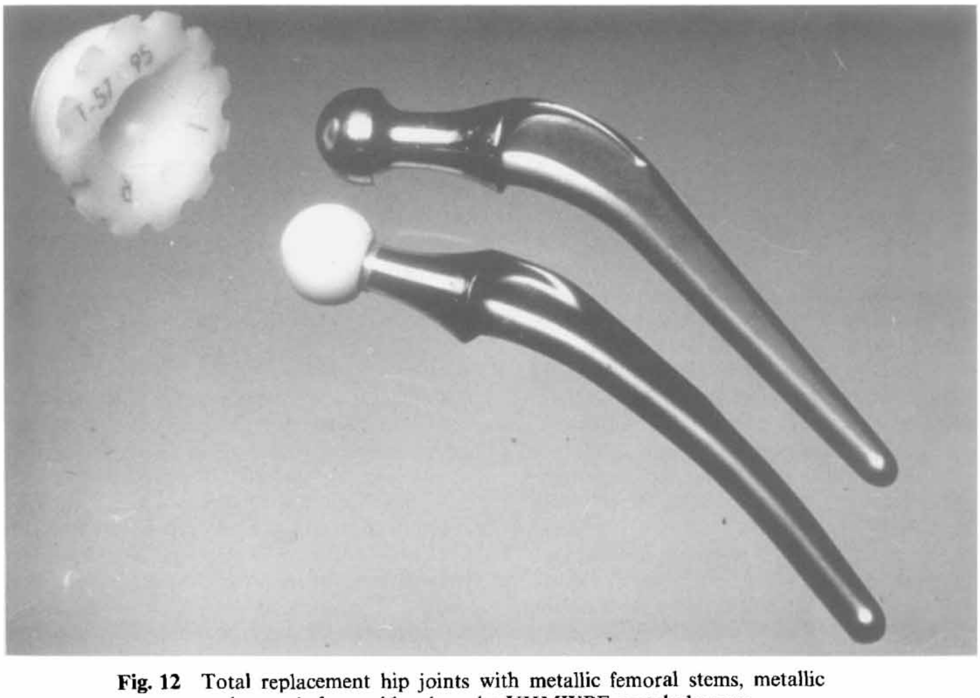
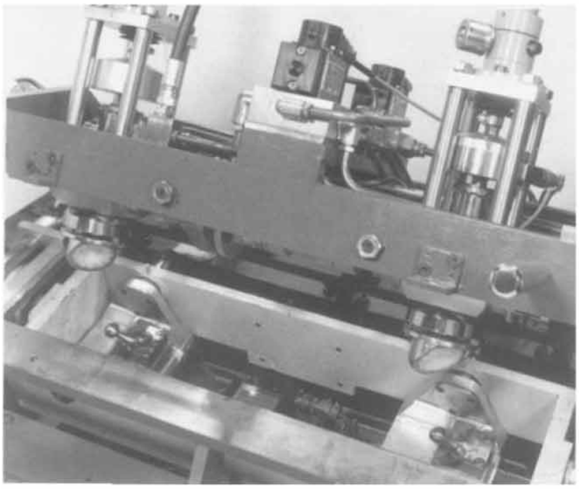
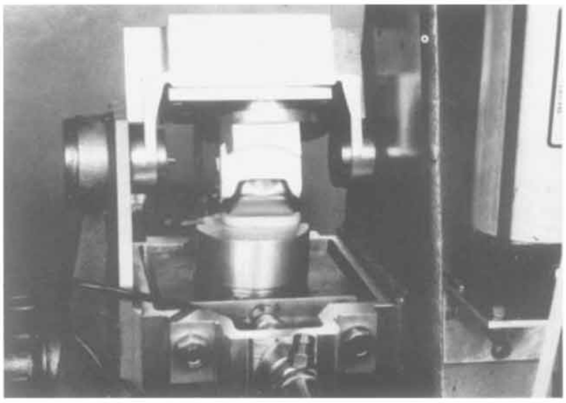


Fig. 12 Total replacement hip joints with metallic femoral stems, metallic and ceramic femoral heads and a UHMWPE acetabular cup



(a) Hip joint simulator



(b) Knee joint simulator

Fig. 13 Joint simulators

surgical techniques improve, but it is interesting to speculate that the time might have come for totally new concepts in total joint replacement to be considered.

