

DESIGN, DEVELOPMENT AND PERFORMANCE EVALUATION OF A THREE-AXIS MINIATURE MACHINING CENTER

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MASTER OF SCIENCE

By

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July, 2011

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ABSTRACT

DESIGN, DEVELOPMENT AND PERFORMANCE EVALUATION OF A THREE-AXIS MINIATURE MACHINING CENTER

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There is a growing demand for highly accurate micro-scale parts from various industries including medical, biotechnology, energy, consumer, and aerospace. Mechanical micro-machining which is capable of fabricating three dimensional micro-scale features on a wide range of engineering materials such as metals, polymers, ceramics and composites is a viable micro-manufacturing technique to effectively address this demand. Miniature machine tools (MMTs) are developed and used in mechanical micro-machining since their small size improves the accuracy and efficiency of the process. The output quality of the final product manufactured on an MMT depends on choosing the optimum machining parameters. However, the full potential of micro-machining can not be achieved due to challenges that reduce the repeatability of the process. One of the most significant challenges in micro-machining is the deterioration of output quality due to the MMT vibrations. This thesis demonstrates the development of a three-axis miniature machine tool, the performance evaluation of its micro-scale milling process, and the characterization of its dynamic behaviour using finite element simulations and experiments.

The MMT is designed and constructed using precision three-axis positioning slides (2 micrometers positioning accuracy, 10 nanometers positioning resolution, 60 mm x 60 mm x 60 mm workspace), miniature ultra-high speed spindles (ceramic bearing electrical spindle with maximum 50,000 rpm rotational speed and air bearing air turbine spindle with maximum 160,000 rpm rotational speed), a miniature force dynamometer, and a microscope. Three dimensional finite element simulations are performed on the developed MMT to obtain the static and dynamic characteristics of the spindle side. A maximum static deflection of 0.256 μm is obtained on the designed base when 20 N forces in three directions are

applied to the center of the spindle. Dynamic finite element analysis predicts the first three natural frequencies as 700 Hz, 828 Hz and 1896 Hz; hence corresponding spindle speeds should be avoided for successful application of micro-machining.

To demonstrate the capability of MMT for manufacturing three dimensional (3D) features, micro-milling is proposed as a novel method for fabricating Poly(methyl methacrylate) (PMMA) and poly(lactic-co-glycolic acid) (PLGA) polymer micro-needles. The micro-machinability of PMMA and PLGA polymers is investigated experimentally by machining a group of 3 mm length and 100 μm depth slots using 50,000 and 100,000 rpm spindle speeds with different feedrates (5, 10, 15, and 20 $\mu\text{m}/\text{flute}$). The micro-machinability study concludes that PLGA has better machinability than PMMA. It is also observed that the machining parameters of 50,000 rpm spindle speed and 20 $\mu\text{m}/\text{flute}$ feedrate give better output quality. Using these machining parameters, micro needles with different geometries are successfully manufactured from PMMA and PLGA polymers. During this study, it is observed that polymer pillars bend due to machining forces and vibrations, which causes dimensional errors.

To address the deterioration of the output quality due to vibrations stemming from machining forces and high-speed-rotations, MMT vibrations particularly focusing on the spindle side dynamics are investigated experimentally using runout (spindle axis offset) measurements and experimental modal analysis techniques. The results are compared with those from three-dimensional finite element simulations. The investigation of MMT vibrations indicates that the developed MMT is convenient for accurate applications of micro-machining using air-turbine air bearing spindle. However, the selection of the operation frequencies for electrical spindle is challenging at certain speeds with this design because most of the critical natural frequencies of the developed MMT appear in the operating frequency range of electrical spindle.

Runout measurements using two laser doppler vibrometer (LDV) systems and experimental modal analysis which utilizes an impact hammer and accelerometer are conducted to obtain spindle side dynamics. Runout measurements performed on the miniature ultra-high speed ceramic bearing electrical spindle show that both magnitude and shape of the runout errors vary considerably with spindle speed. A peak of 1.62 μm synchronous runout is observed at 15,000 rpm. Asynchronous runout errors become significant between spindle speeds of 40,000 and

50,000 rpm and reach to a maximum of $0.21 \mu\text{m}$ at 45,000 rpm. On the other hand, experimental modal analysis is conducted to obtain both the steady-state and speed dependent frequency response functions (FRFs) of the mechanical structures. Steady state FRFs indicate that 750 Hz and 850 Hz are two important natural frequencies for successful application of micro-machining. Compared to the three dimensional finite element simulations, there is 7 % difference for the first mode and 3 % difference for the second mode. Both steady-state experimental modal analysis and finite element simulations could not consider the speed-dependent dynamics. Therefore, experimental modal analysis at different spindle speeds is also performed and it is concluded that natural frequencies of the mechanical structures change significantly depending on spindle speed. Speed-dependent FRFs show that the maximum response of about $0.35 \mu\text{m/N}$ is obtained while the spindle is rotating at 16,000 rpm but the peak occurs at 24,000 rpm (400 Hz). In addition, the vibration amplitude grows between the spindle speed of 40,000 rpm and 50,000 rpm.

Experiments and finite element simulations provide a machine operation frequency selection guide. It is suggested to avoid two different spindle speed ranges (15,000- 25,000 rpm and 40,000-50,000 rpm) to prevent vibration related inaccuracies. In addition, structural modifications can be achieved to further optimize the design based on the experimental data obtained in this work. The obtained experimental data can be used to derive mathematical model of the MMT and to perform stability studies to increase the productivity of the micro-machining processes.

Overall, the novel micro-machining technique tested on the developed MMT highlights the quality and ranges that can be achieved in micro-manufacturing.

Keywords: mechanical micro-machining, experimental modal analysis, micro-machinability, miniature machine tools, finite element method, structural dynamics.

ÖZET

3-EKSENLİ MİNYATÜR İŞLEME MERKEZİNİN TASARIMI, GELİŞTİRİLMESİ VE PERFORMANSININ DEĞERLENDİRİLMESİ

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Medikal, biyoteknoloji, enerji, tüketim ve uzay gibi endüstrilerden yüksek doğrulukta minyatür parçalara olan talep artmaktadır. Metal, polimer, seramik ve kompozit gibi malzemelerin üzerine üç boyutlu geometrileri işleyebilme özelliğine sahip mekanik mikro-işleme yöntemi mikro-işleme için oldukça uygun bir yöntemdir. Minyatür takım tezgahları prosesin doğruluğunu ve verimliliğini arttırdıkları için geliştirilmekte ve mekanik mikro-işlemede kullanılmaktadırlar. Minyatür takım tezgahlarında üretilen ürünün kalitesi en iyi kesme şartlarının seçilmesine bağlıdır. Fakat, mikro-işlemenin sahip olduğu potansiyelin tamamı prosesin tekrarlanabilirliğini azaltan bazı problemlerden dolayı kullanılamamaktadır. Bu problemlerin en önemlilerinden bir tanesi elde edilen ürünün kalitesinin takım tezgahının titreşimleri yüzünden düşmesidir. Bu master tezi 3-eksenli bir minyatür işleme merkezinin geliştirilmesini, geliştirilen işleme merkezinin mikro-frezeleme performansının değerlendirilmesini ve geliştirilen takım tezgahının dinamik davranışının deneyler ve sonlu elemanlar yöntemiyle karakterize edilmesini amaçlamaktadır.

Tez kapsamında takım tezgahı tasarlanır ve 3-eksenli pozisyonlama kızakları, minyatür yüksek hızlı motorlar, minyatür kuvvet dinamometresi ve mikroskop kullanılarak yapılır. Tasarlananan minyatür işleme merkezinde motorun bulunduğu kısmın statik ve dinamik karakteristiklerini elde etmek için sonlu elemanlar yöntemi ile üç boyutlu simülasyonlar gerçekleştirilir. Motorun merkezine her üç yönde 20N kuvvet uygulandığında, tasarlanmış olan mekanik parçaların üzerinde maksimum $0,256 \mu\text{m}$ 'lik bir statik deplasman elde edilir. Dinamik sonlu elemanlar analizi mekanik parçaların ilk üç doğal frekansını 700 Hz, 828 Hz ve 1.896 Hz olarak tahmin eder; dolayısıyla bu frekanslara karşılık gelen motor hızları

başarılı bir mikro-işleme için kaçınılmalıdır.

Bu master tezinde geliştirilen mikro-işleme tezgahının üç boyutlu mikro geometrileri işleyebilme yeteneğini göstermek amacıyla; mikro-frezeleme, Poly(methyl methacrylate) (PMMA) ve poly(lactic-co-glycolic acid) (PLGA) adlı polimer mikro-iğnelerin yapımı için orjinal bir yöntem olarak önerilir. PMMA ve PLGA'in mikro-işlenebilirliği, 3 mm boyunda ve 100 μm derinliğindeki kanalların 50.000 devir/dk ve 100.000 devir/dk dönme hızlarında ve farklı ilerleme değerlerinde (5, 10, 15, and 20 μm /kesmeucu) kesilmesiyle incelenir. Mikro-işlenebilirliğin incelenmesi sonucunda PLGA'in işlenebilirliğinin daha iyi olduğu gözlemlenir. Ayrıca, 50.000 devir/dk ve 20 μm /kesmeucu kesme parametrelerinin en iyi ürün kalitesini verdiği gözlemlenir. Bu parametreler kullanılarak farklı geometrilerdeki iğneler PMMA ve PLGA polimerlerinden başarılı bir şekilde üretilir. Bu çalışma esnasında, polimer iğnelerin kesme kuvvetleri ve titreşimden dolayı eğildikleri ve bunun da boyutsal hatalara sebep olduğu gözlemlenir.

Ürün kalitesinin kesme kuvvetlerinden ve yüksek hızla dönüşten kaynaklanan titreşimden dolayı azalmasını engellemek amacıyla, geliştirilmiş olan makinenin titreşimleri özellikle motorun bulunduğu kısma odaklanarak motorun eksenden kaçıklığının ölçülmesi ve modal analiz ile deneysel olarak incelenir. Elde edilen sonuçlar sonlu elemanlar yöntemiyle yapılan üç boyutlu simülasyonların sonuçlarıyla karşılaştırılır. Bu inceleme göstermektedir ki, geliştirilmiş olan minyatür işleme merkezi, havalı motorla mikro-işleme için başarılı bir şekilde kullanılabilir. Öte yandan, bu tasarım ile elektrikli motor kullanıldığı zaman belirli hızlarda çalışmak oldukça risklidir. Çünkü tasarımın doğal frekanslarının çoğu elektrikli motorun çalışma aralığı içindedir.

Motorun ekseninden kaçık dönmesinin ölçülmesi lazer dopler titreşimölçerler kullanılarak, deneysel modal analiz de darbe çekici ve ivmeölçer kullanılarak gerçekleştirilerek motorun bulunduğu kısmın dinamiklerinin elde edilmesi amaçlanır. Yüksek hızda seramik rulmanlı elektrikli motorun üzerinde yapılan eksenden kaçık dönme ölçümleri hem bu kaçıklığın şeklinin hem de büyüklüğünün motorun hızıyla değiştiğini gösterir. Motorun hızıyla senkronize olan eksen kaçıklığının 15.000 devir/dk dönme hızında maksimum değer olan 1,65 μm 'ye ulaştığı görülür. Motorun hızıyla senkronize olmayan eksen kaçıklığının 40.000 devir/dk ve 50.000 devir/dk dönme hızları arasında önemli olduğu ve 45.000 devir/dk'da maksimum değer olan 0.21 μm 'ye ulaştığı görülür. Öte yandan,

mekanik parçaların durgun halde ve hıza bağlı frekans tepki fonksiyonlarını bulmak amacıyla deneysel modal analiz gerçekleştirilir. Durgun haldeki frekans tepki fonksiyonları 700 Hz ve 850 Hz'i geliştirilen MMT'de iki önemli doğal frekans olarak işaret eder. Bu sonuçlar üç boyutlu sonlu elemanlar methodu ile yapılan simülasyonlar ile karşılaştırıldığında; ilk mod için % 7, ikinci mod için % 3 fark olduğu görülür. Hem sonlu elemanlar yöntemi hem de durgun haldeki frekans tepki fonksiyonları hıza bağlı dinamikleri göz önüne alamaz. Bu nedenle deneysel modal analiz farklı dönme hızlarında da gerçekleştirilir ve mekanik yapıların dinamiklerinin dönme hızıyla değiştiği gözlemlenir. Dönme hızına bağlı olan frekans tepki fonksiyonları maksimum $0.35 \mu\text{m}/\text{N}$ bir tepkinin, motor 16.000 devir/dk dönme hızında dönerken 24.000 devir/dk dönme hızına karşılık gelen frekansta olduğunu işaret eder. Bunun yanı sıra 40.000 ve 50.000 devir/dk dönme hızlarında titreşimin arttığı görülür.

