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摘要

磨潤技術為一門探討材料表面之接觸、摩擦、磨損與潤滑之微觀工程科技，自從國際磨潤學會理事長 Prof. Jost 在五十年前發表之磨潤學報告迄今，磨潤科技對於人類文明之貢獻以及未來展望，為本次在英國里茲所舉辦之第 43 屆里茲-里昂磨潤學大會的主題，會中並緬懷在今年 6 月過世之 Prof. Jost，以及他對於磨潤學的貢獻。本次大會共有 32 國 230 位以上之研究學者參與。軸承與滾動元件、表面花樣與塗層以及潤滑流體之流變行為分析暨實驗為探討元件摩擦與潤滑作用之重點，有助於發展表面花樣與摩擦、滾動元件傳動理論開發，對於研究之推展極有助益。

關鍵字：磨潤，接觸，摩擦，磨損，里茲，軸承，傳動理論，表面花樣

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一、 目的

傳動元件的傳動效能與使用壽命之關鍵在於內部接觸界面間的摩擦與潤滑，良好的潤滑可以有效降低摩擦與減少磨損。參加本次研討會之目的在於了解磨潤科技最新發展，同時磨潤界的先驅全球摩擦學會前主席 Jost 教授所提出的磨潤學報告今年為 50 周年，同時 Jost 教授在會議舉行的前幾周以 94 歲高齡過世，因此為回顧過去磨潤學在世界發展的趨勢以及對世界的影響，故參加此次會議以了解磨潤科技的發展歷史以及未來展望，並應用在傳動元件之研究與教學為本此行程之主要目的。

二、 過程

本會議自 1974 年開始舉辦以來已經經歷 43 年，舉辦規模逐年擴大，今年共 32 國參加，200 多位世界各地學者參與，如圖 1 所示，除了歐洲本地外，包含亞洲、美洲、澳洲以及日本等各地主要磨潤學者來參與，如圖 2 所示。本次會議主辦人 Prof. Neville，如圖 3 所示，主要研究領域在於生醫磨潤學，探討各種表面塗層與膠體對於人工關節磨潤行為之影響，並找出如何延長關節壽命方法，對於老人醫學方面的研究，成果豐富。



圖 1 研討會起源與世界各國參與狀況



圖 2 各地與會者參加開幕



圖 3 本次會議舉辦人 Prof. Anne Neville

由於國際磨潤學會主席 Prof. Jost 在 50 年前提出磨潤學對於工業以及民生影響報告，時至今日科技一日千里，而磨潤學在這 50 年間的改變為何？因此大會演講安排了許多相關主題來討論，包含軸承發展、潤滑科技、汽車演變以及科普教育，此影響是全面的改善了人類的生活，使得機械變得更有效率、使用壽命增加以及節省能源，相關研究更進一步影響了科學教育，使磨潤學教育深入學生的學習以及增進相關認知。此外，適逢 Prof. Jost 於今年六月以 94 歲的高齡過世，所以世界各地學者亦藉此機會來緬懷他對於磨潤學的貢獻。

滾動元件的磨潤學研究為我多年來的研究主軸，表面形貌與摩擦、磨損、潤滑研究為極具挑戰性的課題，因此本次研討會的參與，收穫十分豐富。SKF 研發部主管 Pascal Ehret 博士指出近 50 年 SKF 在軸承研究之演進，1966 年為 Prof. Jost 提出磨潤學報告當年，在此之前，軸承設計只考慮動態負荷對於軸承設計之影響，潤滑只是輔助軸承，使之工作順利的次要因素，如圖 4 所示。然而當 Prof. Jost 提出磨潤學報告後，潤滑與表面形貌的影響受到重視，為影響軸承壽命之重要因素之一，因此在近 50 年中 SKF 對於磨潤學與軸承壽命的研究非常重視。由靜態的模擬分析，到今日的動態應力與潤滑分析，逐步建立一套完整之分析理論。當軸承壽命終了時，其表面的破壞機理主要為點蝕(pitting)，如圖 5(a)所示，請其剖面深度在特定深度，亦可發現產生十分嚴重之裂紋。此裂紋之產生機理與表面粗糙度、潤滑、應力有關，如圖 5(b)所示，表面粗糙度的變化使得應力集中在軸承軌道面下方幾微米深度之次表面(subsurface)，因此經由長期之往復應力作用下使得軸承表面產生點蝕疲勞破壞，而在更深處的應力破壞產生機制與點蝕大不相同，如圖 6 所示，當滾珠與軸承表面產生接觸應力時，應力集中區域會發生在軌道次表面，由剖面之晶格排列可發現微裂紋產生在次表面，因此會產生點蝕的效應。如果產生接觸應力的點在同一時間內有數個，亦即一捲滾珠滾過軸承表面，經由模擬分析此時可發現其集中應力作用區除了在次表面產生外，在更深處亦產生另一個更大的集中應力區，此為造成軌道內部裂紋的主要原因。此外，此研究可以應用在不同材料熱處理所產生之缺陷以及析出物對於裂紋產生之影響，進而找到最佳製程條件。

Tribology in SKF: The journey...