Cushion joints

The current combinations of materials used in implants already exhibit remarkably low wear and hip replacements have been particularly successful. In focusing attention upon the combination of sliding pairs of materials which will best resist wear in replacement joints, it has become necessary to adopt materials that are quite unlike the biological materials that they replace. The polymers are several times stiffer and the metals and ceramics at least a thousand times stiffer than articular cartilage.

Since the highly successful functioning of natural synovial joints appears to be related to their ability to develop films of lubricants which effectively separate the articular cartilage surfaces, while current forms of total replacement joints have to rely upon excellent wear resistance under boundary or mixed-film lubrication conditions, the intriguing possibility arises of designing

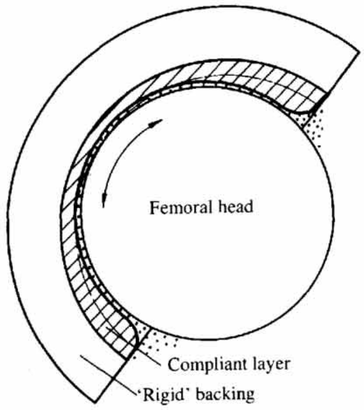


Fig. 14 The cushion joint

replacement joints that could enjoy the benefits of fluid-film lubrication. This might be achieved by introducing synthetic cartilage-like bearing materials, such that fluid-film lubrication would be promoted, in a manner similar to that in which it is developed in natural joints. The concept, which I have described as a 'cushion joint' (**22**), is illustrated in Fig. 14. Preliminary studies in various centres in Canada (**23**), the United Kingdom (**24–26**) and Japan (**27**) have demonstrated that fluid films and correspondingly very low coefficients of friction can indeed be generated in such configurations in the laboratory, based upon polyurethane, silicone rubber and hydrogels, and design guidance is now emerging for such systems (**27**). The fluid films appear to be of the same order of thickness as in the natural joint, typically 0.5 μm or less, and it is therefore likely that micro-elastohydrodynamic lubrication concepts will have to apply if satisfactory lubrication is to be ensured in the long term. Furthermore, the materials selected will need to possess adequate resistance to boundary lubrication and maybe even dry conditions of operation in successful implants.

The adoption of the cushion joint concept would represent a complete reversal of approaches to the total joint replacement problem throughout the second half of the twentieth century. The possibility of designing a joint replacement that is much more akin to the natural joint than to the present implants, in both form and performance, represents an exciting challenge to the tribologist and bioengineer of the twenty-first century.

4 EDUCATION OF ENGINEERS

There have been many changes in approach to the education of engineers throughout my professional life, yet many concepts remain unscathed. Perhaps the greatest change during and since the post-war period of expansion has been the relentless move towards increasing specialization, yet it is easy to detect interest in a move back towards a more general form of education at the present time, at least for the early stages of higher education. The smooth transition from school and the development of mathematical skills closely integrated with an introduction to the fundamentals of core engineering science subjects like solid mechanics and thermo-fluid mechanics remain priorities. Equally important is the enhancement of understanding of physical phenomena and an appreciation of the properties of engineering materials, both solid and fluid. However, it is a comprehensive approach to design that frequently distinguishes the engineer from the scientist, since this activity embraces, more than any other, the essence of synthesis of knowledge rather than analysis alone.

It is equally important for undergraduate engineers to develop experimental skills, both for the comfort which is derived from practical confirmation of analytical predictions of system behaviour based upon the principles of engineering science and for the revelation of new knowledge that cannot readily be achieved by other means. In my own career I have rarely carried out an experiment without finding some novelty in the outcome or the need to adjust my understanding of a phenomenon. The general development of laboratory skills in formal laboratory classes is usually supplemented by guided project work and, in many cases, the opportunity to undertake a comprehensive problem based individual project in the final year of study. The latter often results from direct interaction between an academic supervisor and an engineer in industry and in this form exemplifies work at the interface between universities and industry.

Engineers have always found it necessary to develop skills that enable them to obtain approximate solutions to many of their problems, since few practical situations permit neat analytical solutions to be obtained. The need to develop computing skills has impinged upon the undergraduate engineering curriculum in a major way during the past 20 years or so and it is only now that balanced judgements are being reached on optimum approaches to the teaching of computing in engineering courses. Substantial advances in affordable hardware and powerful, user friendly, software are changing not only the approaches to the teaching of design and manufacture but also to analysis and the learning of the fundamentals of engineering science.