Deneyler ve sonlu elemanlar yöntemiyle gerçekleştirilen simülasyonlar geliştirilen makine için bir çalışma frekansı seçme rehberi sağlar. Bu rehber gere göre titreşimle ilgili problemleri engellemek için iki farklı dönme hızı aralığı (15.000-25.000 devir/dk ve 40.000-50.000 devir/dk) sakınılmalıdır. Buna ek olarak, bu tez kapsamında elde edilen deneysel veriler baz alınarak yapısal modifikasyonlar yapılabilir ve tasarım daha da iyileştirilebilir. Elde edilen deneysel veriler makinenin matematiksel modelini elde etmek için ve kararlılık limitlerini elde edip verimliliğini arttırmak için de kullanılabilirler.

En genelde, geliştirilmiş olan minyatür işleme merkezi üzerinde test edilen mekanik mikro-işleme yöntemi, mikro-işlemede ulaşılacak kalite ve aralığı ortaya koyar.

Anahtar sözcükler: mekanik mikro-işleme, deneysel modal analiz, mikro-işlenebilirlik, minyatür işleme merkezleri, sonlu elemanlar methodu, yapı dinamiği.

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Chapter 1

Introduction

There are several benefits of miniaturization such as reduction in space, material, and energy requirements and improved efficiency. Highly accurate miniature components with micro-scale features are increasingly in demand for various industries such as medical, biotechnology, consumer, aerospace and energy for using the advantages of micro-scale parts [20, 88, 21, 9, 58].

Miniaturization is very promising for medical and biotechnology applications which require micro-systems for interacting with molecules, proteins, cells and tissues. For instance, with the recently developed micro-/nano-manufactured devices, cancer agent molecules like PSA, CA can be detected at early stages of the cancer. Miniaturizing the cancer detection devices will reduce the cost of cancer monitoring and save many lives [16]. Furthermore, to avoid tissue damage during surgeries, most implants and surgery equipments are required to be miniature [16, 17, 30]. Miniature medical equipments including probes, stents and fiberoptic cameras have been increasingly used in surgeries, and their market is expected to grow rapidly [59].

While miniaturization is a necessity in biotechnology and medical applications such as the ones described above, it is advantageous to use miniature components in other applications. With miniaturization, products with more functionality is

achieved. For example, today a cell phone not only provides mobile communication, but also has wireless internet connection, global positioning service, camera for high quality pictures, audio/video player and video games. Digital data storage systems (hard-disc drives) that include miniature mechanical components get smaller and store more data. Researchers are working on developing miniature fuel-cells which will be replaced with batteries in portable devices. Increasing usage of fuel-cells will reduce the negative effects of batteries on environment [86]. Furthermore, with miniaturization, orbiting costs of space satellites can be lowered, satellite life and maneuverability can be increased. Research projects have been recently initiated to develop satellites that weight less than a kilogram [11]. Shortly, miniaturization have been becoming increasingly popular in many applications [20].

Recent reports related to applications and market share of micro-systems have indicated that the demand for micro-devices was expected to double and reach from \$12 billion dollars to \$25 billion dollars from 2004 to 2009 (see Figure 1.1) [5]. Furthermore, it is predicted that non-invasive surgery equipments consisting micro-scale parts will increase its market from \$16 billion dollars in 2009 to \$23 billion in 2014 [59].

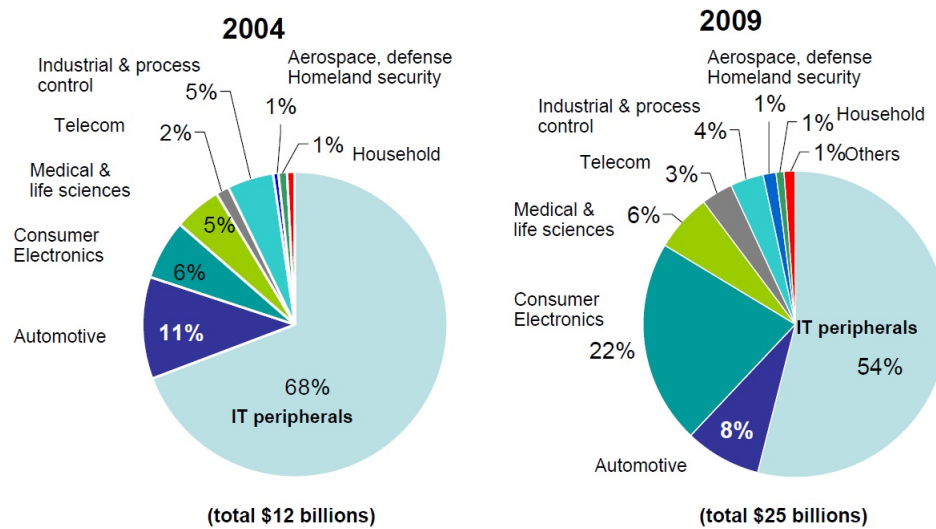


Figure 1.1: Applications and market share of micro systems [5]

To effectively address the increasing demand in micro-manufacturing, reliable and repeatable micro-component fabrication methods are required [14]. The most commonly used micro-manufacturing technique today is lithography/etching based fabrication where silicon materials are photo-etched through chemical and dry processes, usually in large batch production. Although successful in micro electro mechanical system (MEMS) applications, lithography based methods have geometric and material limitations [57]. The feasibility of other micro-fabrication processes such as focused ion beam machining (FIB), femtosecond laser micro-machining (FLM), selective laser sintering (SLS), and electro-chemical machining (ECM) to manufacture commercially viable micro-components has been investigated by many researchers. They concluded that the majority of these methods are slow, and limited to a few silicon-based materials and essentially planar geometries [57, 51, 6]. Since the possibilities of the miniaturization are expanding into three dimensional features fabricated on a variety of engineering materials such as metals and ceramics, the increasing demand in micro-systems cannot be effectively addressed due to limitations in the currently used micro-fabrication techniques.

Recently, processes with less geometric and material limitations increasingly have received more attention to overcome the drawbacks of the aforementioned methods. These processes are mechanical micro-machining, micro-forming, laser micro-machining, laser micro-sintering, micro-electro discharge machining and micro-injection molding. Each micro-manufacturing technique has specific advantages and application area. Having minimal material and geometric limitations, and higher productivity, mechanical micro-machining is a quite promising technique for micro-manufacturing [43]. This thesis mainly focuses on mechanical micro-machining.

1.1 Mechanical micro-machining

Mechanical micro-machining is one of the viable micro-manufacturing techniques for fabricating micro-scale features and components with three-dimensional complex geometries on metals, polymers, ceramics and composites [48, 30, 26, 20, 32, 33]. It is the scaled down version of the traditional metal cutting techniques such as drilling and milling where the material is removed mechanically using micro-scale cutting tools [48, 84, 85, 49]. Although it might be possible to perform mechanical micro-machining on traditional precision machine tools, it is generally performed on miniature-machine-tools (MMTs) to achieve a better control in dimensional and thermal errors, and to reduce the required space, power and cost for operation [75, 22, 63, 83, 90, 47, 8, 40]. Miniature machine tools are equipped with high precision positioning stages, ultra high speed spindles, and measurement devices such as dynamometers and microscopes to monitor the process [47, 8, 40, 39]. Figure 1.2 shows some examples of miniature machine tools.

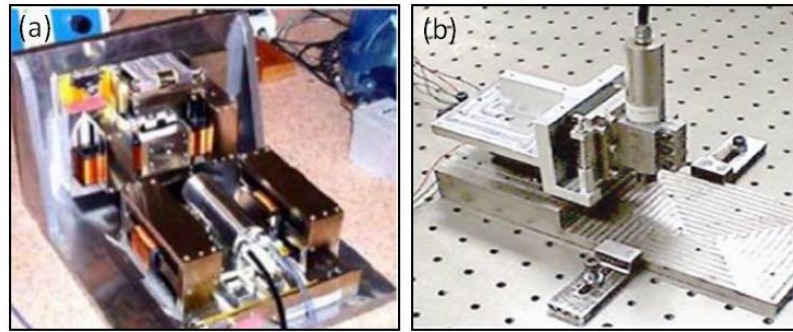


Figure 1.2: Examples of Miniature Machine Tools (a) 2nd Generation UIUC MMT [84] (b) Recently developed MMT in USA [46]

During micro-machining, micro-scale cutting tools which are produced from hard materials such as tungsten carbide or diamond, and rotated in the ultra-high speed spindles to attain effective material remove rates are used for mechanically removing the material [48, 30, 26].

1.2 Challenges of mechanical micro-machining

However, the full potential of mechanical micro-machining can not be achieved due to the challenges that reduce the repeatability of the process [30, 26, 14]. The challenges include non-ideal micro-cutting tool geometry, uncertainty arising from micro-structure of the workpiece, lack of knowledge in micro-machinability of materials, and vibrations due to periodic machining forces and rotating unbalances [30, 14, 37, 36, 46]. These issues have to be investigated and eliminated for successful application of micro-manufacturing.

There is a fundamental limitation of how sharp the cutting tools can be made in micro-scale due to the limitations in the tool manufacturing process (grinding) so, the micro-cutting tools cannot be considered as ideally sharp. The edge radius (sharpness) of the tools in micro-machining are in the order of machining parameters such as feedrate and uncut chip thickness, which makes the cutting edge "blunt" [30, 61]. Bluntness of the cutting edge makes mechanics of the process complicated. It renders the process ploughing (rather than shearing) dominated, in which a large portion of the material is deformed and pushed under the tool [26, 45].

Blunt edges introduce the phenomenon referred as the minimum chip thickness effect. This phenomenon shows that when the uncut chip thickness is below a certain chip thickness, no chip is produced [48, 72, 34, 26]. Large cutting edge radius also causes large forces, tool wear and breakage, poor surface finish, and extensive burr formation along the edges of the machined feature [45, 26, 53].

Micro-machining experiments in Advanced Microsystem Technologies Laboratory of Mechanical Engineering Department at Bilkent University indicated that different materials have different burr formation characteristics. It was also observed that with increasing wear of the cutting-tool, burring increases.

In micro machining, tool wear mechanism is also different and the tool life is reached very abruptly [78, 53]. The tool diameter significantly decreases because of the tool wear, which affects the output quality of the process. Since higher

spindle speeds (≥ 20000 rpm) are required to attain effective material removal rates, fatigue failure of the micro-cutting tools by repeated loading and unloading may also become important during micro-machining [26, 10].

Non-homogeneous micro-structure of the workpiece material also plays an important role in micro-machining. In conventional machining, with respect to the uncut chip thickness, the grains are smaller, so the effect of individual grains is averaged and the workpiece material can be assumed as isotropic. However, in micro-scale machining, the size of workpiece micro-structures is of the same order of magnitude as the process geometry. The cutting-tool goes through individual crystals in micro-machining, so the micro-structure of the workpiece cannot be assumed as homogeneous. Crystallographic anisotropy caused by non-homogeneous workpiece structure brings complications to the mechanics of the process [44, 62, 74].

Due to the aforementioned differences between micro-machining and conventional machining, the micro-cutting process experiences different machinability characteristics and the existing knowledge and experience in machinability of materials cannot be directly applied to the micro scale [62, 80, 26]. The lack of knowledge in the relationship between the micro-machining process parameters (feedrate, spindle speed, depth of cut) and the machining output quality (accuracy, surface roughness, productivity, etc.) brings another challenge in the application of micro-machining [26]. To enable effective application of micro-machining, extensive machinability studies have to be performed.

One of the most significant challenges in successful application of micro-machining is the deterioration of output quality and process efficiency due to the dynamic deflection of machine-tool parts (vibrations) during machining [7, 53, 28]. In order to avoid vibration related inaccuracies, it is necessary to investigate and eliminate the vibrations stemming from machining forces and high-speed-rotations in micro-machining.

1.3 Motivation

The knowledge of the conventional machining has been well researched and established during last several years. However, there are a few studies for mechanical micro-machining. Therefore, there is a lack of knowledge developed in this field. For achieving a more repeatable micro-machining process, more research on mechanical micro-machining is required to be conducted to investigate, understand and eliminate the aforementioned challenges. This thesis focuses on design, development and performance evaluation of a 3-axis miniature machine tool particularly concentrating on its dynamic characteristics.

Applications on miniature machine tools require to obtain optimized parameters for surface performance and dimensional accuracy [62, 80]. Since lack of experience in selection of micro-machining parameters is an important challenge in mechanical micro-machining, it is necessary to investigate the effect of machining conditions on the output quality of the process [26]. Previous work on micro-machining has proven that the dynamics of the cutting process should be investigated to acquire more accurate machining parameters [80]. Although there are previous studies focusing on the dynamics of micro-machining, these studies do not include the effect of machine structural dynamics on the machining output [48, 19].

