微機電元件之電彈性質研究現況介紹

Review on the Studies of Electro-mechanics for MEMS Devices

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摘要

靜電式驅動的微機電元件通常包含機電、光電、熱電、電磁等許多能量域的耦合，由於元件工作時是非線性的，在分析上格外複雜。本文針對靜電式驅動的微機電元件其準靜態吸附電壓物理模型、動態特性分析、空氣阻尼效應、可靠度、數值模擬方法與應用做逐一介紹。

一.前言

微機電系統(Micro-Electro-Mechanical System;簡稱 MEMS)意指元件尺寸或作動範圍在微米等級的微型機電整合系統。微機電系統元件的製造方式與傳統機械加工製造不同，是利用與積體電路相容的半導體製程，包含面型矽微加工技術(Surface micromachining)與體型矽微加工技術(Bulk micromachining)，由於製程技術日趨成熟，目前已經可以做出許多複雜的微結構與功能元件，因而更進一步朝向最佳化元件性能方向發展。而靜電式驅動的微機電元件有反應速度快、低損耗功率與積體電路(integrated circuit)標準製程相容等優點，因此現有的微機電元件中有許多是靜電式驅動的微結構，如電容式壓力感測器(capacitive pressure sensors)[1]、梳狀致動器(comb drivers)[2]、微幫浦結構(micro pumps)[3]、印表機噴墨頭(inkjet printer head)[4]、射頻開關(RF switches)[5]、真空式共振器(vacuumed resonators)[6]等等。

對於靜電式驅動元件而言，結構變形會導致兩電極之間距或重疊面積改變，使得靜電力亦隨之改變，而靜電力之改變又會影響結構之變形，因此成為一非線性的機電耦合(electrical-mechanical coupling)系統，在分析上必須考量非理想邊界(non-ideal boundary)、非均質結構、空氣阻尼效應(air damping)、結構預變形、三維雜散電場(fringing field)等，是一個相當複雜的問題，如圖1所示。因此承受靜電力作用下微結構的電彈性質(eletromechanics)一直是許多研究的探討主題，其相關研究包含：元件作動時的不穩定性(instability)[7-10]，驅動時與元件變形的相互關係[11-14]，電極形狀與位置對元件特性的影響[15-17]，動態響應與最佳

化[18, 19]，利用套裝模擬軟體(如ANSYS, ABAQUS, COULOMB, MEMCAD system)分析元件的動態行為[20-23]，與元件的損壞機制、材料選擇與可靠度(reliability)分析等[7, 24-30]。

若不能深入瞭解元件作動時的不穩定性、非線性行為、破壞機制與可靠度等因素對元件的影響，便無法進一步改良元件性能而達到最佳化的目的。因此，本文將在下面章節針對微機電元件其準靜態(quasi-static)吸附電壓(pull-in voltage)物理模型、動態特性分析、空氣阻尼效應、可靠度、數值模擬方法與應用等議題作探討與分析。

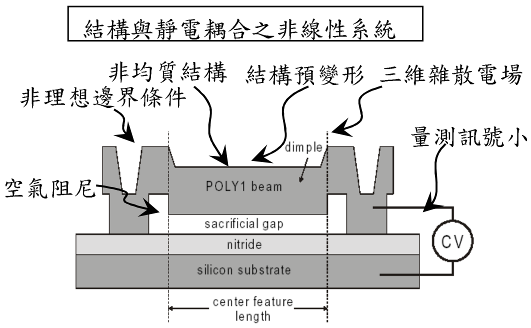


圖1 非線性機電耦合系統

二.微機電元件電彈性質相關研究發展

2.1 元件準靜態吸附電壓物理模型

如圖 1 所示，在樑與基板間施加一電壓，微結構樑會因受靜電力作用而發生變形，樑的變形改變的表面電荷的分佈狀況，使得電場重新分佈再作用於樑上，如此進行反覆的過程直到結構達到穩定狀態。當施加電壓較小時，樑處在平衡的穩定狀態，但隨著加大施加電壓，樑會產生大變形，最後與基底接觸，使樑失去穩定狀態的臨界電壓(threshold voltage)稱為吸附電壓(pull-in voltage)，因此分析微結構電彈性質的關鍵在於研究元件的吸附特性。