It is regrettable that fewer undergraduates manage to secure training today with an intercalated year between school and university, since the 1–3–1 schemes were found by many to provide a sound, integrated form of engineering education and training. The introduction of programmes on 'Engineering Applications—EA1' has undoubtedly been beneficial, albeit at substantial cost in financial terms and in relation to increased pressure on the curriculum.

We are all anxious to include broader aspects of education into the engineering curriculum, such as management, business and economic studies, law, marketing, languages, communication skills, the history of technology and other related liberal studies, yet the opportunity to do so is severely restricted by other pressures on our courses. Likewise, specialists understandably defend the opportunity to present their options in the final years of engineering courses, thus imposing further demands upon the structure.

The opportunity to learn from a teacher who is a leading authority in some aspect of engineering research, in a final year option, is nevertheless a most attractive feature of many degree schemes. I still believe passionately in the merits of university education and learning in an environment of research. In most engineering degree schemes, the essential, core material is covered in the first two years, perhaps with some seepage of compulsory material into the third and fourth years. This permits students to select packages of options in fields that interest them and that often indicate their career preferences in the latter stages of their courses. This general structure has proved to be particularly attractive over many years.

Such pressures, coupled with vastly increased student–staff ratios, make continuous review of the curriculum essential. *It is increasingly evident that we can no longer teach all that we have taught before, in the manner in which we have taught it.* The increasing emphasis upon alternative teaching methods and the assessment of performance and efficiency in teaching, while preserving the quality associated with United Kingdom higher education, are essential corollaries to the above changes. The main challenge is to establish the foundations of sound engineering principles and to develop skills in their application to the exciting range of problems encountered in our subject, while at the same time ensuring that the undergraduate develops an understanding of the human, social, political and economic interactions affecting responsible professional engineering activity.

4.1 The shortage of engineers

There was a good deal of debate in the 1980s about demographic trends and the likely participation rates in engineering degree schemes towards the end of the twentieth century. Fewer births in the United Kingdom between 1964 and 1977 caused the 16–19 year old population to fall from 1982 to the present day. This will continue until 1994 and thereafter there should be a modest rise. The position is shared with other Western industrial nations, but it should be noted that about twice as many 18 year olds enjoy full-time education in France, in Italy and in Germany as in the United Kingdom.

Other factors affect the entry to engineering degree schemes, including changes in the schools, particularly the shortage of teachers of mathematics and physics and changes in the curriculum, the growing diversity of university courses and the perceived decline in the attractiveness of careers in manufacturing industry. While enjoying the benefits of an industrial society, many began to question its progress and direction, as major accidents in process plants, construction, the nuclear industry and transportation were reported and long-term damage to the environment was recorded. Engineers in general and manufacturing industry in particular took the brunt of the criticism and there seemed to be little appreciation of the deep sense of social responsibility in our profession. Furthermore, if society is now ready to pay the real price of safety and the protection of the environment and still enjoy the benefits of industrial progress, it is the engineers who will have to put things right in the future.

The concern was sharpened by our move towards Europe and the perceived need to sustain an active and successful manufacturing base in the United Kingdom beyond 1992 and into the twenty-first century. The shortage of engineers became a major concern towards the end of the 1980s (**28**–**31**) and it is therefore impor-

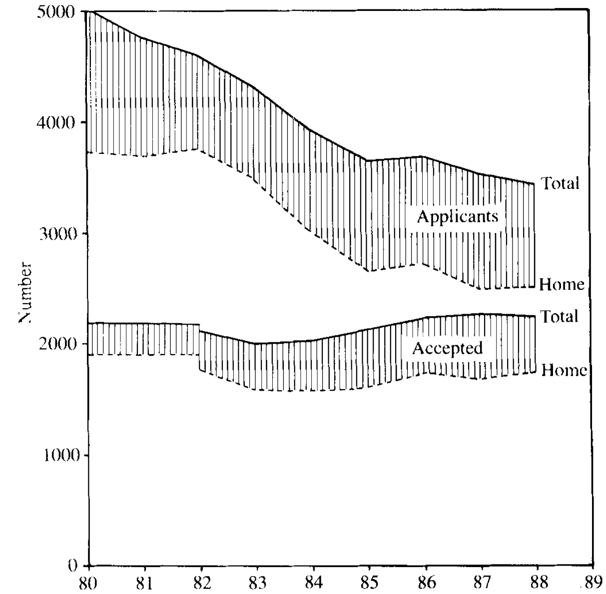


Fig. 15 Applicants (first choice) and accepted students for mechanical engineering [UCCA]