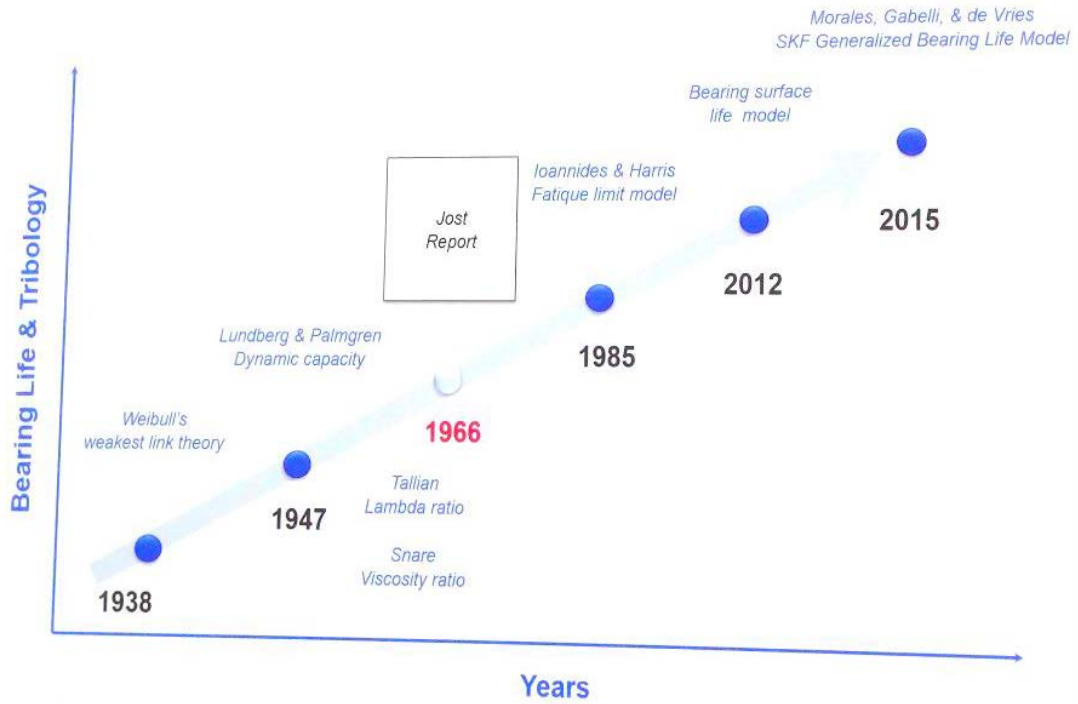
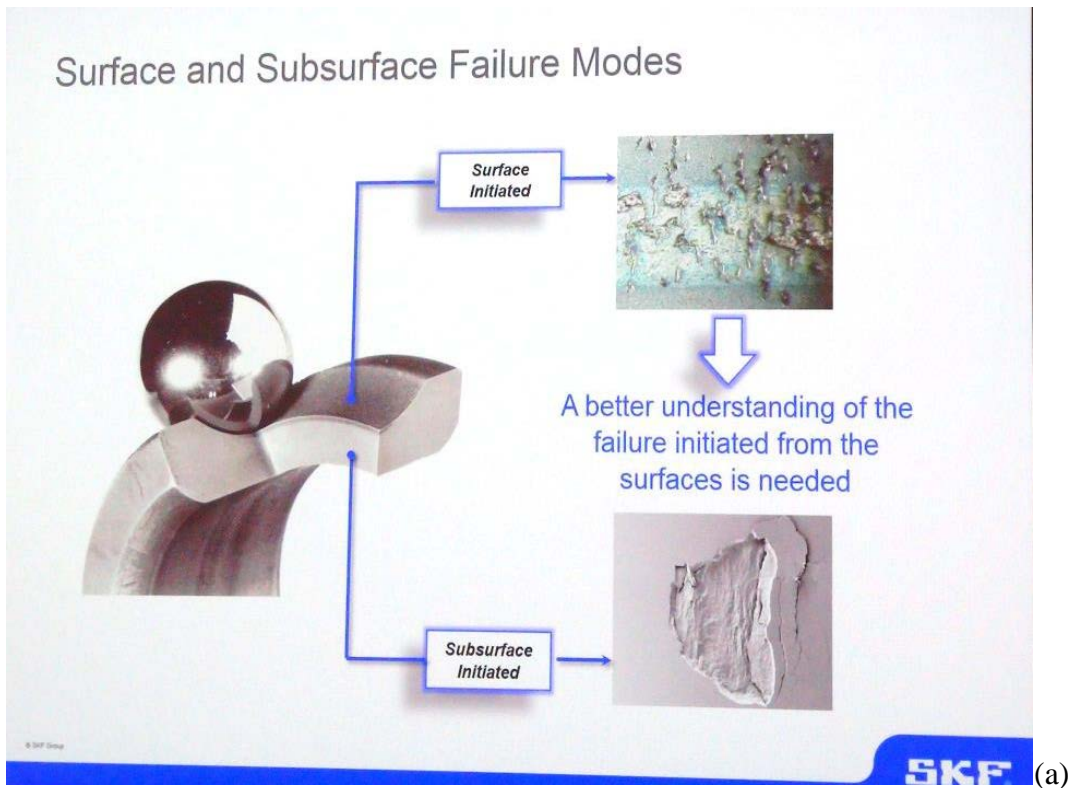