1994 至 1997 年間 Senturia 研究團隊發表了一系列對於微結構電彈性質的研究成果：1994 年，Senturia [31]將一受靜電力驅動的微橋狀樑模擬為一等效彈簧與平行電容板之離散模型(lumped model)(圖 2)，以得到吸附電壓與幾何尺寸及材料參數的基本函數型式(functional form)。因離散模型之誤差頗大，故於 1997 年提出 M-Test [32, 33]技術，利用半導體製程技術以單晶矽、複晶矽作為微結構之材料，製作微懸臂樑、微橋狀樑以及微扇形板三種不同微測試結構(圖 3)，並製作大量不同長度之微型樑，量測其吸附電壓，藉由大量之量測數據與數值模擬，歸納出修正因子(correcting factors)，據以修正由離散模型所得之函數型式。在 2002 年，S. Pamidighantam [34]等人將系統模擬為一等效彈簧與平行電板之離散系統，如圖 4 所示，其中等效彈簧勁度與平行電板的等效面積乃是以商用模擬軟體 CoventorWare 分析求得，因而進一步得到微橋狀樑的吸附電壓關係式，但誤

差高達 18 %。2003 年 C. O'Mahony [35]等人亦以有限元素模擬軟體 CoventorWare 分析微橋狀樑受靜電力驅動下行為，在考慮雜散電場、平板效應以及不同的邊界(圖 5)條件下，推導出微橋狀樑吸附電壓的數值解。2005 年 M. Lishchynska [36]等人在考慮殘餘應力、非理想邊界條件下，利用模擬軟體 CoventorWare 推導出懸臂樑吸附電壓的數值解，其誤差在 4 %以內。2006 至 2007 年 Y. C. Hu [37-39]提出在考慮初始應力(initial stress)、雜散電場、與彈性邊界的條件下，懸臂樑與橋狀樑吸附電壓的近似解析模型，較上述以數值方法分析微結構電彈性質的研究具備更明顯的物理意義。

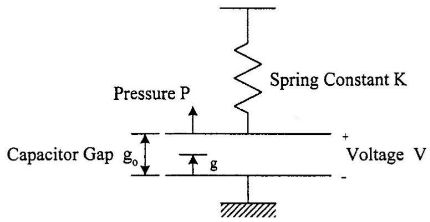


圖 2 等效彈簧與平行電板之離散模型[31]

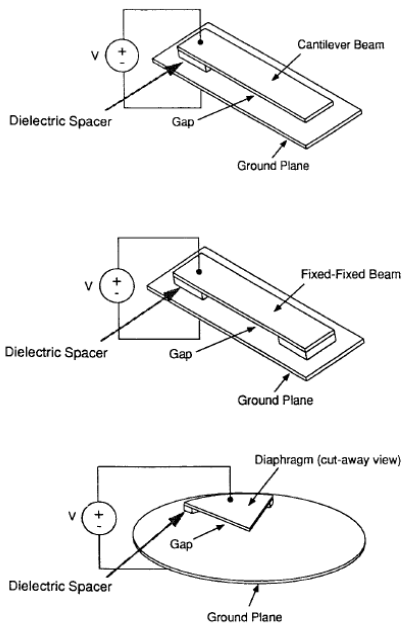


圖 3 微懸臂樑、微橋狀樑以及微扇形板之微測試結構[7]

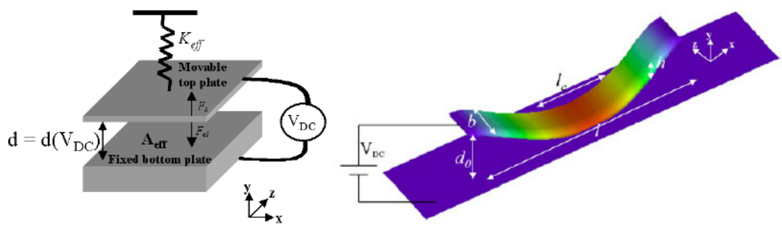


圖 4 S. Pamidighantam 提出的等效彈簧與平行電板離散模型[34]