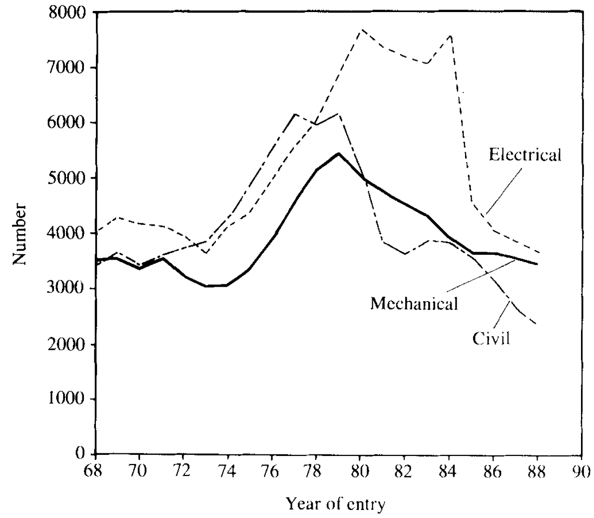


Fig. 16 Applications to major engineering disciplines [UCCA]

tant to review the supply side of the story over a reasonable time-scale.

The UCCA (Universities' Central Council on Admissions) statistics for the 1980s show how the noose was tightening on the engineering degree schemes. Annual statistics for 'candidates for admission to universities through UCCA by subject of first preference', a measure of the number of students who have indicated a firm interest in a subject, and the 'candidates accepted' enable Fig. 15 to be constructed. The near convergence of the two bands towards the end of the decade vividly reflects the underlying reasons for the concern.

The balance of applications to major schemes of study in engineering over a longer time-scale is shown in Fig. 16. By and large mechanical engineering has experienced neither the exhilaration of considerable increases nor the despondency of major falls in applications over the period reviewed. However, all three curves exhibit the fall in applications in the 1980s discussed above.

The UCCA system of recording applications changed in 1989, but it is clear that engineering has benefited from the general rise in applications for university places in recent years. Some local information has enabled me to examine trends over a similar period of time for each of the major subjects in a large civic university (Fig. 17). It has also enabled me to illustrate the rapid increase in applications for engineering schemes of study which now appears to be developing and which is supported by the UCCA statistics for total applications to university engineering departments. One important factor responsible for this trend is the introduction of attractive, flexible degree schemes in which an opportunity is presented to develop a sound basis in mechanical engineering alongside substantial components of associated subjects such as management, mathematics and electronics (for example mechatronics). All are based upon substantial components of core mechanical engineering degree schemes. This is illustrated for my own department of mechanical engineering by Table 1.

4.2 Women in engineering

The buoyant indications of current applications to university degree schemes in engineering masks the curious fact that we are still failing to attract a sensible proportion of women into our courses. The national average number of women entering mechanical engineering schemes is still only slightly above 10 per cent. This proportion is curiously and disappointingly low compared with other industrial nations. The reasons for this inadequate involvement of women in engineering are deeply rooted in the structure of our society and are of

Table 1 Degree schemes in a department of mechanical engineering

Year of entry	1989	1990	1991	1992
Degree schemes*	Mechanical engineering	Mechanical engineering	Mechanical engineering	Mechanical engineering
		Manufacturing systems engineering	Manufacturing systems engineering	Manufacturing systems engineering
			Mechatronics	Mechatronics
				Management and mechanical/ manufacturing engineering
				Mathematical engineering

* Three-year BEng and four-year MEng schemes available in each case.

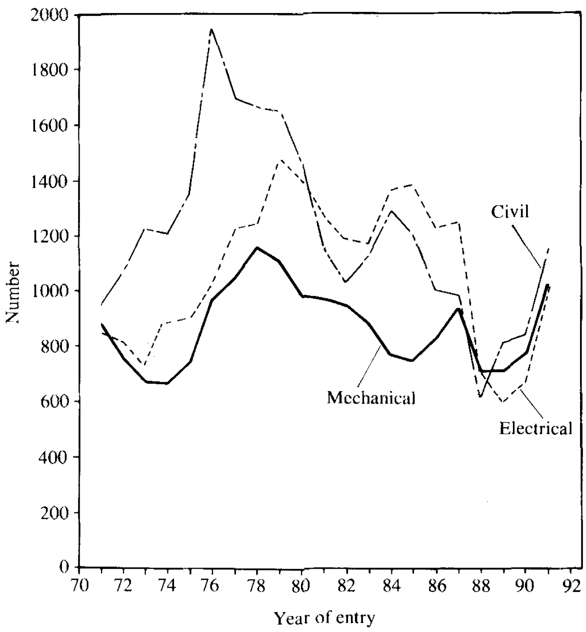


Fig. 17 Applications to major engineering departments in the University of Leeds

long standing, being related to the wider misunderstanding of the nature of professional engineering activity, the status of the engineer, patterns of education and training and the structure of our profession.