圖 4 SKF 軸承磨潤之發展歷史



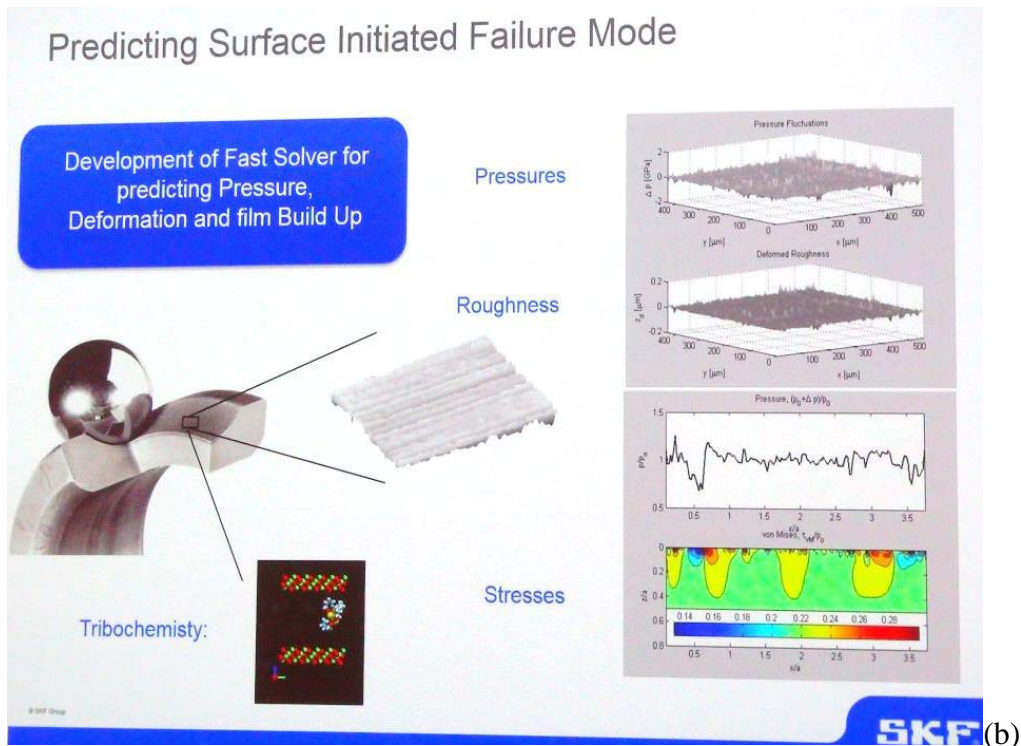


圖 5 軸承損壞機制 (a)失效模式；(b)表面粗糙度之影響。

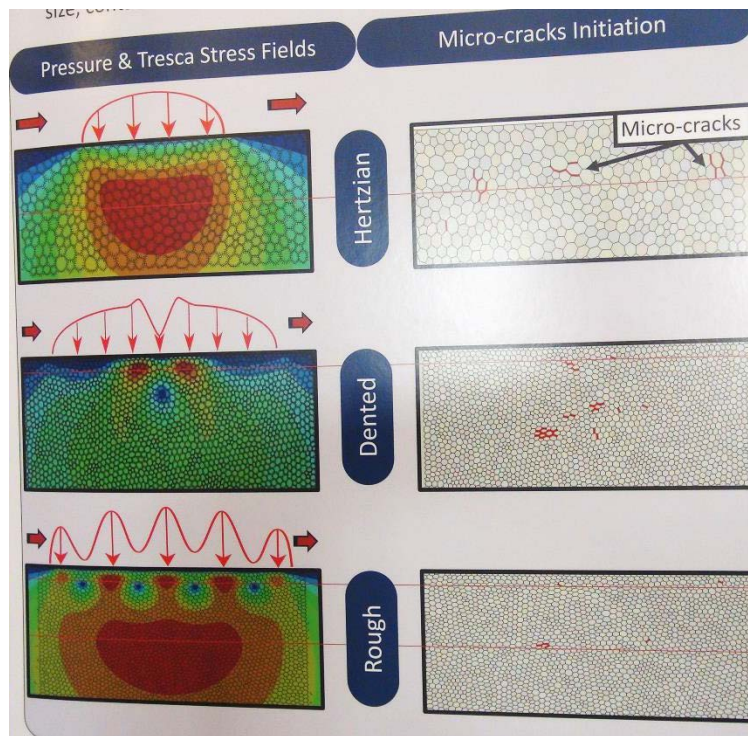


圖 6 軸承表面應力影響分析

軸承潤滑為另一個防止因潤滑不良導致軸承破壞的主要因素，圖 7 所示為分析軸承油脂潤滑之個軸承元件運動關聯示意圖，潤滑之在軸承內部因流動的不易，因此在需要潤滑的接觸區會產生缺乏(Starve)的現象，因此 SKF 與歐洲各大學間建立緊密的產學合作關係，開發潤滑分析動態模型，如圖 8 所示，此模型可以對潤滑油或脂的流動狀態、溫度、元件應力進行動態模