The output quality of the final product manufactured on an MMT is deteriorated by the vibrations stemming from periodic machining forces and rotating unbalances. Recent studies in mechanical micro-machining show that vibration characteristics of a miniature machine tool have to be investigated to prevent undesired effects of vibration on the output quality of the process [46]. Precision stages where the workpiece is attached and spindle side with the cutting tool are two important structural vibration loops in a typical miniature machine tool (see Figure 1.3). Accurate prediction of the process dynamics require to consider those vibrations for achieving more successful applications of micro-machining.

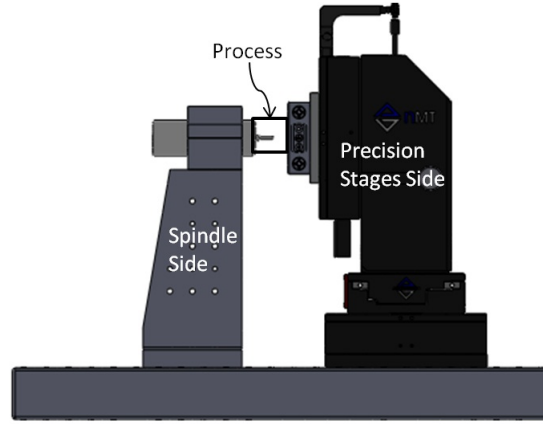


Figure 1.3: Structural loops of a miniature machine tool

During micro-machining, periodic machining forces generated as a result of material removal action cause the miniature machine tool to vibrate. Vibration amplitude determined by dynamics of the cutting-tool/machine tool alters the periodic machining forces. Due to their sizes, miniature machine tools have reduced stiffness compared to the ultra-precision machine tools. Therefore, they are more likely to experience relatively large vibrations and forces [19, 38, 53, 28].

Imbalances rotating with high speed also generate undesired vibrations. In micro-machining, tool tip run-out arising from spindle axis offset, tool tilt and the vibrations of the structural loop can be as large as feed rate and causes variations in the cutting forces [53, 62]. For achieving desired output quality and obtaining accurate dynamics of micro-machining, the runout has to be characterized [49].

1.4 Objective

The objective of this thesis is to accomplish the design, development and performance evaluation of a three-axis miniature machine tool particularly focusing on its dynamic characteristics. To fulfill this objective, a three-axis miniature machine tool is designed and constructed. To construct this machine tool, precision equipments are used and mechanical parts for the integration of spindle are designed. Subsequently, precision alignment of the developed MMT is completed to make it ready for manufacturing micro-parts.

To demonstrate the capability of the developed MMT for manufacturing three dimensional features, micro-milling is proposed as a novel method for fabricating polymer micro-needles. In order to obtain optimized parameters for high surface quality and dimensional accuracy, the effect of machining conditions on the output quality should be studied [26, 45]. Experimental investigation of micro-machinability of biocompatible polymers are conducted to obtain optimum parameters for micro-milling of polymer micro-needles.

The output quality of the final product also depends on vibration characteristics of MMT [56]. Having smaller stiffness than the stage side, the spindle side (cutting tool, spindle and base) is, in most of the cases, the main source of vibrations. Thus, dynamic characteristics of the developed MMT particularly focusing on spindle side are investigated. Since spindles have complicated designs with multiple materials and joints, deriving an analytical solution for the spindle dynamics is impractical. Therefore, spindle dynamics is obtained using finite element simulations and experiments. Experimentally obtained spindle dynamics can be combined with the cutting-tool dynamics using the Receptance Coupling Substructure Analysis (RCSA) approach so that the tool point dynamics is obtained [15]. The tool point dynamics can be used for improving the productivity of the machining processes by predicting the limits of stability [13, 15].

The experimental analysis of MMT vibrations conducted in this thesis can also be used as a methodology for other researchers who work on micro machining vibrations.

Chapter 2

Background Information and Literature

This thesis demonstrates the development of a 3-axis miniature machine tool, the performance evaluation of its micro-scale milling process, and the characterization of its dynamic behaviour. This chapter reviews the background information and previous work in these areas. First, literature survey on the development and performance evaluation of miniature machine tools is introduced. Next, research on the dynamics of conventional machine tools is summarized. Finally, previous work on dynamics of mechanical micro-machining processes is presented.

2.1 Development and performance evaluation of miniature machine tools

Miniature machine tools are developed and used in mechanical micro-machining since their small size improves the accuracy and efficiency of the process. The demands of the machine tools that would be capable of achieving micro-machining include high positional accuracy, ultra-high spindle speed and excellent dynamic performances. Considering these demands, two types of machines are adopted

to achieve successful micro-machining. The first one is traditional precision machine tool and the second one is miniature machine tool (MMT)[50]. Due to the large dimension of the precision machine tool, these machines generally require expensive and specialized design features to achieve the desired level of accuracy [71]. On the other hand, miniature machine tools have several advantages over conventional precision machines. MMTs are cost-effective and require smaller amount of materials. They occupy less space and consume less energy. Due to their small size, thermal expansion and angular misalignment errors are smaller [48]. Thus, they have been increasingly in demand for successful application of micro-manufacturing.

Numerous research efforts to develop miniature machine tools have been undertaken. In 1998, the microfactory concept was introduced in Japan [31]. Then, a three-axis meso-scale machine tool with 15 x 15 x 15 mm workspace, 0.5 μm encoder resolution, and maximum spindle speed of 200,000 rpm was developed in 2002 [73]. Next, first generation of MMT and second prototype of this miniature machine tool were developed in University of Illinois at Urbana-Champaign (UIUC) [83, 39]. The miniature machine tools developed in UIUC were 3 axis and actuated by voice-coil actuators. The updated version was equipped with 160,000 rpm air-turbine spindle, 0.1 μm encoder, and 25 x 25 x 25 mm workspace was achieved in the second prototype. In 2006, 3-axis miniature machine tool, which was driven by a miniaturized piezoelectric linear stage with 13 mm stroke and 0.25 μm encoder resolution in each direction was developed by Ni and his group [46]. Ni and his groups used an air-turbine spindle with 120,000 rpm maximum rotational speed. Each machine tool has its specific design and key components based on the available micro-technologies.

Evaluation of the machining performance of the developed MMTs are significant to demonstrate their machining capabilities for fabricating different geometries and materials [90, 47]. It is suggested to consider the effect of machining conditions and miniature machine tool vibrations on the output quality of the process during performance evaluation [46].

2.2 Dynamics of conventional machine tools

Dynamic characteristics of machine structures have been widely studied for conventional machine tools in order to enhance their machining performance [7, 80, 42]. Research on dynamics of conventional machining processes show that in most cases, cutting tool and spindle are the main source of vibrations and they should be investigated to prevent chatter instability which causes the deterioration in the output quality of the process [70, 81, 23, 67].

Accurate prediction of the tool point frequency response functions is significant to obtain stable cutting conditions. The negative real part of the tool point frequency response function can be used to obtain optimal cutting parameters that will maximize the chatter-free material [68]. Equation 2.1, where K_s and μ are material-dependent constants, z is the number of flutes and $G(\omega)$ is the tool point frequency response function over the frequency range of interest, can be used to obtain stability lobe diagram which defines regions of stable and unstable cutting zones as a function of depth of cut ($b_{critical}$) and spindle speed ($60 \times \text{frequency}$). Then, this stability lobe diagram can be used to select appropriate machining parameters to improve output quality and productivity of the machining processes.

$$b_{critical} = \frac{-1}{K_s \mu \text{Re}[G(\omega)]z} \quad (2.1)$$

Cutting tool dynamics can be approximated using multi-DOF modeling (see Figure 2.1 (a)) and distributed parameter models (see Figure 2.1 (b)) [60]. Previous work on cutting tool dynamics has proven that distributed parameter models provide more accurate results than multi-DOF system because they can accurately account for the variations in the dynamic response of the system [70, 23]. Earlier stability studies predicted the tool point frequency response functions using one of these models and ignoring the effect of machine tools structural dynamics on the output quality of the machining process [7, 60].

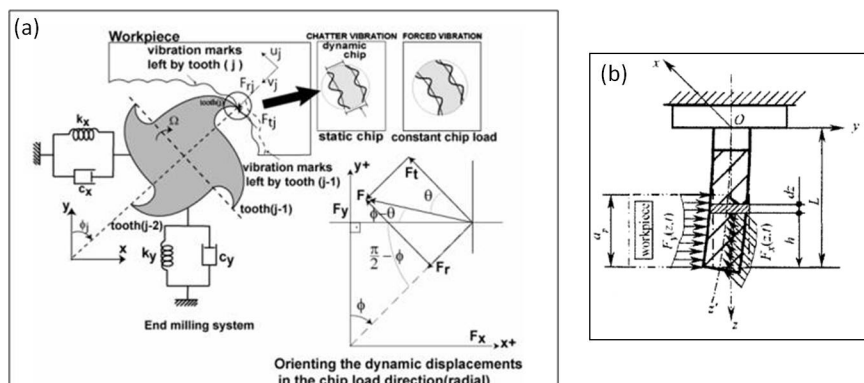


Figure 2.1: Dynamics of milling (a) Multiple-DOF cutting tool dynamic models in reference [7] (b) Distributed parameter model of the cutting tool in reference [89]

However, it is also necessary to consider vibrations of the machine tool parts for more accurate tool point frequency response functions prediction [66]. To address this problem, receptance coupling method was proposed. Receptance coupling procedure obtains the spindle dynamics using experimental modal analysis and combines it analytically with theoretical model of the cutting tool to calculate more accurate tool point frequency response functions [81, 25].

2.3 Dynamics of miniature machine tools

Dynamics of miniature machine tool components and micro-cutting tools have been becoming significant as the demand for precision miniature products increases [15, 84, 85, 19, 52, 46]. However, research in this area is scarce and required to be conducted for improvement of the micro-machining process output [52, 46].

Micro-scale cutting tool dynamics was studied by several researchers. Jun et al. [36, 37] predicted the micro-endmill dynamics by approximating the cross-section of the fluted region to be circular. They used the Timoshenko beam model, and discretized the boundary-value problem using the finite elements. They analyzed the effect of imbalance due to the setup errors and showed that the vibrations due to imbalance are significant in micro-scale. Filiz et al. [27]

improved this model by considering the actual twisted geometry of the fluted region. They also used spectral-Tchebychev (ST) technique (rather than finite element technique) for solving boundary value problem of microendmill dynamics. The use of the ST technique resulted in a simple but very accurate description of the micro-endmill dynamics. It was shown that a small number of polynomials is sufficient to obtain the natural frequencies with high accuracy.

The fundamental characteristics of micro-machining such as higher spindle speeds, flexible tooling and high accuracy requirements increase the significance of miniature machine tool dynamics. The methods used for characterizing the dynamics of a miniature machine tool are the finite element method [46] and experimental modal analysis [15]. Ni et al. [46] compared the finite element predictions of a miniature machine tool with experimental results to demonstrate that FE method can be utilized for modelling the dynamics of the machine tool. Schmitz et al. [15] combined the dynamics of the micro-cutting tools obtained analytically with experimentally acquired spindle/machine tool dynamics to obtain accurate dynamic model.

In addition to vibrations stemming from periodic machining forces, spindle runout motion errors caused by rotating unbalances become crucial in micro-machining. Runouts, which are mainly neglected in conventional machining, can be as large as feed rate in micro-machining [41]. Thus, characterization of the error motions of the miniature ultra-high speed spindles is necessary for successful application of micro-machining. Previous research show that the quasi-static measurement of runouts do not provide sufficient information about the runout characteristics of the spindle because it was frequently observed that stiffness and damping characteristics of spindles vary with spindle speed [35, 69]. Therefore, non-contact measurements of spindle error are required while spindle is rotating. Laser doppler vibrometry (LDV) is a well-established non-contact measurement technique to measure the runout motions while the spindle is rotating [79, 12]. Rantatalo et al. measured the runout motions of a spindle up to the rotational speed of 24,000 rpm [64, 65].

Chapter 3

Design and Construction of MMT

To address the increasing demand in miniature components, an ultra-precision miniature machine tool (MMT) was designed and developed at Advanced Microsystem Technologies Laboratory of Bilkent University (see Figure 3.1 (a)). This MMT includes precision three-axis nano-positioning slides with 60 mm x 60 mm x 60 mm workspace, high positioning accuracy and positioning resolution, miniature ultra high-speed (UHS) spindles with maximum 160,000 rpm rotational speed, a miniature force dynamometer, and a microscope.

This chapter presents the procedure we followed to design and build a 3-axis miniature machine tool that is capable of achieving significantly higher cutting speeds and producing three dimensional features in metals, polymers and different materials. First, the major subsystems of the designed MMT are introduced. Next, static and dynamic finite element analysis to design mechanical parts for integration of the spindle are presented. Finally, integration of the machine components using computer aided drawings and precision alignment method are discussed.