The situation must change; although the numbers are still very low, there are some encouraging trends, since

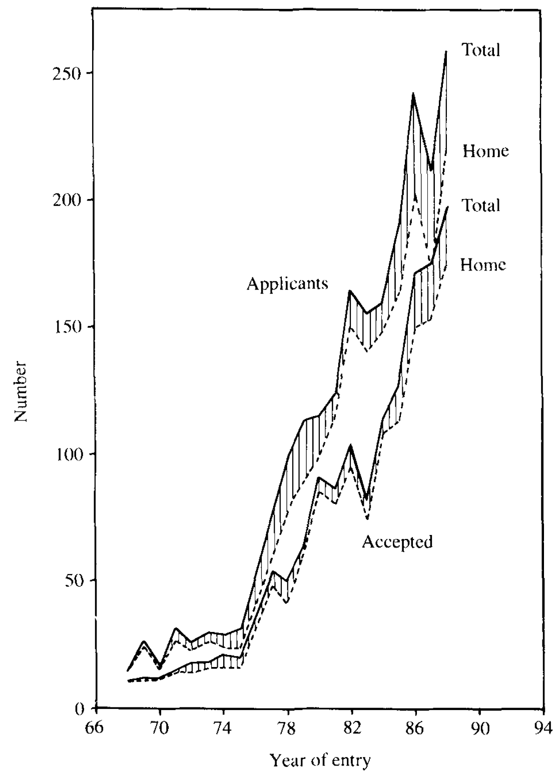


Fig. 18 Women applicants and accepted students for mechanical engineering [UCCA]

they are rising at an increasing rate. Both first and second differentials are positive, as shown in Fig. 18!

4.3 An international experience

Three-year courses are still the norm for the majority of undergraduate schemes of study in the United Kingdom, but while the long-standing debate on the merits of both longer and shorter courses continues, it is timely to draw attention to the growing popularity of four-year courses involving a period of study overseas. Four-year degree schemes are generally available for academically sound students with appropriate motivation and personal qualities in United Kingdom universities. One attractive variant offers the opportunity to spend the third year of a four-year (MEng) degree scheme overseas under exchange schemes between compatible institutions. Such schemes are developing rapidly in Europe under the European Community Action Scheme for the Mobility of University Students (ERASMUS) structure, with exciting opportunities for credit transfer under the European Community Course Credit Transfer System (ECTS). We have also established exchange schemes with Canada and the United States and the opportunity for Transatlantic or European mobility is proving to be very attractive to sixth formers contemplating entry to engineering degree schemes.

This development is particularly encouraging and my enthusiasm for the promotion of such schemes stems partly from the recognition that our engineering graduates must be prepared for international careers, but also because we need to attract bright, enthusiastic young people into our degree schemes.

5 THE ACADEMIC–INDUSTRIAL INTERFACE

The main features in the formation of professional engineers are education, training and, of course, experience. University education must therefore be seen as a preparation for professional life and cannot be immune from the needs of industry. Successful academics in university engineering departments should themselves continue to be active in their profession and this is generally achieved through participation in the affairs of our professional Institution and close working with fellow engineers in industry. Much of the research carried out in United Kingdom universities is directly sponsored by industry, and this results in frequent visits and discussions between engineers in the two sectors. Lecturers engaged in research and consultancy are thus aware of current developments and the education of undergraduates can flourish in this lively and meaningful environment. The direct input by industrially based professionals into teaching programmes through occasional formal lectures, sponsored projects, discussions and visits to companies can also be valuable, but only if they are well planned and there is a full commitment to and understanding of the educational process. I believe that our profession is well served by its hard pressed academic community. Varied courses are continually being introduced and enhanced and the engineers of the future are stimulated to seek careers in industry. Likewise, the research carried out in universities provides that longer-term fundamental knowledge base which underpins more immediate industrial developments. Neither teaching nor research thrive within a framework of short-term decisions, but I am not yet convinced that the value of long-term research in selected fields which can underpin our industrial base is fully recognized by society.