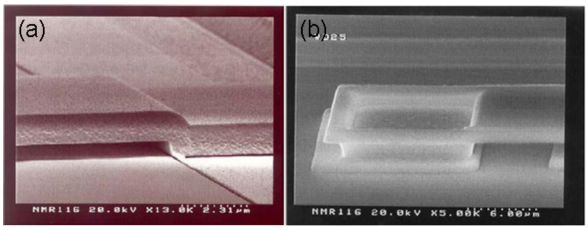
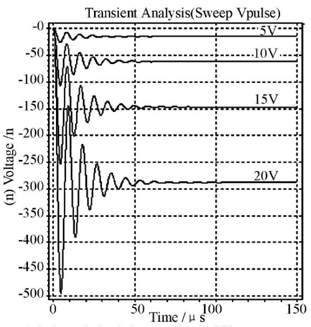


圖 5　(a)步階型邊界(b)凹狀邊界[35]

2.2.動態行為

樑在運動過程中分別受到靜電吸引力、彈性回復力以及阻尼力作用，此耦合作用下的運動方程式通常是由靜電力方程式、尤拉樑(Euler beam)方程式及壓膜阻尼方程式聯立而得的偏微分方程式，此偏微分方程式闡述了元件在三維空間下的動態行為，若利用數值方法對此三維耦合場進行分析，求解難度很大！因此通常採用引入狀態變量轉換、基函數展開等數學操作將無限維度的偏微分問題轉化為有限維度常微分方程組，此即為所謂的降階模型法(reduced order method)[40]，但降階模型下分析對考慮空氣阻尼條件的元件動態行為十分困難，且模型中的相關參數仍舊依賴由數值方法取得，因此並未提升分析效率。為解決此問題，J. Clark[41]採用節點法將複雜的系統劃分為數個基本結構單元，利用相似系統間的類比規則對基本結構建立等效的電路模型[42, 43]，對微機電元件的動態行為提供了有效的分析方法。F. Wen[44] 運用基於偏置點附近線性化處理的模態分析法進行樑的交流小信號頻域分析。J. Chang[45]透過受力分析與能量法將受靜電驅動的懸臂樑等效為一個單自由度模型，進而建立其解析形式，並利用回饋機制實現耦合作用，對懸臂樑的動態行為進行時域與頻域分析，時域分析上，由瞬態特性曲線圖(圖6)可看出驅動電壓越大樑的過沖現象越明顯，在頻域分析上，由震幅與頻率的特性曲線圖(圖7)可得知隨著電壓升高，懸臂樑的固有頻率逐漸減小。



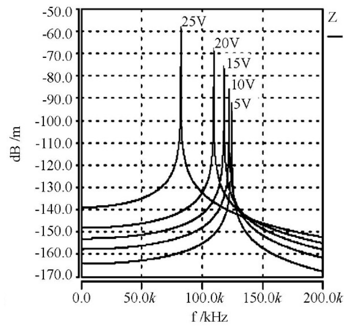


圖6 不同電壓下的瞬態響應[45]　　圖7 震幅與頻率特性曲線圖[45]

2.3.空氣阻尼

沿垂直方向做相對運動的微結構廣泛的被應用於微機電元件中如微加速度計[46]與微扭矩計[47]等，而結構在運動過程會受到元件與基板間的空氣阻尼影響，當元件處在工作震幅較大或是共振狀態時，空氣阻尼力將明顯增大，因此，建立元件在作動行為下的空氣阻尼模型就十分重要，其相關研究有：1999 年，B. Li[48]等人分析在樑在共振狀態時的阻尼效應影響。2001 年，Y. J. Yang[49]分