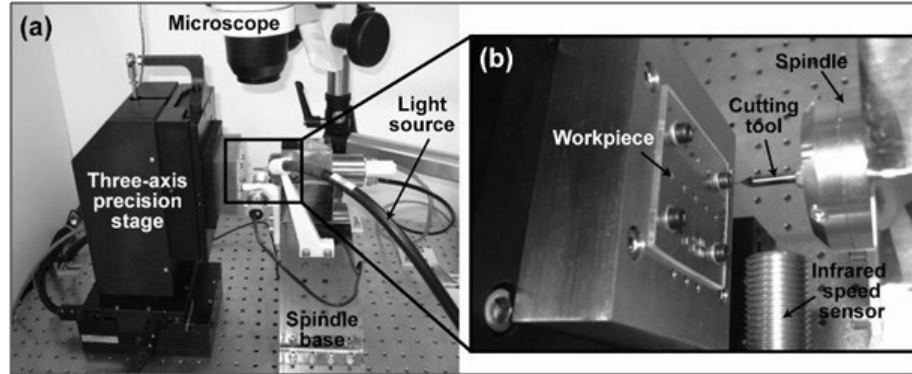


Figure 3.1: (a) The ultra-precision miniature machine tool, (b) the zoomed in machining area

3.1 Subsystems of the Miniature Machine Tool

The major subsystems such as high-precision positioning subsystem, motion control subsystem, miniature ultra-high-speed (UHS) spindle subsystem and process monitoring subsystem of the designed 3-axis miniature machining center are discussed in this section.

3.1.1 High-precision positioning subsystem

To facilitate relative motion between tool and workpiece, the positioning subsystem is necessary. Since the slides move the workpiece attached on them during machining (see Figure 3.1 (b)), precision of the positioning subsystem affects the output quality of the micro-manufacturing processes. Therefore, it is necessary to ensure that positioning accuracy and resolution of the stages provide the required performance for successful application of micro-manufacturing. Considering the desired accuracy level and special characteristics of micro-machining, available high accuracy positioning systems in the industry has been investigated. After careful investigations of the available products in the market, a three-axis stage Aerotech ANT130-XYZ plus was used. The technical specifications of the stages are provided in the Table 3.1.

Table 3.1: Specifications of the slides [1]

	X-Axis	Y-axis	Z-axis
Aerotech Type	ANT130-060-L-PLUS	ANT130-060-L-PLUS	ANT130-60-L-Z-PLUS
Travel	60mm	60mm	60mm
Accuracy	$\pm 250\text{nm}$	$\pm 250\text{nm}$	$\pm 300\text{nm}$
Resolution	1nm	1nm	2nm
Maximum Force	23N	23N	23N
Maximum Speed	350mm/s	350mm/s	200mm/s

Table 3.1 shows that the ultra-precision positioning stages of the developed miniature machining center are capable of achieving successful micro-manufacturing applications due to their advanced properties such as relatively higher positioning accuracy and positioning resolution.

3.1.2 Motion control subsystem

The ultra-high precision positioning stages of the MMT are driven by brush-less linear servomotor. The motion control subsystem includes a computer, an automation 3200 (A3200) Multi-Axis Machine Controller and the software for Computer Aided Manufacturing (CAM) and motion control.

The positioning stages have their encoders on them to measure their position and to provide feedback during well-known PID control, which is used to satisfy commanded position. The slides are programmed with G-codes for moving the workpiece attached on them (see Figure 3.1 (b)) such that the desired geometry is machined on the workpiece.

G-codes can be created manually or using a suitable CAM program. The part designed using a computed aided drawing (CAD) software is imported in the CAM program. The cutting tool and machining parameters are selected to generate the G-codes to machine the part. Finally, the G-codes are uploaded to the stage controller software. Due to capabilities of the controller and CAM programs, complex motions for manufacturing three dimensional (3D) parts with complicated geometry features can be generated.

3.1.3 Miniature ultra-high-speed (UHS) spindle subsystem

In order to machine micro-scale features, micro-scale cutting tools (milling, drilling) with diameters as small as $10\text{ }\mu\text{m}$ are used. To attain effective material removal rates while using micro-scale tooling, ultra-high-speed (≥ 20000 rpm) miniature spindles are utilized during micro-milling [82]. Furthermore, in order to effectively study the machining processes at feed values of a few micrometers per cutting tooth, a spindle with submicron runout (spindle axis offset) is desired.

In the developed MMT, two types of NSK Nakanishi brand miniature ultra-high speed spindles (miniature ultra-high speed air-bearing air-turbine spindle and miniature ultra high speed ceramic bearing electrical spindle) are utilized to attain necessary cutting speeds.

3.1.3.1 Miniature ultra-high-speed (UHS) air-bearing air-turbine spindle

The first type of spindle used in the developed MMT is the miniature ultra-high speed air-bearing air-turbine spindle with maximum 160,000 rpm rotational speed and a 3mm precision collet. The technical specifications of this spindle are provided in Table 3.2.

Table 3.2: Specifications of the air-turbine spindle [2]

Type	Maximum speed	Max.Power Output	Spindle Accuracy	Diameter
Air-turbine	160,000 rpm	14 W	$1\text{ }\mu\text{m}$	40mm

Table 3.2 shows that the miniature ultra-high-speed air-bearing air-turbine spindle provides the required performance for successful application of micro-machining due to its high precision and high rotational speed. Furthermore, the air-bearing mechanism means this spindle produces low vibration or heat [2].

The air bearing spindle does not have a speed sensor or a speed controller. Hence, a non-contact infrared (IR) sensor (Monarch Instruments IRS-W) was used for measuring the speed. In the developed MMT, infrared sensor was connected to Monarch ACT-3X tachometer which transforms the coming voltage into rotational speed to visualize spindle speed directly. The IR sensor can measure speeds between 1-999,990 rpm. Due to fluctuating air pressure and varying machining load on the spindle, the spindle speed changes during machining. A speed control mechanism is necessary to keep the speed constant. The speed control system includes the IR sensor for feedback, a mini proportional solenoid valve for varying the inlet pressure to the spindle, a data acquisition card (National Instruments PCI-6229), and a control environment such as MATLAB/SIMULINK R2008a and LABVIEW 2010 environment. The representation of the speed control can be seen in Figure 3.2.

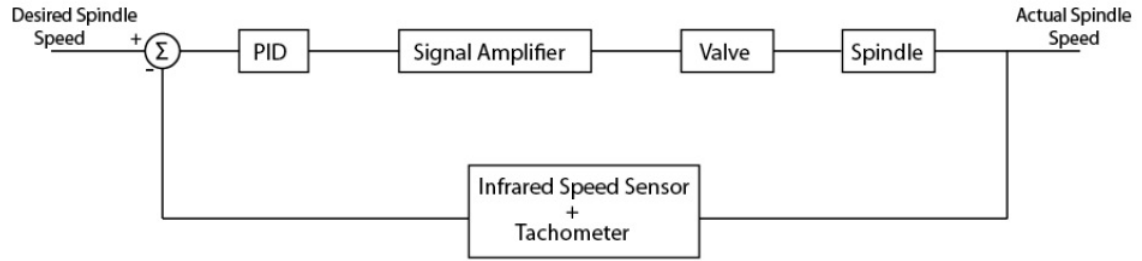


Figure 3.2: General block diagram for speed control

The first step in the speed control is to acquire the spindle speed in control environment. In order to achieve this, the connection between computer and infrared sensor was provided through the data acquisition card and the connector block of this card. Subsequently, the analog output terminals of the tachometer shown in Figure 3.3 was connected to the analog input terminals of the connector block. Finally, spindle speed in terms of voltage between 0 and 5 V was obtained using the analog voltage output option of tachometer.



Figure 3.3: Analog option of the Tachometer

Although this tachometer is capable of measuring 1 to 999,990 RPM range, it is also possible to adjust zero scale (0SCALE) and full scale (FSCALE) values of this tachometer according to the type of application. PM Remote Tachometer software and RS232 to RS232 serial interface can be used to adjust these values. The standard analog output has 32,000 steps from zero to full scale. This full scale value is the value at which the analog outputs are at a maximum, 5Vdc and this zero scale value is the value at which the analog outputs are at a minimum, 0Vdc, and the spindle speed will be linear between 0SCALE and FSCALE. Since the number of steps between 0SCALE and FSCALE is constant, increasing the difference between these values will decrease the resolution. Therefore, the measurement range of the tachometer is usually set to give a reasonable working range for the analog input.

In the MMT, in order to provide reasonable working range for air-turbine spindle, 0SCALE and FSCALE values were set to 8,000 rpm and 200,000 rpm, respectively. Using these values and corresponding voltages, the linear relationship between voltage and spindle speed was represented as shown in Figure 3.4.

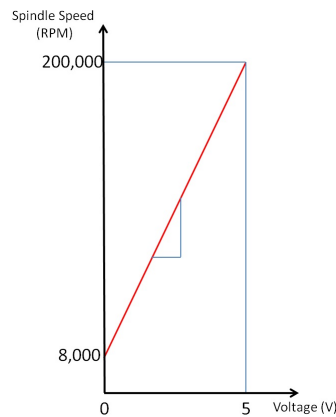


Figure 3.4: Spindle Speed-Voltage Relationship

Then, the mathematical relationship between voltage and spindle speed was derived based on Figure 3.4.

$$Slope = \frac{y_2 - y_1}{x_2 - x_1} = \frac{200,000 - 8,000}{5 - 0} = 38,400 \quad (3.1)$$

$$SpindleSpeed = Slope * Voltage + 0SCALE = 38,400 * Voltage + 8,000 \quad (3.2)$$

Equation 3.2 can be used to find corresponding spindle speed for a given voltage value. It is also possible to find resolution of the measurement with known steps from 0SCALE to FSCALE using Equation 3.3.

$$Resolution = \frac{FSCALE - 0SCALE}{NumberofSteps} = \frac{200,000 - 8,000}{32,000} = 6rpm \quad (3.3)$$

It is clear that changing 0SCALE and FSCALE of the tachometer improved the resolution from 32 rpm to 6 rpm.

To acquire actual spindle speed in MATLAB/SIMULINK environment, Equation 3.2 was represented by blocks available in SIMULINK as shown in Figure 3.5. The real time acquisition of the spindle speed was achieved by interfacing MATLAB/SIMULINK and data acquisition card using Real Time Windows Target.

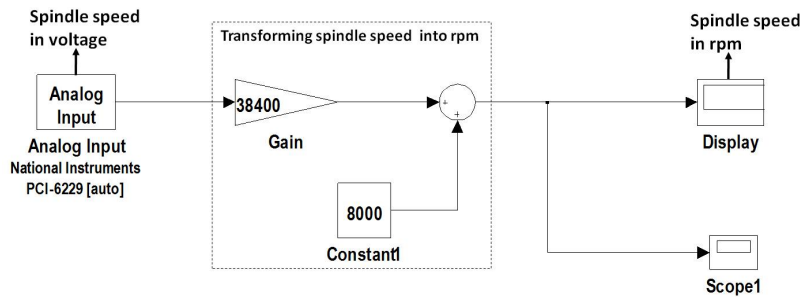


Figure 3.5: Block diagram for acquiring spindle speed

Block diagram in Figure 3.5 transforms coming voltage from the sensor into rotational speed and gives the actual spindle speed. Now, acquiring actual spindle speed is achieved for the use of speed control.

Next, calibration of the valve was completed. Proper connections between signal amplifier and external power supply, signal amplifier and mini proportional solenoid valve and, signal amplifier and DAQ connector block were made as shown Figure 3.6 (b).

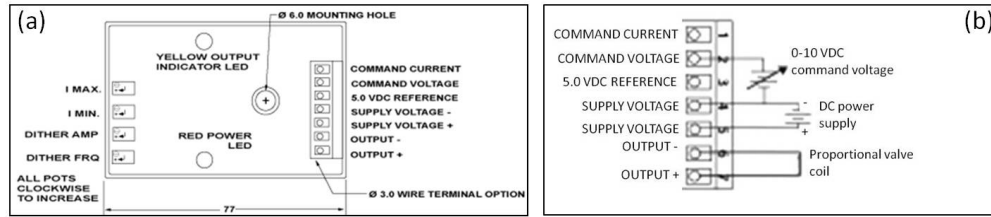


Figure 3.6: (a) Signal Amplifier (b) Signal Amplifier Connections

To switch the signal amplifier on, it is recommended to supply 9-32 VDC to the signal amplifier. An external power supply was used in MMT to supply this voltage. As a result of many trials, it was recognized that having supply voltage close to the upper limit provides better performance. Therefore, 30 V supply voltage which is the maximum voltage that available power supply can reach was supplied and red power led shown in Figure 3.6 (a) was glowed.