擬分析，可以協助廠商規畫適合的注油孔方位設計、潤滑狀態評估與應力分析。

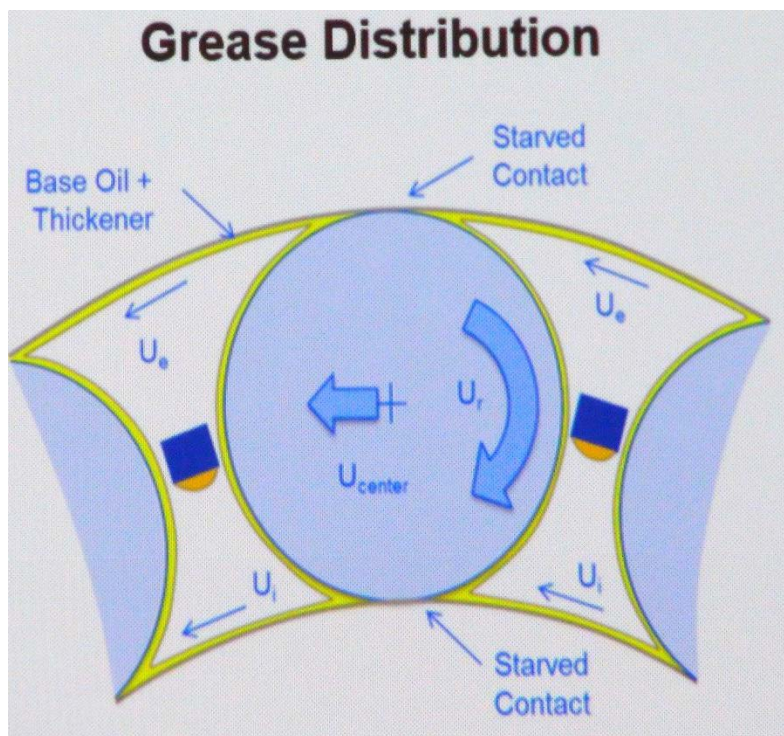


圖 7 軸承油脂潤滑

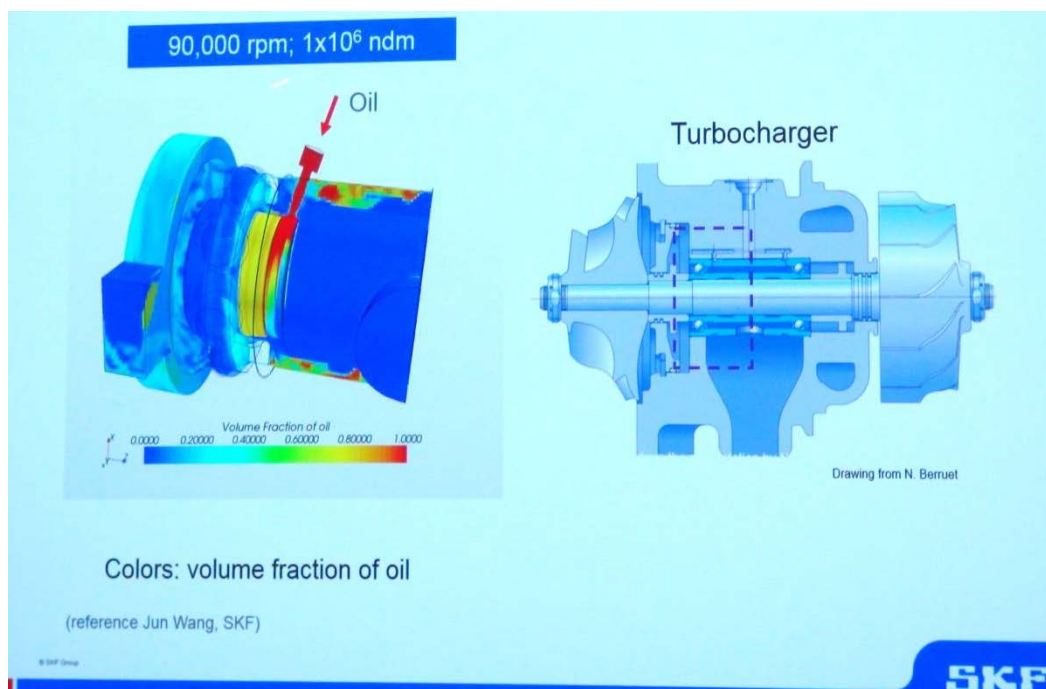


圖 8 軸承潤滑動態分析

此外，油膜動態監控亦為研究之主軸，如圖 9 所示，法國 INNSA 為機械工業研究法人學術單位，與 SKF 合作開發油膜光譜分析，使用透明環狀藍寶石玻璃製作元件，以光學干涉原理探討油膜厚度之變化，此為非接觸方法，可探討不同操作條件下油膜厚度之變化，如圖 10 所示，在高速下油膜厚度會因流體動壓的關係而增厚，但是摩擦熱亦會增加，導致潤滑油