析微機電元件的空氣阻尼效應與工作頻率的關係。2005 年，W. Zhang 與 G. Meng [50]考慮非線性的空氣阻尼，提出簡化的靜電驅動式懸臂樑模型，研究諧振響應參數和非線性動力學的關係。同年 X. J. Wang[51]考慮稀薄氣體效應，建立微平面結構的空氣阻尼模型，利用有限差分法求解而得到諧振擠壓運動週期內擠壓膜的性能變化，研究顯示，必須將氣體稀薄效應計入理論分析模型中，否則將高估空氣阻尼的影響，微結構的平面尺寸增大將加大阻尼力，且阻尼力增大的速度大於微結構面積的增大速度，而諧振頻率的提高也將顯著增強空氣阻尼效應。2006 年 X. J. Wang[52]更進一步建立在考慮滑移邊界與稀薄氣體效應條件下，微諧振器的非線性動力學模型。2007 年，Y. M. Zhu[53]透過將平版沿垂直方向的位移運動方程式展開為傅立葉級數，得到微平面結構所受的空氣阻尼力與阻尼係數的解析公式，研究顯示，空氣阻尼係數近似與兩平板間氣隙厚度的三次方成反比，並以為加速度開關為例，求得元件工作過程中的變阻尼關係式，分析空氣阻尼係數對於開關性能的影響。

2.4.數值模擬方法(Numerical/CAD methods)

微機電系統的開發，從設計理念到產品的實現，必須經過設計、製造、封裝、及系統整合等步驟，開發過程十分複雜。微機電元件與IC電路、一般機械結構相同，可採用電腦輔助設計來提高元件的性能和可靠性，同時降低開發週期與成本。但不同的是MEMS CAD還在發展當中。在電子產品設計方面，電子設計自動化EDA(electronic Design Automation)的技術提供一平台，讓電路設計者可藉由電腦輔助設計及分析，並配合代工廠所提供的元件模型庫(model libraries)及相關設計工具庫（design kit），以最經濟及最有效率的方式來完成元件的設計開發及製造測試，相關的套裝軟體如SPICE、SABER、Simulink等。在機械產品設計方面，MDA(Mechanical Design Automation)亦有許多大型的通用軟體來進行輔助設計、製造與分析，如I DEAS、UGII、ProPEngineer 等等。而微機電電腦輔助設計需要一種連結EDA與MDA這兩種領域的工具，以進行多種物理耦合場效應的計算，增加MEMS CAD在發展上的困難度。

微機電元件的數值模擬主要是採用有限元素法、邊界元、或有限差分技術，有限素元、邊界元等數值方法可用於各種結構元件的行為模擬且精度高，但是缺點為計算量大，分析效率低，因此有相關研究致力於如何減低龐大的計算量，如E. S. Hang[54]研究如何在元件作動下定義網格使其產生最有效的降階模型。J. T. Stewart[55]發展一套可用於微結構微小震動時的模擬方法。N. R. Swart[56]發展一種電腦輔助工具，名為AutoMM，可自動化產生微結構的動態模型。

2.5可靠度分析(Reliability analysis)

可靠度分析在微機電產品開發中是相當重要的一個環節。微機電元件的失效是指元件不能再達到其預定的功能，而微機電元件的主要失效模式與失效機制如表1所示。

表1 微機電元件的失效模式與失效機制[57]

Failure mode	Failure mechanism	Example	Reference
Stiction and adhesion	Surface contact	Comb finger actuator,	[58, 59]

		beam	
Electrostatic interference	Electrical contact	Electrostatic micromotor	[24, 60]
Dielectric changing and breakdown	Nuclear radiation	Accelerometer, RF MEMS switch	[61-63]
Wear and friction	Surface contact and rubbing	Micro-motor, microengine	[64, 65]
Fracture	Intrinsic and applied stress	comb finger actuator	[66]