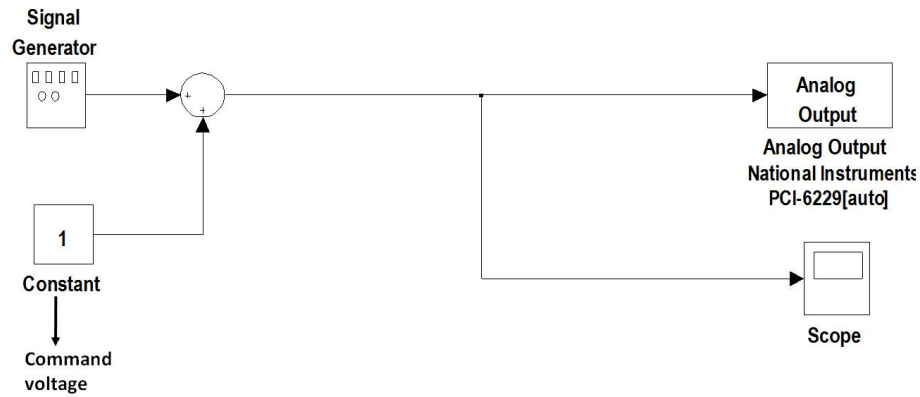


Figure 3.7: Calibration block diagram

Then, to supply command voltage to the signal amplifier and make the yellow output indicator led glowed , the block diagram created in Simulink (see Figure 3.7) was used. Since it is suggested to use 0-10 V command voltage, the calibration was achieved between these voltage values using I_{max} and I_{min} screws shown in Figure 3.6 (a) and changing the constant voltage value available in the block diagram.

On the other hand, pressure oscillation on the pressure indicator of air turbine was a significant challenge during calibration. Firstly, although the whole speed range (Analog output:0-10 V and corresponding spindle speeds 0-165,000 rpm, respectively) was covered at 0.52 MPa pressure by adjusting the I_{max} and I_{min} screws, it was not possible to obtain stable air-turbine pressure indicator for these conditions. Then, considering applications of MMT, I_{max} and I_{min} screws were adjusted to cover the speed range of 0-155,000 rpm at 0.5 Mpa. Although oscillation was decreased, it was still there. As suggested, dither frequency and dither amplitude screws (see Figure 3.6 (a)) were adjusted to prevent this oscillation. It was observed that dither amplitude has a little effect on oscillation but dither frequency affects oscillation directly. After preventing pressure oscillation by adjusting the dither frequency screw, valve calibration results listed in Table 3.3 were obtained.

Table 3.3: Calibration results

Voltage	0	1	2	3	4	5	6	7	8	9	10
Speed	4,300	7,900	18,000	37,000	71,000	114,000	138,000	150,000	153,400	154,100	155,000

The results shown in 3.3 indicates that valve was calibrated such that spindle speed of 0-155,000 rpm can be controlled by supplying controlled voltage between 0-10 V to the signal amplifier which amplifies the voltage and gives it to solenoid valve to adjust the spindle speed.

Finally, obtaining desired spindle speed requires to control command voltage in real time. Therefore, a well-known PID strategy (see Figure 3.8) was applied to control the spindle speed and its proportional (K_p), integral (K_i) and derivative (K_d) gain constants were tuned using Ziegler-Nichols rule.

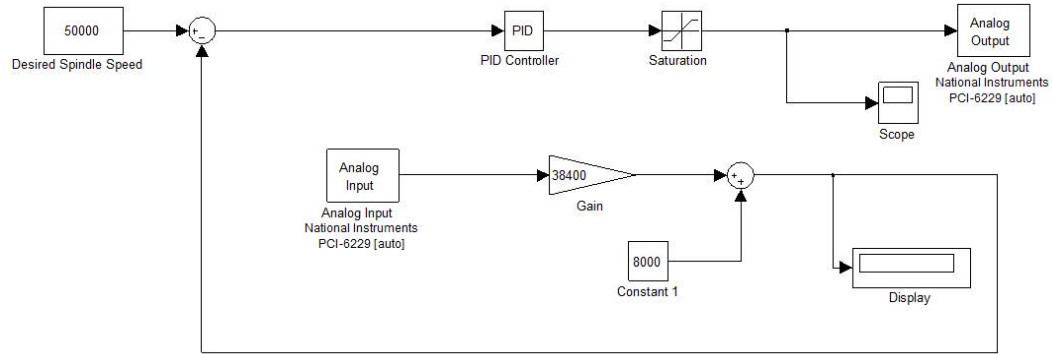


Figure 3.8: PID control block diagram created in SIMULINK

The lower part of this block diagram is exactly same with the block diagram used for acquiring spindle speed and the upper part is used to supply necessary command voltage to the signal amplifier by comparing the desired spindle speed and actual spindle speed. Furthermore, saturation block used in the block diagram plays an important role especially during the tuning process because it limits the analog output voltage between 0 and 10 V, and prevents signal amplifier and valve damage.

The successful spindle speed control in MATLAB/SIMULINK was achieved using the block diagram shown in Figure 3.8 and step response of the system for different spindle speeds such as 50,000 and 100,000 rpm are given in Figure 3.9 and Figure 3.10, respectively.

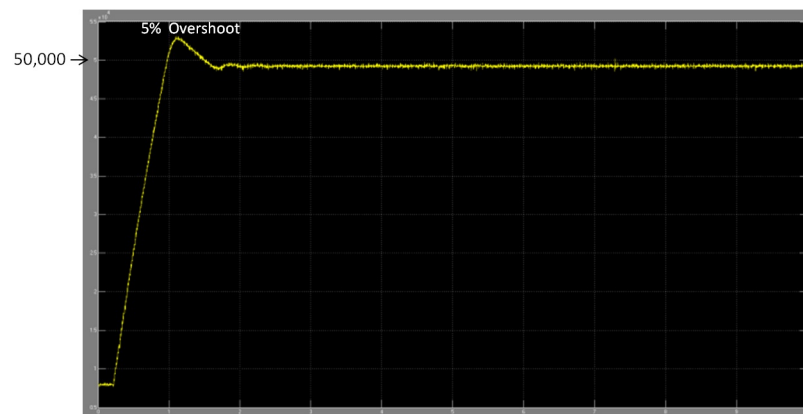


Figure 3.9: Step Response for the desired spindle speed of 50,000 rpm

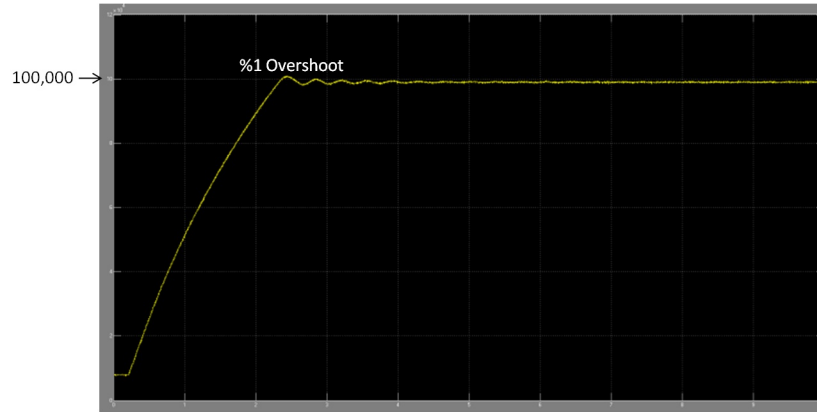


Figure 3.10: Step Response for the desired spindle speed of 100,000 rpm

Those figures show that maximum overshoot 5 percent occurs at lower speeds and it decreases as the spindle speed increases. On the other hand, maximum settling time around 3 second occurs at higher speeds and it decreases as the spindle speed decreases.

Although the spindle speed control was achieved using the trial version MATLAB/SIMULINK environment and its Real Time Workshop toolbox, it was decided to buy LABVIEW for real time applications. LABVIEW was selected because it is an environment designed professionally for relatively higher accuracy and better performance, and it is designed by the manufacturer of the data acquisition cards that are used for the experiments and control applications in the MMT. Furthermore, it was aimed to prevent sudden stop of the program due to the memory problems in MATLAB/SIMULINK by using LABVIEW. Therefore, the speed control learned and achieved by using SIMULINK was also conducted in LABVIEW 2010 environment (see Figure 3.11) to prevent possible errors in the speed control.

Although it is possible to achieve same control using MATLAB/SIMULINK or LABVIEW, it was realized that LABVIEW is more flexible than MATLAB/SIMULINK. It has more options and allows users to create more complex block diagrams using less number of blocks.

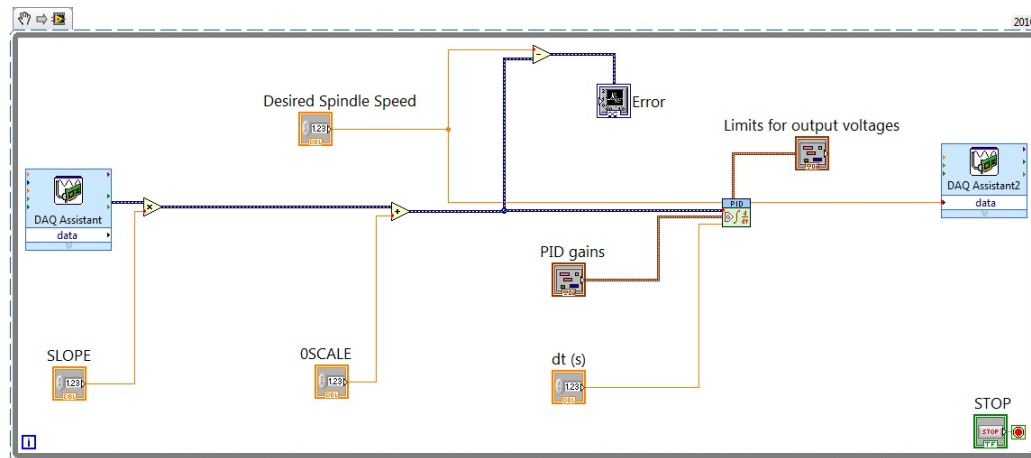


Figure 3.11: PID control block Diagram created in LABVIEW

Since it is an environment created by the manufacturer of the data acquisition cards, DAQ assistant blocks (see Figure 3.11) give the properties of the data acquisition card, which is actually good for proper connections and sampling time selection. Due to LABVIEW, the users of the MMT do not have to understand the block diagram and control, they can use only the front panel of the LABVIEW (see Figure 3.12) created by professional engineers.

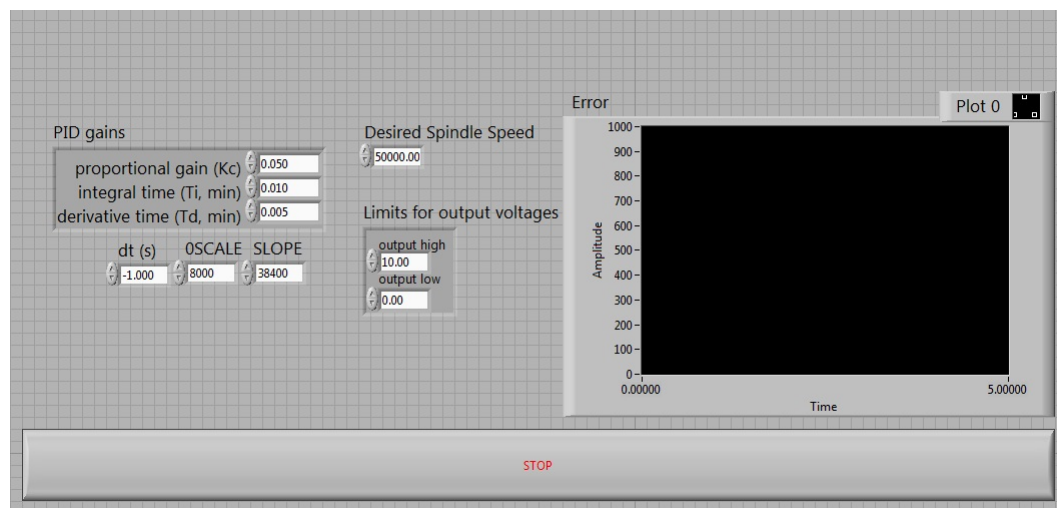


Figure 3.12: Front Panel created in LABVIEW

3.1.3.2 Miniature ultra-high-speed (UHS) ceramic bearing electrical spindle

Miniature air bearing air turbine spindle is not suggested to use under the spindle speed of 50,000 rpm because of the sudden torque decrease. Therefore, a new type of miniature spindle providing enough torque between the rotational speed of 1,000-50,000 rpm was also utilized during micro-machining. It is miniature ultra-high-speed (UHS) ceramic bearing electrical spindle with 50,000 rpm maximum rotational speed and 2, 3, 3.175 and 4 mm collets. The technical specifications of this spindle are provided in Table 3.4.