黏度下降，因此油膜厚度在達到一定滑動速度後便不會繼續增厚。

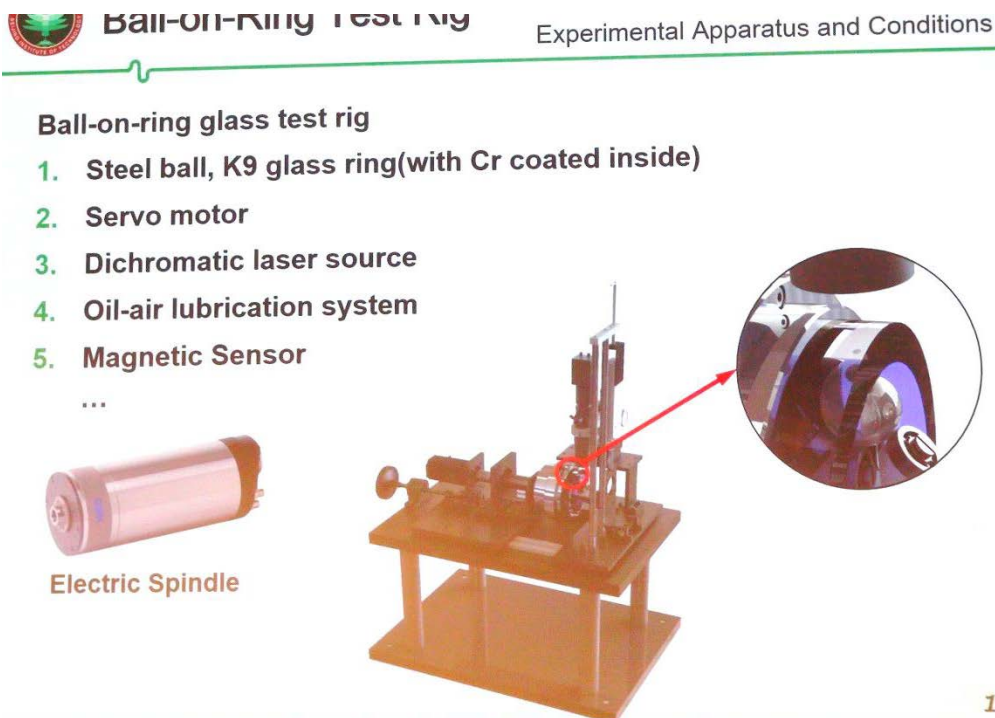


圖 9 軸承油膜厚度量測

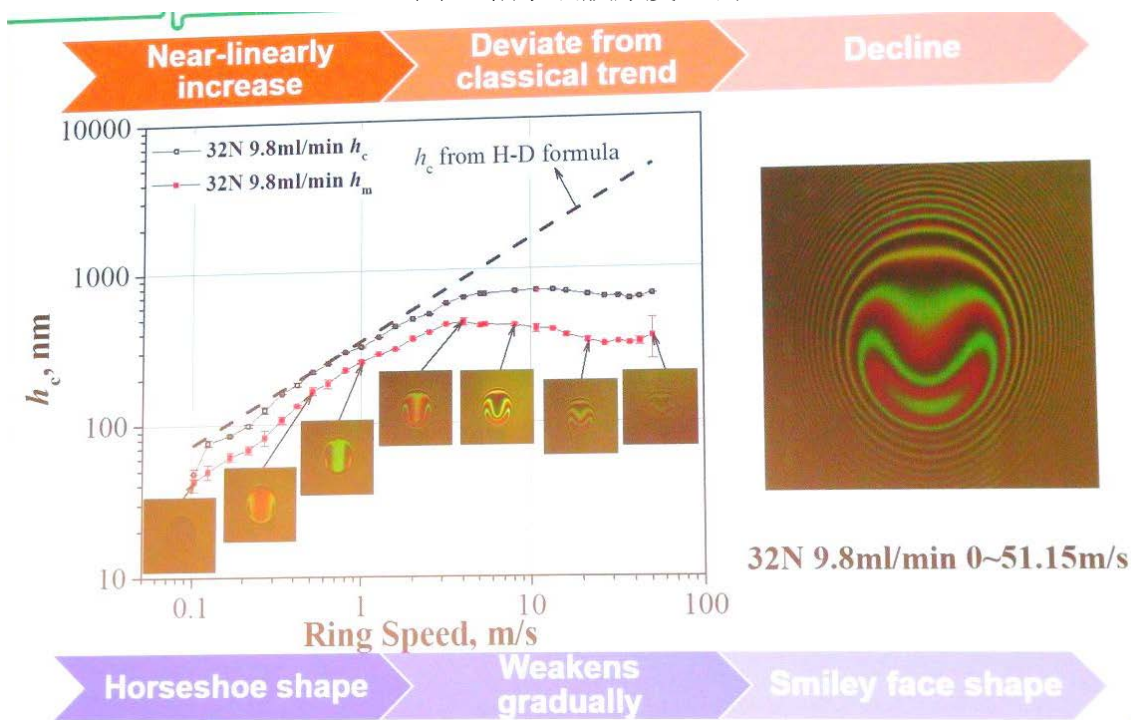


圖 10 點接觸油膜動態量測

表面形貌對於儲存潤滑液極具助益，因此如果在表面犁耕出不同溝槽(furrow)是否有助於潤滑?如圖 11 所示，此答案是肯定的，但是設計的參數不同會造成不同結果，如溝槽的密度、形狀、排列、深或寬等皆會使得潤滑狀況變好抑或是變壞。此與本人正進行的高分子材料表面形貌與花樣對於摩擦、潤滑影響研究具有極大的關聯。