K. Komvopoulos[67]於研究中發現微機電元件的主要失效模式是摩擦(friction)、磨損(wear)及黏附(stiction)，要瞭解並且避免此失效模式的產生才能有效的提高元件的可靠度，因此接下來將針對此三種失效模式作相關研究的介紹：

2.5.1摩擦(friction)

摩擦是使元件無法正常運轉的主要原因之一，在1992年，S. F. Bart[68]提出包含動摩擦分析的動態模型，研究中提到表面粗糙度對元件摩擦力的大小影響重大。Y. C. Tai[69]提出摩擦力矩的模型並推算出元件的靜摩擦係數。

2.5.2磨損(wear)

由於轉子(rotor)與輪轂(Hub)間隙較小因此十分容易產生接觸磨損(圖8[24])，K. J. Gabriel[64]於實驗研究中發現在高轉速下，輪轂會劇烈的腐蝕與變形。磨損縮短了元件的壽命並限制了性能的發揮，對此我們可以採用支撐結構[70]來避免磨損。

2.5.3黏附(stiction)

接觸面間的黏附現象使元件不能進行重複性的操作甚至會使其無法運轉，W. M. Van[59]在其研究中提到接觸元件的表面粗糙度是影響黏附現象的一個重要因素。S. L. Ren[71]等人使用單分子自我組裝膜(self-assembled monolayers, SAMs)降低元件表面的黏附作用。

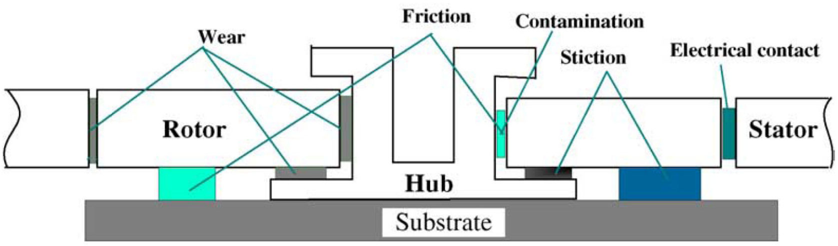


圖8 元件運轉過程中的摩擦學問題[24]

三、應用

靜電式驅動的微元件已廣泛的被使用於各種感測與制動元件上，並可應用於生物感測器，或是用於萃取薄膜材料機械性質方面。以微結構之電路行為反算薄膜機械性質技術，過去十年來最重要之成果均出自MIT之Senturia[7, 32]研究室，其技術關鍵是以大量之數值模擬歸納出靜電吸附時的臨界電壓與微結構機械性質之經驗公式，並以此經驗公式搭配測試微結構實測及反算薄膜機械性質。此技術之優點是臨界電壓相當容易量測，缺點是經驗公式需搭配特定之測試微結構，測試微結構改變經驗公式就需跟著改變。此外，經驗公式很難處理非理想狀

況，如預變形及非均勻性斷面等情況。而Y. C. Hu[72-74]在研究微機電結構之機電耦合行為方面，與Senturia研究室提出之研究方法不同，是提出具一非理想邊界、雜散電場、及殘餘應力之微結構吸附電壓近似解析模型來模擬實際的非線性機電耦合系統，並研發出一套適用於晶圓級檢測的全電信號的薄膜材料性質檢測方法，以檢測微結構之楊氏模數(Young’s modulus)與殘留應力(residual stress)，其所建立之全電性信號薄膜材料性質檢測技術，可利用現有之半導體量測設備，於晶圓製程線上進行即時的量測與監控，適合大量應用在半導體與微機電製程中。

四.結語

對靜電式驅動的微機電元件而言，由於包含許多能量域的耦合，使其電彈性質在分析上將變的更為複雜。本文針對靜電式驅動的微機電元件的各項研究議題作相關的文獻探討與介紹，包含：準靜態吸附電壓物理模型、動態特性分析、空氣阻尼效應、可靠度、數值模擬方法與應用，望能藉由瞭解元件作動時的不穩定性、非線性行為、破壞機制與可靠度等因素，進一步改良元件性能而達到最佳化的目的。

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