Table 3.4: Specifications of the electrical spindle [3]

Type	Maximum speed	Max.Power Output	Spindle Accuracy	Diameter
Electrical	50,000 rpm	350 W	$\leq 2 \mu\text{m}$	40mm

Table 3.4 indicates that maximum power output of miniature ceramic bearing electrical spindle (350 W) is much higher than that of air bearing air turbine spindle (14 W). Therefore, electrical spindle can provide relatively higher torque which makes electrical spindle capable of machining hard materials such as stainless steel and ceramic. Another advantage of this spindle is not requiring speed control because it has its own controller which is working with electricity. On the other hand, the accuracy of air-bearing air-turbine spindle ($1 \mu\text{m}$) is better than that of ceramic bearing electrical spindle ($2 \mu\text{m}$) and smaller cutting tool diameters can be achieved with air bearing air-turbine spindle because it provides relatively higher spindle speed to reach desired cutting velocity for small cutting tool diameters.

To sum up, the specifications of miniature ultra high speed ceramic bearing electrical spindle are good enough for successful application of micro-machining when lower cutting velocity and high torque are required. Utilizing both electrical and air-turbine spindle makes the designed miniature machine tool capable of achieving higher cutting speeds and producing three dimensional features on a variety of engineering materials such as polymers, metals, ceramics and composites.

3.1.4 Process monitoring subsystem

The process parameters in micro-machining cannot be detected due to the extremely small working zone and the ultra-high spindle speed. Furthermore, relatively smaller tool sizes make the tool wear and breakage issues really significant in micro-milling processes [76, 77]. Therefore, it is desired to have a camera to magnify the image to facilitate the tool and workpiece set-up and to monitor the tool condition. In addition, some other equipments are utilized to monitor the process during micro-machining.

Designed 3-axis miniature machining center utilizes a stereo microscope with 95X magnification to view the process and to indicate the workpiece surface during the initial tool approach. The problems during machining can be detected using this microscope and the process can be stopped. Another online monitoring option is to use a cutting force sensor. Since the variation in cutting forces provide information about runout characteristics, tool wear and tool breakage, a Kistler three-axis dynamometer (9256C1) with 2 mN noise threshold was attached to the slides for measuring the micro-machining forces. It is capable of measuring cutting forces in three direction with maximum force of 250 N.

Although force measurement is not one of the major part of this thesis, since it is aimed to prepare a MMT testbed, the force measurement set-up using Kistler three-axis (9256C1) dynamometer, an amplifier, a data acquisition card and LABVIEW was prepared in this thesis. First, the basic block diagram for force measurement (see Figure B.5) in three directions was prepared in LABVIEW environment. This block diagram can only be used to obtain machining forces in time domain, but it can be further improved by adding a few blocks for frequency domain analysis. It is important to note that the constants available in the block diagram are obtained from the manual of the Kistler dynamometer to convert voltage into the newton. Then, since the Kistler three-axis (9256C1) dynamometer uses an amplifier to amplify the coming voltage, the connections between amplifier and data acquisition card (PXI-7854R) which is capable of simultaneous measurement were made using suitable BNC cables to obtain machining forces in real time.

3.2 Machine Integration

Previous section discussed the motion accuracy and dynamic stiffness of the key machine subsystems and it presented that specifications of the major subsystems provide required performance to achieve desired accuracy level for mechanical micro-machining. However, besides having high performance individual subsystems, integration of key components of the miniature machining center is critical for successful application of micro-machining. In order to control the point of contact between the cutting tool and the workpiece accurately and repeatedly, integration of these components have to be achieved successfully. This section summarizes the integration of the subsystems of the developed miniature machine tool.

First, the mechanical parts for integration of the ultra-high speed spindle were designed. Subsequently, the finite element analysis of these mechanical parts was completed to ensure that they have convenient static and dynamic properties. Next, the integration of all machine subsystems was made virtually in a computer aided drawing environment to ensure that the real parts would be assembled accurately. Finally, precision alignment of the developed MMT was achieved to ensure that spindle axis is perpendicular to the surface of the stages.

3.2.1 Design of the mechanical parts

In mechanical micro-machining, spindle is a key element because spindle motion errors have significant effects on the output quality of the process [54, 55, 29]. Therefore, integration of the miniature ultra high speed spindle to the miniature machine tool is critical for the successful application of micro-machining.

Two additional mechanical parts such as clamp and base shown in Figure 3.1 were used to integrate spindle to the miniature machine tool. To guarantee that ultra high speed spindle and miniature machining center will operate efficiently, design of the mechanical parts were carried out using ANSYS 12 software. Since the material and configuration selection are the major design issues to achieve

high static and dynamic stiffness, comprehensive static and dynamic analysis of the spindle clamp/base structure were conducted to select the appropriate configuration and material for this structure.

3.2.1.1 Static Analysis

Geometric accuracies better than $1\text{ }\mu\text{m}$ are generally required in micro-machining processes. To achieve this accuracy level, it is expected to have maximum static deflection of less than $1\text{ }\mu\text{m}$ during micro-machining. To ensure that, finite element simulations of the spindle clamp/ base structure were conducted using ANSYS 12 software. Eight different configurations shown in Figure 3.13 were considered in the static analysis. For each configuration two different and common materials such as aluminium alloy 7050-T73510 and AISI 304 stainless steel were considered. The properties of these materials related to static analysis are given in Table 3.5.

Table 3.5: Properties of materials considered in the static analysis

Material	$d(kg/m^3)$	$E(N/m^2)$	$\nu(N/A)$	Thermal Exp. Coeff.(1/K)
Al Alloy 7050-T73510	2830	7,2e10	0,33	2,36
AISI 304 Stainless steel	8000	1,9e11	0,29	1,8

It is clear from Table 3.5 that density (d) of the aluminium is much smaller than that of stainless steel. Therefore, aluminium is more suitable to provide lighter design and it is also cheaper than stainless steel in terms of machining cost. To be able to provide a light, cheap and compact design with sufficient static deflection, aluminium was the first consideration for the material selection.

On the other hand, modulus of elasticity (E) of the stainless steel given in Table 3.5 is larger than that of aluminium so it is considered as a second choice in the case that aluminium does not satisfy necessary static stiffness.

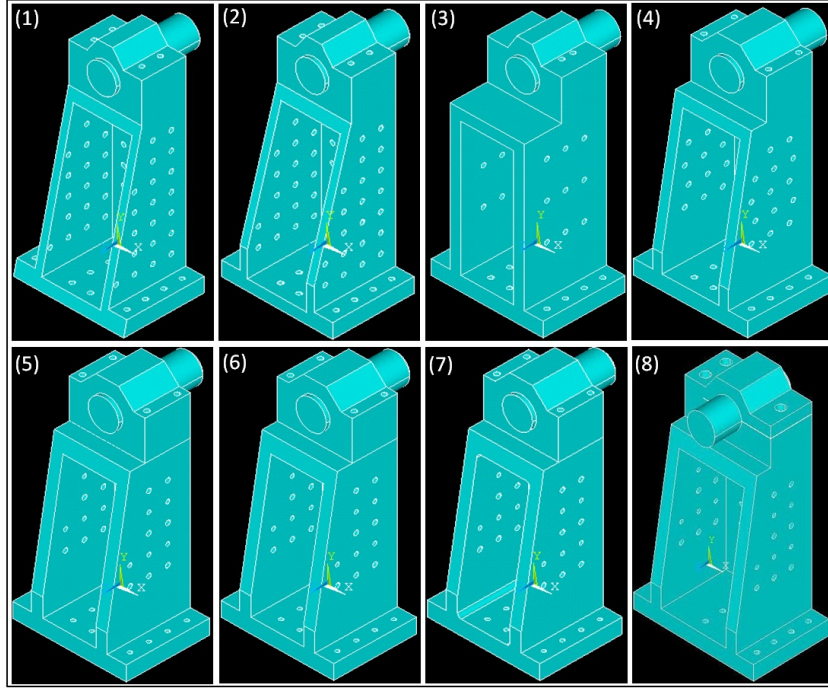


Figure 3.13: All configurations for spindle clamp-base structure

For simplicity, the procedure to conduct static analysis of one configuration was explained and this procedure was applied for each configuration. The first step was to create finite element model of the spindle clamp/ base structure in ANSYS 12 finite element simulation software. Since drawing the three dimensional (3D) model of the structure using a Computer Aided Drawing (CAD) program which is compatible with ANSYS 12 is relatively simple, SOLIDWORKS 2010 was used to create finite element model of the spindle clamp/base structure and file saved as .igs was imported into the ANSYS to make the model ready for analysis.

Next, selecting the required options and entering necessary parameters in ANSYS were completed. The analysis type was specified as static. Solid element, tet 4 node 28, was selected for meshing. It is also important to note that the simulations with different kind of elements having larger number of nodes were also conducted for convergence analysis. Finally, material properties listed in Table 3.5 were entered for corresponding iteration to make the process ready for meshing.

After meshing , boundary conditions and forces on the structure were specified. Displacements for all degrees of freedom were set to zero at the location of $y=0$. 20 N external force in each x, y and z direction was applied on the front face and center of the spindle. Since stages stop itself when 23 N force limit is exceeded as specified in Table 3.1, 20 N was selected as a threshold to be safe in the static analysis and it is actually very high cutting force value for micro-manufacturing processes.

Subsequently, the simulations with increasing number of elements were completed for each configuration and material combination. The results obtained as a result of the convergence analysis were summarized in Table 3.6. Static deflection values in each X, Y and Z direction as well as maximum static deflection (M^*) for each iteration were listed in this table.

Table 3.6: Results of the static analysis

Iteration	Al Alloy 7050-T73510				AISI 304 Stainless steel			
Iteration	X μm	Y μm	Z μm	M* μm	X μm	Y μm	Z μm	M* μm
1	0.864	0.894	1.54	1.87	0.326	0.339	0.585	0.708
2	0.825	0.810	1.31	1.66	0.311	0.308	0.496	0.627
3	0.646	0.567	0.721	1.08	0.243	0.215	0.273	0.410
4	0.668	0.610	0.892	1.21	0.252	0.232	0.338	0.459
5	Al Base and Steel Clamp				0.509	0.438	0.749	0.935
6	0.651	0.595	0.821	1.15	0.247	0.228	0.299	0.416
7	0.649	0.585	0.815	1.12	0.248	0.229	0.301	0.419
8	0.598	0.571	0.680	1.01	0.111	0.0256	0.229	0.256

All results in Table 3.6 were obtained without considering the joint dynamics in the spindle clamp/base structure, so it can be said that the structure was assumed to be rigid. This assumption is necessary for these kind of structures because ANSYS is not capable of conducting finite element simulations of complex shapes as much as the spindle clamp/base structure. Considering this assumption, it might be said that the finite element results should be supplemented by experimental modal analysis.

Simulation results summarized in Table 3.6 show that static deflection of the structure made of aluminium was not in the admissible range for micro-manufacturing applications. Third configuration which has less material removed was the most extreme structure which is expected to have minimum static deflection. However, it is not stiff enough for micro-manufacturing processes because maximum deflection at the desired location is higher than $1\text{ }\mu\text{m}$.

Since aluminium did not satisfy the desired static displacement, second material choice, AISI304 stainless steel, was considered for each configuration. For AISI 304, third configuration having $0.410\text{ }\mu\text{m}$ was a suitable design in terms of maximum static displacement. However, some additional iterations were carried out to check whether it is possible to make the design lighter, cheaper, compact and also more aesthetic without reducing the static stiffness in a considerable amount.

As a result of static analysis, first, it was decided to go with 7th configuration made of stainless steel which has 0.419 micrometer static deflection. However, since the clamping area of the miniature ultra-high-speed air bearing air turbine spindle was considered during the finite element simulations, it was realized that the clamping area of the electrical spindle is different than air turbine spindle. Therefore, a common clamping area which is suitable for both spindles is selected for the final finite element simulation.

The structure of the clamp was also changed for the final simulation. For the previous configurations the clamp was designed as two parts and one of them were placed on top of another having the spindle between them. For the final iteration, it was decided to make a single clamp design which can be machined by using conventional milling process and wire electric discharge machining. Since joint dynamics did not considered during the simulations, having a single part clamp rather than two part clamp did not affect the simulation results too much. However, changing the clamping area of the spindle affected the results affirmatively and as indicated in Table 3.6 (8), the static stiffness of the structure increased in a considerable amount. Simulation results of the final iteration made of stainless steel is shown in Figure 3.14.

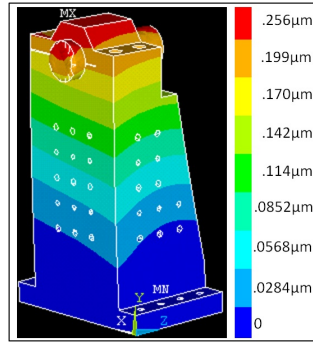


Figure 3.14: Finite element simulation of last configuration with the properties of AISI 304 Stainless Steel

Figure 3.14 shows that maximum deflection, 0,256 micrometer, occurs at the front face of the spindle. The answers of the two important questions for the spindle clamp/base structure design were obtained in static analysis. The material (AISI 304 Stainless steel) and the configuration (see Figure 3.14) of the structure were selected. The three dimensional CAD models of the mechanical parts (spindle base and clamp) with selected configurations are shown in Figure 3.15.