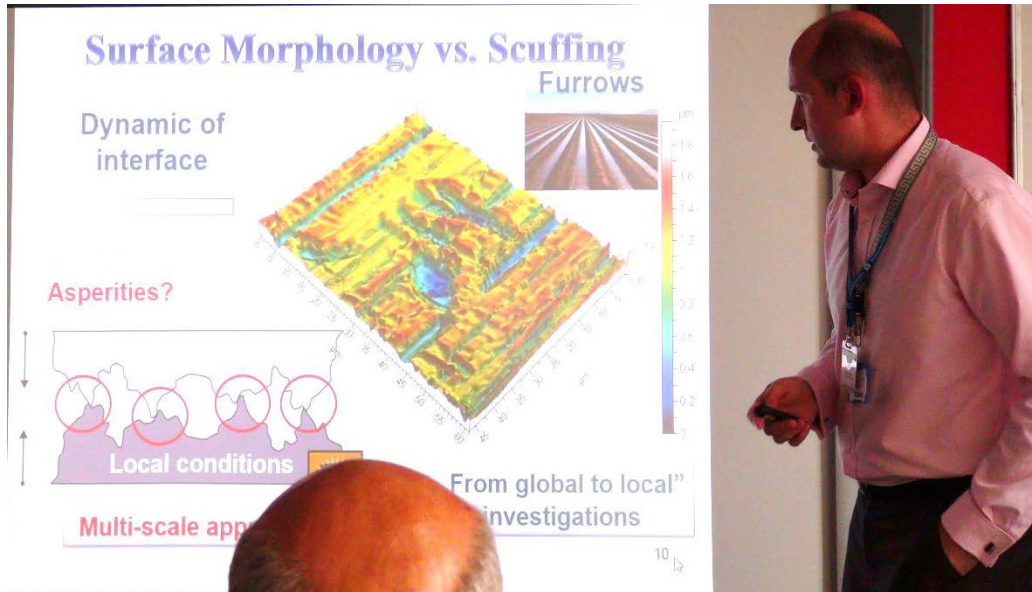


圖 11 表面犁耕形貌對於潤滑影響研究

由於投稿論文眾多，因此本次報告被安排為海報報告形式，但是大會規定兩個報告時段，發表者必須在現場報告給與會者，並進行評分與提問，與口頭發表的嚴謹度不相上下。如圖 12 所示，在報告會場認識國際磨潤學會副主席 Prof. Chouli，並與之交流了解義大利磨潤學的現況，以及產學合作的情況。

本此所發表的論文海報如附件一，論文主題為探討雙螺帽滾珠螺桿在垂直軸運動狀況下，預壓力下降對於傳動性能之影響，研究結果顯示預壓力下降會使得滾珠螺桿內部摩擦力下降，因此所需的驅動扭矩應該降低，但是預壓力下降使得機台結構剛性下降，而使得所需的驅動扭矩增加來彌補剛性降低的影響。

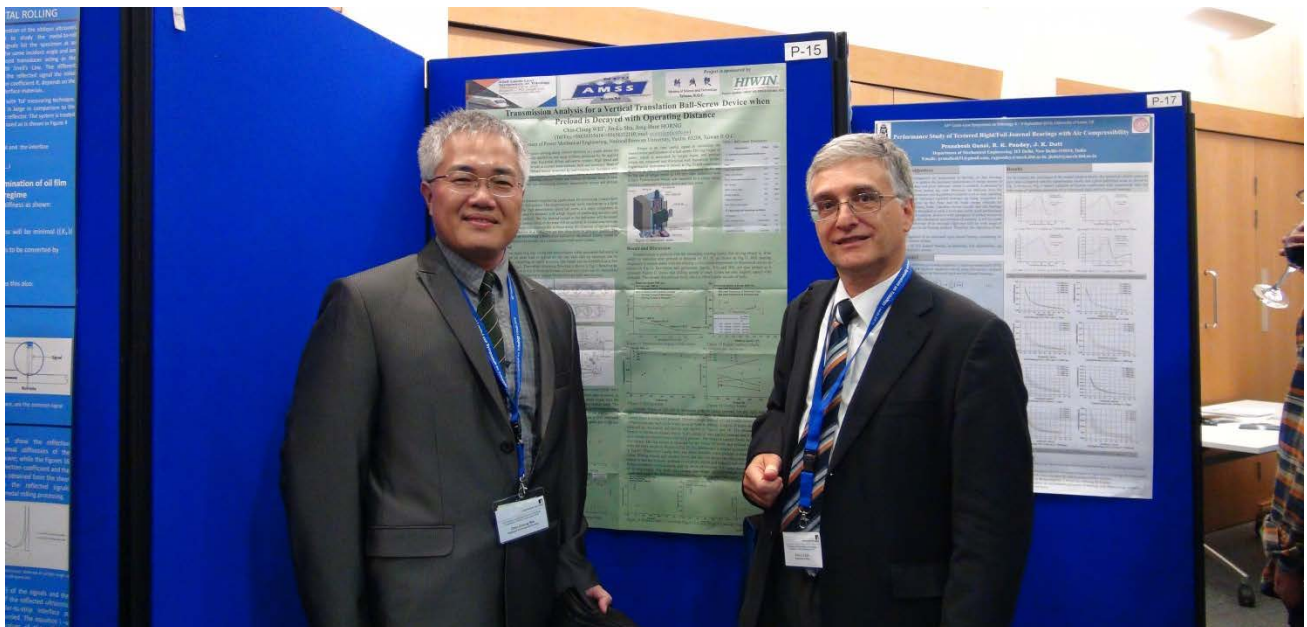


圖 12 海報論文發表以及與國際磨潤學會副主席 Prof. Chouli 合影

大會閉幕時會頒發 Dowson 論文獎，為本研討會之最大獎，如圖 13 所示，用以鼓勵年輕研究學者，因此只有學生才有資格領獎，為磨潤學界之最高榮譽，本次得獎者為瑞