This is the well-tried and traditional approach to the academic–industrial interface, but there are other forms of collaboration that are being developed to bring university expertise and resources closer to industry. Industrial units, technical centres, industrial service companies and science parks all come into this category. One example of this in my own field of tribology, which has stood the test of time, was the establishment in 1968, as a consequence of the publication of the Jost Report (**32**), of an Industrial Unit of Tribology within the Department of Mechanical Engineering. The Unit sits alongside a vigorous traditional research group in tribology and active teaching programmes in the subject at undergraduate, master's degree and continuing professional education (CPE) levels in an Institute of Tribology. This structure can benefit from the expertise of academic staff in many departments and faculties, together with access to an extensive range of analytical, design and experimental facilities, while the students and staff in our Department of Mechanical Engineering are conscious of the immediate interests of industry in this and related subject areas.

This is but one example of working at the interface with industry from an academic base. I am sure that we shall see many other developments of a similar nature in the future. Another important role for academic members of our profession is to see that the fruits of their research are communicated, in an appropriate form, for exploitation by manufacturing industry. It is often said that, in the United Kingdom, we have the talents and the structure to promote outstanding research, but that the findings are too often developed elsewhere. I think that we are getting better at technology transfer, which is a two-way process, but some academics still fail to appreciate the wider issues associated with commercial exploitation of invention, and thus experience frustration when their bright ideas are not enthusiastically developed, while industry often seems to be unduly critical of the academic approach and to mis-judge the nature and time-scale of knowledge generation through research. Such frictions need to be removed if we are to develop a sound, innovative industrial base for the twenty-first century. The case for full integration of our academic, industrial and professional skills has been impressively presented by Brian Manley, President of the Institution of Electrical Engineers (**33**).

6 PROFESSIONAL INSTITUTIONS

Initially there were civil and military engineers, but as industrialization and specialization developed, separate institutions and societies were formed. Our own Institution of Mechanical Engineers was established in 1847 by a group of enthusiastic railway engineers, with George Stephenson, father of the railways, as our first President. This took place at a time of unprecedented industrial expansion, and since that time further fragmentation has occurred and numerous institutions have been established to represent particular professional engineering interests. The story has been brilliantly told by Robin Wilson, President of the Institution of Civil Engineers (**34**), in his Inaugural Address.

In recent years the disadvantages of fragmentation have attracted much attention, and a number of mergers have taken place between engineering institutions. While we all wish to promote technical and learned society activities within our particular engineering institutions and societies, and even within specialisms inside those institutions, there are some matters on which a collective view would undoubtedly be beneficial to the profession of engineering as a whole. It was, therefore, encouraging to note the ready response, in mid-January 1992, of the Council of Presidents, representing some 46 engineering institutions and the Engineering Council, to the personal initiative of Sir John Fairclough to the effect that a steering group should be established to:

> ... consider the formation, role and organisation of a new single body to act as a focal point for the engineering profession.

The steering group started its meetings in March 1992 and is due to report back to the Council of Presidents in 1993.

7 SUMMARY

I make no apology for focusing my Address on matters educational, since I believe that the future prosperity of our manufacturing industry depends upon the maintenance of quality teaching and the pursuit of imaginative research in the engineering sciences.

A recognition of the significance of basic and applied research, both for the universities and the competitiveness of manufacturing industry in the 1990s and the twenty-first century, must be emphasized. A long-term investment in engineering education and the promotion of research in engineering science is essential for the economic well-being of our society.

The excitement of engineering must be communicated to young people in the schools, while careful attention is given to the needs of established engineers for continuing professional education. It is particularly important that young women are encouraged to enter engineering if we are to provide an adequate number of well-qualified professional engineers to deal with the highly competitive future ahead of us. In short, we need to preserve a positive second differential in the curve of applicants for some time to come!

Sensible integration of academic aspirations and industrial needs should be carefully addressed. There is, perhaps, no more important interface than that between the universities and manufacturing industry.

Finally, it is to be hoped that a greater coherence between our somewhat fragmented, but proud and distinctive, institutions will emerge to assist the promotion of an energetic, enthusiastic and responsible engineering profession in our nation.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to all who have enabled me to enjoy learning, teaching, research and the practice of mechanical engineering. I owe a particular debt to the University of Leeds, where

I have spent much of my professional career, to all my colleagues in the Department of Mechanical Engineering and the many undergraduate and postgraduate students with whom I have worked. The opportunity to pursue research in tribology and bioengineering with talented colleagues has been a particular privilege.

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