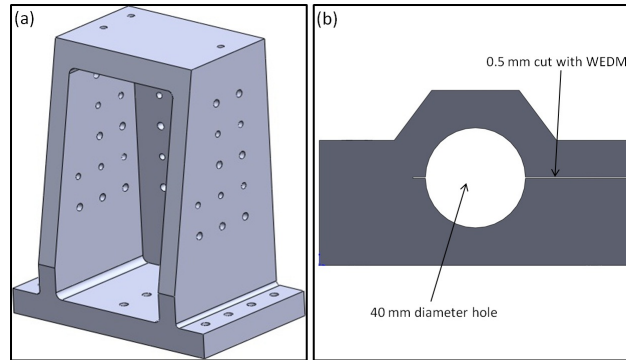


Figure 3.15: 3D CAD models of the designed mechanical parts (a) Spindle base (b) Spindle clamp

The final base design shown in Figure 3.15 (a) has many holes on its front face and sides to attach some sensors and other equipments and the considerable amount of material was removed to have a lighter design. The clamp shown in Figure 3.15 (b) has a 40 mm diameter hole to attach the spindle and a 0.5 mm cut was made for proper attachment and removal of the spindle.

3.2.1.2 Dynamic Analysis

Static analysis itself does not guarantee that the mechanical parts will operate efficiently. Therefore, dynamic analysis of the mechanical structures were also carried out using ANSYS 12 finite element simulation software. The finite element model of the decided configuration in the previous section was used during the simulations. The dynamic characteristics of the designed mechanical parts were investigated. During the simulations, modal analysis which is one of the available methods in the literature were used to determine the fundamental vibration modes and corresponding natural frequencies of the mechanical structures.

During dynamic analysis, Block Lanczos eigensolver algorithm was used to obtain first 10 mode shapes and corresponding natural frequencies. Procedure applied for the static analysis was also followed for the dynamic analysis. However, in this part external forces were not applied because natural frequencies of the structure do not depend on the external forces. Since it is also difficult to carry out dynamic analysis of complex shapes in ANSYS environment, dynamic analysis of mechanical parts also ignored the joint dynamics and assumed the structure is rigid. The natural frequencies obtained as a result of the modal analysis are provided in Table 3.7.

Table 3.7: Properties of materials considered in the static analysis

Set	1	2	3	4	5	6	7	8	9	10
N.F.	699.59	827.91	1895.8	2787	3195	3419	3635	4471	5468	5487

The speed range of 1,000-160,000 rpm is available in the developed MMT. The natural frequencies in the operating frequency range (16,667 Hz-2666,6667 Hz) are significant for successful application of micro-machining. When the forced frequency becomes equal to one of them, vibration amplitude is altered and affects the machine performance adversely. Frequencies listed in Table 3.7 show that there are three fundamental vibration modes (see Figure 3.16) in the operating frequency range and corresponding frequency values are 699.59 Hz, 827.91 Hz and 1895.8 Hz. Figure 3.16 indicates that the first two modes are bending modes and the third one is the torsion mode.

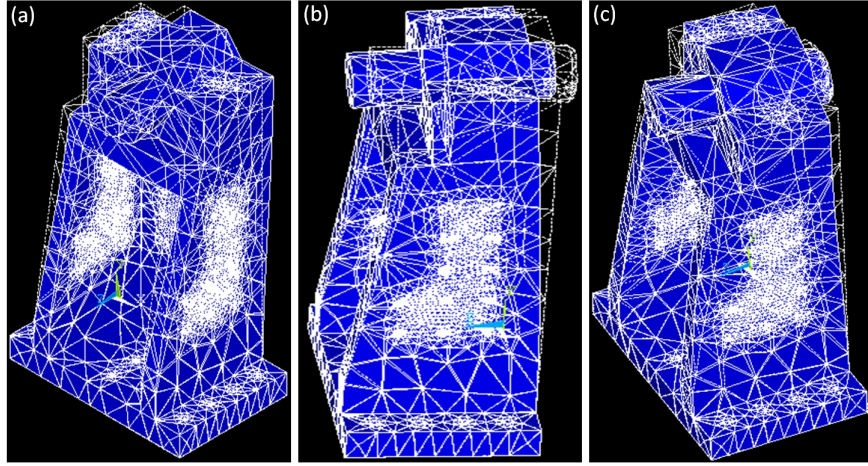


Figure 3.16: Fundamental mode shapes in the operating frequency range (a) First mode shape (699.69 Hz) (b) Second mode shape (827.91 Hz) (b) Third mode shape (1895.8 Hz).

Dynamic analysis concluded that even though in conventional precision machine design, the first natural frequency is expected to be higher than the maximum spindle rotational frequency, it can not be the case in miniature machine design because of ultra-high spindle speeds. Since the maximum spindle speed in the developed MMT is 160,000 rpm, it is extremely difficult to design a MMT which has the first natural frequency over the maximum spindle speed.

In this thesis, dynamic analysis results were obtained to provide a machine operation frequency selection rather than a threshold for maximum spindle speed and it showed that natural frequencies in the operation frequency range should be avoided to prevent vibration related errors on the output quality of the process. Since it is known that natural frequencies are directly proportional to the ratio of stiffness to mass (see equation 3.4), further design improvement for the dynamics of the mechanical structures can be achieved by changing the configuration and materials of the mechanical parts.

$$w_n = \sqrt{\frac{k}{m}} \quad (3.4)$$

Detailed computer aided drawings of the base and clamp shown in Figure 3.15 were created to get them manufactured. Considering the specifications of the conventional machine tools available in the industry and desired accuracy in the MMT, geometrical and dimensional tolerances of the mechanical parts were specified. Surface finish values of the significant surfaces were given. Since the area where the spindle is placed is very critical in terms of surface roughness and, geometric and dimensional accuracy, these values were selected carefully to make mechanical parts design ready for manufacturing.

3.2.2 Computer Aided Drawing Model of Miniature Machine Tool

Precision equipments and designed mechanical parts of the MMT are decided to be integrated on a IG Series, 600 x 600 x 58 mm newport optical breadboard. The accurate integration of the all components on the breadboard requires CAD model of the whole miniature machining center before manufacturing stage. Therefore, 3D CAD model of the designed MMT was created using SOLIDWORKS 2010 as shown in Figure 3.17

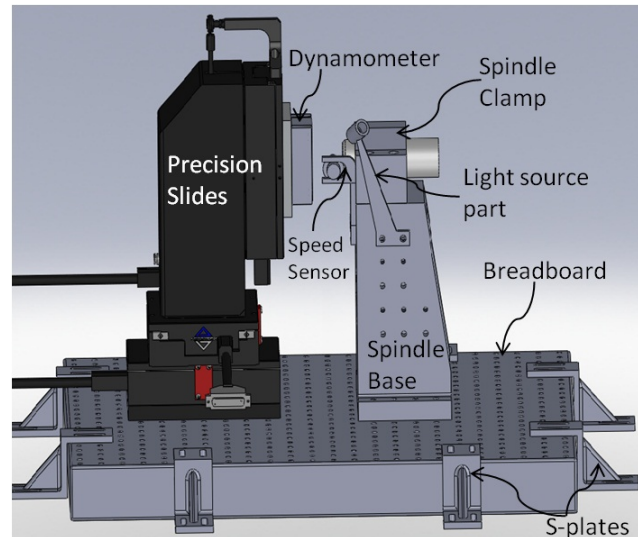


Figure 3.17: 3D CAD model of the developed MMT

Figure 3.17 shows that stages were integrated in horizontal configuration and

mechanical parts were used to integrate spindle accurately on the breadboard. Since it was decided to place the entire set-up on a vibration isolation table (Newport RS 4000 with tuned damping) with laminar flow isolator legs, the rigid connection between breadboard and vibration table was provided by using S-plates according to CAD model.

Considering the static and dynamic analysis results and created CAD model of the 3-axis miniature machine tool, first mechanical parts (spindle clamp, base and S plates) were manufactured using milling and wire electric discharge machining processes. Wire electric discharge machining in the manufacturing was used for 0.5 mm cut in the clamp. It provided great advantage for obtaining higher geometric accuracy in terms of circularity of the 40 mm diameter hole where spindle is placed. Both clamp and base were manufactured from steel and they were coated with chromium-nickel. On the other hand, S-plates were made of aluminium.

Additional plastic parts manufactured by using rapid prototyping machine were used to attach sensors and light source (see Figure 3.17). Speed sensor part was designed considering the measurement distance of the infrared sensor and light source part was designed to make coming light perpendicular to the machining area.

3.2.3 Integration of major subsystems and precision alignment

Accurate integration of the miniature machine tool was achieved based on the 3D CAD model. First, the ultra-precision slides side was integrated on the breadboard and proper connections between slides and their controllers were made. Next, the integration of the spindle was achieved by using designed mechanical parts. To enable miniature machine tool working efficiently, the precision alignment of the developed miniature machine tool was achieved using a Coordinate Measuring Machine (CMM).

The perpendicularity of the spindle axis to the surface of the stages (see Figure 3.18) is critical for successful application of micro-machining. In order to achieve this perpendicularity, angle measurements in 3D space was performed using CMM.

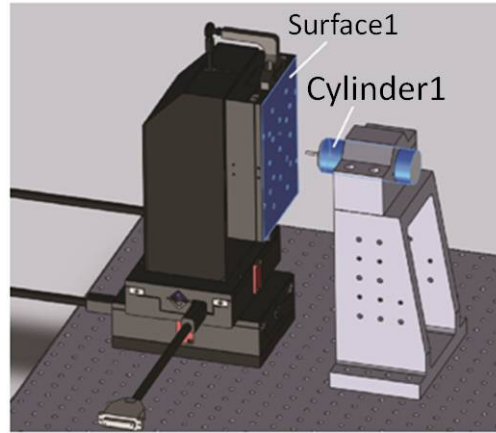


Figure 3.18: Perpendicularity of spindle to the stages

Surfaces used in the precision alignment can be seen in Figures 3.18 and 3.19. In order to guarantee that spindle axis is perpendicular to the stages, it is necessary to ensure that Surface1 and Surface2 are parallel to each other, and cylinder1 and surface2 are perpendicular to each other.

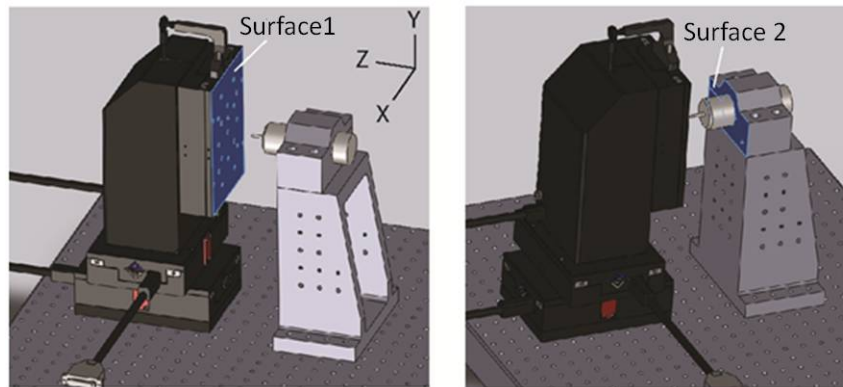


Figure 3.19: Precision alignment surfaces and coordinate system

In the developed MMT, the precision alignment was accomplished by achieving the parallelism between surface1 and surface 2 in both xy and yz plane. Thus, a parallelism in 3D space was obtained. The parallelism of better than 0.01 degree in xy plane was completed using a precision block as shown in Figure 3.20. In order to achieve the parallelism of better than 0.01 degree in yz plane, copper shims with different thickness of 5 μm , 25 μm and 50 μm were used. Thus, the perpendicularity of better than 89.99 degree between spindle axis and stages were accomplished as a result of these steps.

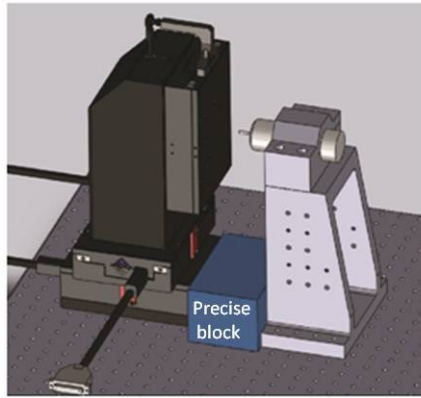


Figure 3.20: Alignment in xy plane using precision block

Finally, the sensor and light source were attached to the base using the manufactured ABS parts and the entire set-up assembled on the breadboard was placed on the vibration isolation table using S-plates.