士的年輕研究學者，如圖 14 所示。此外，參加本研討會亦認識其他年輕學者，如圖 15 所示，對於未來國際交流的發展具有助益。



圖 13 大會閉幕與論文獎頒獎



圖 14 論文獎得主領獎

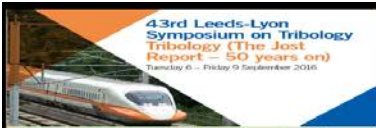


圖 15 與認識的國際友人合影

心得與建議

本次參與會議心得與建議條列如下：

1. 本國際研討會之特色在於小型與多樣化主題討論設計，尤其是分段式議程規劃可有助於提升研討效果，未來在規劃具特色之研討會，可以延伸其規劃方法來提高研討效益，同時可以讓較多不同專長學者一同激盪創意。
2. 攜回有助科研的資料以及促進國際交流，國內磨潤領域專家有限，此類研討會有助於連結國際間相關專長學者，有利於國內舉辦國際研討會來連結這些專家的專業成果，提升國內磨潤科技的競爭力。
3. 此次研討會可以發現許多具有創造力的研究，例如滾動元件與潤滑流體會因為摩擦熱與環境中的水氣，產生氫離子而導致材料脆化，影響滾動元件壽命，所以後續研究應加潤磨潤化學的觀念，以便正確評估元件壽命，以及潤滑劑的使用。
4. 參加此研討會可發現國際學者對於磨潤研究之獨到的創意，因此如何在製造創意外提升研究專家的研究創意，可為國內越來越拮据的研究環境得到突破的一線生機。



Transmission Analysis for a Vertical Translation Ball-Screw Device when Preload is Decayed with Operating Distance

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Abstract

High speed transmission ball-screw moving along vertical direction is a major device for z-axis driving. Axial load is extremely applied on nut, axial stiffness produced by the applied preload is become more important than horizontal driven ball-screw system. High speed and high load bring high friction and wear rate at contact areas between balls and raceways. Wear of contact area causes preload decay. Preload torque measured by non-rotating nut decreases with increasing rotating cycles, but driving torques rising after preload decay at a value. The study provides a numerical method for obtaining contact forces and friction at contact areas in each circulating cycles in order to reveal the relationship between transmission torque and preload decay.

Introduction

The increasing demands in precision engineering applications for positioning systems have instigated the investigation into ball screws. The reciprocating ball screw mechanism is a force and motion transfer device. The high transmission speed ball screw is a major component in rapid processing devices, and must be designed with a high degree of positioning accuracy and stiffness by applying a higher preload. But the preload existed in the ball-screw will decrease with the increase of operating strokes owing to the wear will be occurred at contact area between ball and raceway. Preload decay will decrease the stiffness along the direction of applied load. But, contact and motion behavior in a ball-screw are few discussion in previous studies. The motivation of the work is in established a four-cycles ball-screw theoretical kinetic model to reveal contact and transmission properties on a vertical motion ball-screw system.

Research Method

The cross section photo of a four cycles two recirculations offset preloaded ball-screw is shown in Fig.1. When an axial load is applied on the nut, each ball on raceways can be considered as symmetry contacting on radial direction. The model can be simplified as a four balls model as shown in Fig.2. Theoretical calculating flowchart is shown in Fig.3. Based on the past two balls model as shown in Fig.4, force equilibrates of each ball circles can be obtained by the assign method. EHL was considering in contact friction between balls and raceway.

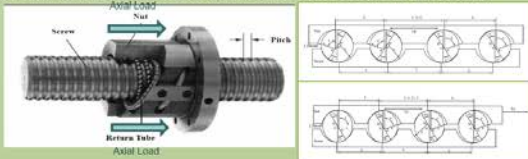


Figure 1 Cross section of a ball-screw

Figure 2 contact model

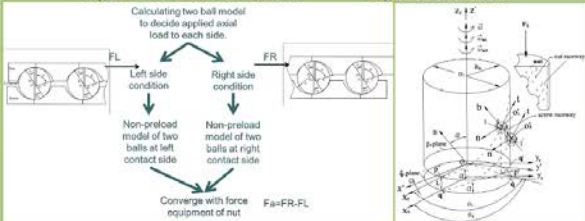


Figure 3 Force assigning flow chart

Figure 4 Two balls model [2009, Wei]

Theoretical model can well find out contact forces and friction at contact area as shown in Figs. 5 and 6. Contact forces increase greatly when the applied load is much larger than the preload, and the difference is also became large between the left and right contact sides. The difference of friction force is slightly increased with the rising load. A finite model is established and given contact force and friction as boundary conditions. Surface strain of nut was measured by strain gauges above the top of grooves as shown in Fig.7. Theoretical data is well confirmed with experiment results as shown in Fig.8. The strain distribution of nut has great gap at the two side of preloading region.

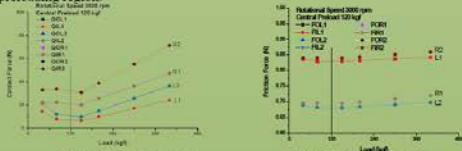


Figure 5 Contact Forces

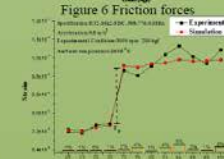


Figure 6 Friction forces

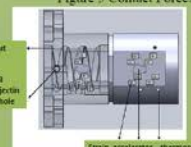


Figure 7 Sensors position on the nut

Figure 8 Strain of nut

Torque is a very useful signal in estimating the transmission performance of a ball-screw. Driving torque of screw, which is measured by torque meter, and preload torque are measured and discussed with theoretical model. Experimental instrument is shown in Fig.10 and parameters is shown in Tab.1. Preload torque was measured on the nut by the use of torque meter at 100 rpm after unbended with holder. Transmission torque was recorded by a torque meter which is connected between motor and ball-screw.

Table 1 Ball-screw Parameters

Parameters	Value	Unit
I. Geometric parameters of ball-screw		
Helix angle	0.67	degree
Pitch L	16	mm
Screw outer diameter	12.91	mm
Screw pitch diameter	10.4	mm
Screw end nut track curvature radius	1.420	mm
Ball diameter	6.35	mm
Initial Contact Angle	45	degree
Density of grease	800	kg/m ³
Viscosity of base oil	68	cSt
Total effective ball number	66	
II. Operating and analyzing conditions		
Acceleration	4.9	m/s ²
Screw rotational speed	100 and 3000	rpm
Preload	1200	N
Applied load on holder	0 and 100	kgf

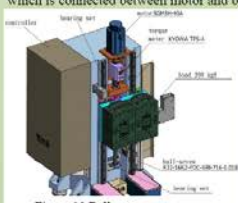


Figure 10 Ball-screw tester

Result and Discussion

Preload torque is reduced with the increasing rotating cycles, but driving torque is from stable to variation after preload is decayed to 931 N, as shown in Fig.11. Ball passing frequency is remain stable with the rotating cycles either experiment or theoretical results as shown in Fig.12. Revolution and gyroscopic speeds, Wm and WR, are also remain as a constant. Figure 13 shows that sliding speeds of each cycles are also slightly varied with preloads. This reveals that preload decay can not affect kinetic motion of balls.

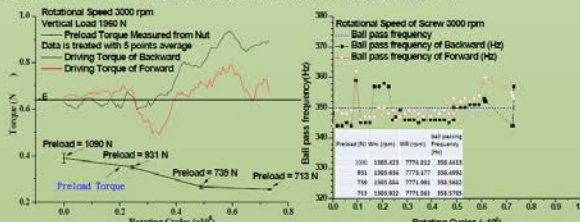


Figure 11 Transmission torques of ball-screw

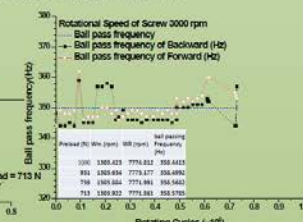


Figure 12 Kinetic motion of balls

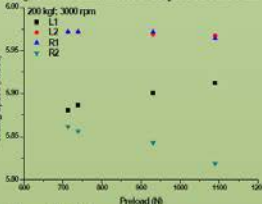


Figure 13 Sliding speed

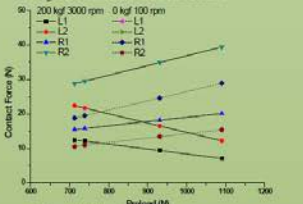


Figure 14 Contact forces

Contact forces of left side is decreased with the rising preload, but the right side has opposite trend when an external axial load is applied, as shown in Fig.14. If no axial load, contact force is rising with preload. Therefore, larger preload will let contact forces have larger difference among each cycle when an axial load is applied. Torques of screw and nut can be obtained by theoretical calculation and shown in Figs.15 and 16. The tendency of screw torques is similar to contact forces. Nut's torque is only applied preload and it's tendency is also similar to contact forces with only preload. The value of contact forces dominates these two torque. Driving torque is obtained by the torque of screw and preload torque is came from the nut's torque as shown in Fig.17. It's phenomena is similar to experiments as shown in Fig.11. Theoretical results does not show unstable when preload is decayed less than a value. Sliding speeds and contact forces are also not shown the phenomena. The supposed reason is that the dynamic stiffness of structure, which will reduced with the decay of preload, is not considered in the analysis, and the decay of structure will cause the rising and unstable of driving torque. The study also reveals that proper value of preload will let transmission stable and reduce the difference of contact forces among each ball cycle.

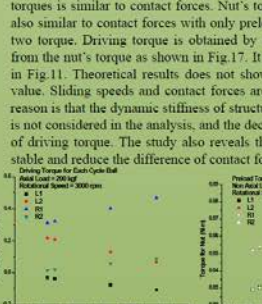


Figure 15 Torque of screw V.S preload

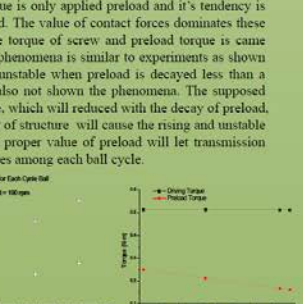


Figure 16 Torque of nut V.S preload

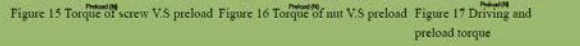


Figure 17 Driving and preload torque