In summary, a-3 axis miniature machine tool was designed and constructed as a testbed for mechanical micro-machining. To construct this machine tool, precision equipments were used and mechanical parts for the integration of spindle were designed. Next, precision alignment of the developed MMT was completed to make it ready for manufacturing micro-parts.

Chapter 4

Performance Evaluation of MMT

Design and construction of the machine tools do not guarantee that it will operate efficiently. Therefore, it is necessary to evaluate the performance of the designed machine tools by conducting some experiments for both conventional and miniature machine tools [50, 18].

To demonstrate the capability of developed MMT for fabricating three dimensional features, mechanical micro-milling is proposed as a novel method for fabricating Poly(methyl methacrylate) (PMMA) and poly(lactic-co-glycolic acid) (PLGA) polymer micro-needles. This chapter mainly presents the procedure we followed to manufacture micro-needles. First, experimental investigation of micro-machinability of PMMA and PLGA polymers is introduced. Next, fabrication of PMMA and PLGA polymer micro needles with different geometries are presented. Air turbine air bearing spindle with maximum 160,000 rpm rotational speed is used during both experimental investigation and fabrication of micro-needles. Since air-turbine spindle is not suggested to use under 50,000 rpm rotational speed, the available speed range during the experiments is between 50,000 rpm and 160,000 rpm.

4.1 An experimental investigation of micro-machinability of PMMA and PLGA polymers

A few studies in the literature show that material dependent complexities make machinability of polymers challenging and achieving a good surface finish during polymer machining is not straightforward as viscoelastic, thermal, and mechanical properties affect the machining process output [87, 24].

Due to lack of experience in micro-machinability of the biodegradable PLGA and the biocompatible PMMA, a micro-machinability study was performed in this section. The ultra high-speed air-bearing air-turbine spindle with maximum 160,000 rpm rotational speed and a two-fluted straight-end micro-endmill with a diameter of 385 μm was used during this study. Prior to micro-machining the micro needles, micro-channels were machined to study the parameters that influence the quality of the machined components.

4.1.1 Study of micro-machining parameters

A parametric study was performed on PMMA and PLGA substrates to select a set of parameters for micro needle machining. PLGA (80L/20G) (Alkermes Inc., Ohio, USA) and PMMA (Plaskolite Inc., Ohio, USA) substrates with thicknesses of approximately 2 mm were used throughout this study. A group of 3 mm length and 100 μm depth slots were machined using 50,000 and 100,000 rpm spindle speeds with different feedrates (5, 10, 15, and 20 $\mu\text{m}/\text{flute}$). During this study, burr formation was qualitatively observed from scanning electron microscopy (SEM) images. White light interferometer measurements were used to study the surface roughness of the micro-machined slots, and analysis of variance (ANOVA) was used to access the repeatability of the process and to compare the effect of machining parameters on the output quality.

4.1.1.1 PMMA

The parametric study performed on PMMA substrates showed that the least amount of burrs were formed during the 50,000 rpm spindle speed and the 20 $\mu\text{m}/\text{flute}$ feedrate, and the most amount of burrs were formed for 50,000 rpm and 5 $\mu\text{m}/\text{flute}$ (see Figures 4.4 (a) and 4.4 (b)).

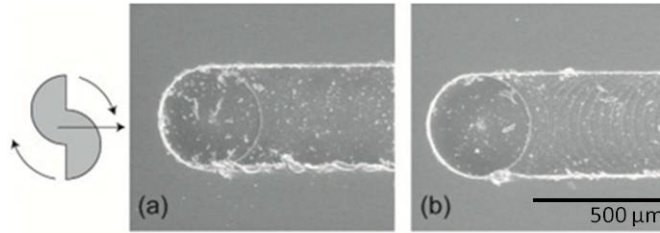


Figure 4.1: SEM images of burr formation for PMMA slot machined with (a) 50,000 rpm spindle speed and 5 $\mu\text{m}/\text{flute}$ feedrate, (b) with 50,000 rpm and 20 $\mu\text{m}/\text{flute}$

The down-milling side was observed to have significantly more burrs than the up-milling side. For the spindle speeds above 50,000 rpm and, 5 and 10 m/flute feedrates, high cutting speeds cause the PMMA chips to stick on the tool and melt the slots (Figure 4.2).

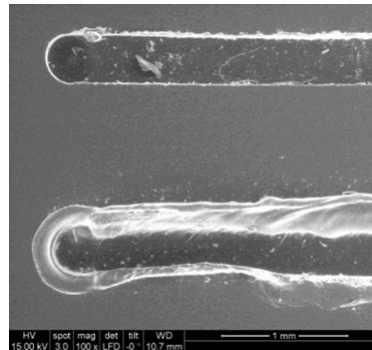


Figure 4.2: PMMA material machined at 100,000 rpm and 10 $\mu\text{m}/\text{flute}$. Top channel did not melt while the second machined channel melted during the process.

The surface roughness (R_a) values were measured in the center of each slot. The averages of three slot values (for the same parameters) are plotted in Figure 4.3. The minimum R_a value was obtained for 50,000 rpm and 10 $\mu\text{m}/\text{flute}$. In micromachining, surface roughness is expected to increase with increasing feedrate, which was not observed during PMMA micromachining.

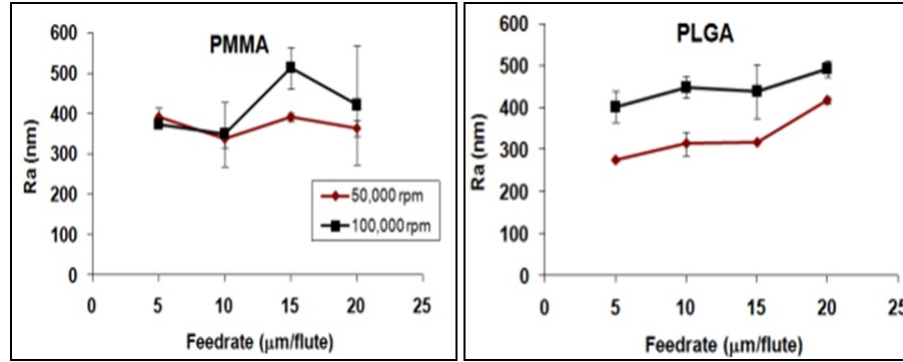


Figure 4.3: Average surface roughness values for PMMA and PLGA

4.1.1.2 PLGA

During PLGA slot machining, the least amount of burr formation was observed during the 50,000 rpm spindle speed and 20 $\mu\text{m}/\text{flute}$ feedrate (see Figure 4.4 (b)). Maximum burr formation was observed during the 100,000 rpm spindle speed and 5 $\mu\text{m}/\text{flute}$ feedrate (Figure 4.4 (a)).

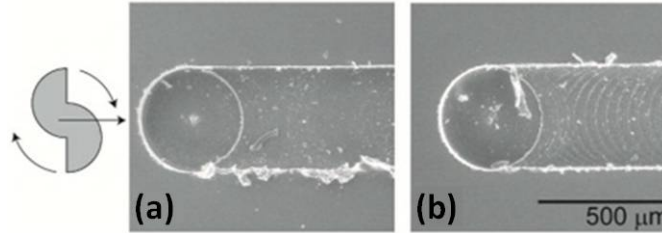


Figure 4.4: SEM images of burr formation for PLGA slot machined with (a) 100,000 rpm, 5 $\mu\text{m}/\text{flute}$, and (b) with 50,000 rpm, 20 $\mu\text{m}/\text{flute}$.

Overall, 50,000 rpm spindle speed resulted in less burrs than 100,000 rpm spindle speed. Burr formation decreased when feedrate was increased. Similar to the PMMA observations, more burrs were formed on the down-milling side. However, unlike PMMA, no melting was observed. PLGA machining resulted in less burr formation than PMMA machining.

Surface roughness measurements demonstrated that 50,000 rpm spindle speed led to smaller Ra values for all feedrates. Spindle axis offset (runout) is different for different spindle speed cases, which could be the main reason behind having high roughness values for the 100,000 rpm spindle speed case. Size and form accuracy, as well as surface roughness, of features created during micro-machining depend on runout characteristics of the spindles. The Ra values increased with increasing feedrate except from 10 $\mu\text{m}/\text{flute}$ to 15 $\mu\text{m}/\text{flute}$ for 100,000 rpm case. The parameters of 50,000 rpm and 5 $\mu\text{m}/\text{flute}$ led to the minimum surface roughness for PLGA.

4.1.2 Repeatability Analysis

The repeatability of the surface roughness results was investigated using a two-way ANOVA. Channel machining tests were repeated and measured three times under same conditions. MATLAB anova2 command was used for the analysis. During the analysis, differences were considered significant for $p \leq 0.05$ (Table 4.1).

Table 4.1: ANOVA results. Surface roughness p values.

P values	Speed	Feedrate	Interaction
PMMA	0.1147	0.0638	0.2886
PLGA	0	0.0001	0.3383

For the PMMA case, the surface roughness values are more sensitive to the changes in feedrate. The effect of speed on the surface roughness is less repeatable. The effect of interaction of the spindle speed and feedrate on the surface roughness has the lowest repeatability with the highest probability value.

On the other hand, the PLGA analysis gave the smallest probability values, i.e., the highest repeatability. With a value very close to zero, the effect of spindle speed on the surface roughness is high and repeatable. The PLGA cases have smaller standard deviation values than the PMMA cases. The smallest standard deviation values are observed for machining PLGA with 50,000 rpm spindle speed (see Figure 4.3). The effect of feedrate is also observed to be high compared to the PMMA case with a 0.0001 probability value. The high probability of 0.3383 (low repeatability) value shows that the effect of the interaction between the spindle speed and feedrate on the surface roughness is low with respect to the variance. Having nearly parallel curves for slow and fast speeds, this conclusion can also be observed on the plots in Figure 4.3. When the speed is increased, the Ra-feedrate curve shifts upward without a significant change in the behaviour.

In overall, the ANOVA shows that with small probability values, micromachining of PLGA is more repeatable compared to PMMA, and 50,000 rpm spindle speed is more desirable over 100,000 rpm spindle speed.

4.2 Fabrication of PMMA AND PLGA micro needles

Based on the parametric study, micro needles were machined using the 50,000 rpm spindle rotational speed and the 20 μm flute feedrate to minimize burr formation.

Having the advantage of G-code capability of the stages, the slides were programmed manually for moving the workpiece attached on them such that the desired geometry is machined on the workpiece. Tool paths generated for micro-milling of needles are provided in Figure 4.5 . The tapered geometry of the micro needles was manufactured by moving the cutting tools with an angle as shown in Figure 4.5. The machining strategies can be further optimized to improve the dimensional accuracy and surface roughness of the machined parts.

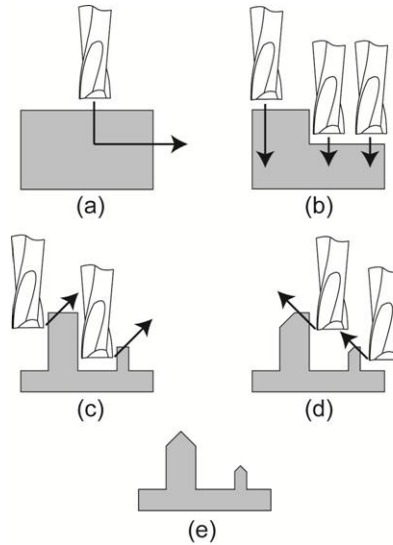


Figure 4.5: Cross section representation of the tool path used to create micro needles (a) Tool opening a pocket within the polymer substrate, (b) tool creating slots that eventually become pillars, (c-d) tool path to create tapers on the micro pillars, and (e) final product.

Images of the different sizes micro needles using the two different polymers are shown in Figure 4.6.

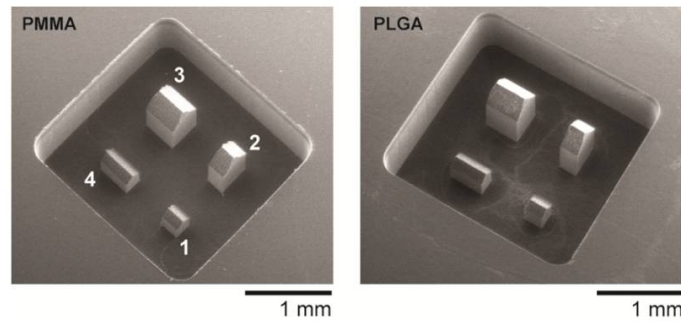


Figure 4.6: PMMA and PLGA micro needle dimensions: (1) width (w)=232x216 μm , height (h)=400 μm , (2) w=220x419 μm , h=800 μm , (3) w=419x416 μm , h=800 μm (4) w=415x216 μm , h=400 μm .

Figure 4.6 shows that the developed 3-axis miniature machine tool is capable of producing 3D micro needles of the same geometry on both polymers repeatedly.

Using the same machining parameters and advantageous of having better machinability of PLGA, needles with different taper geometries were fabricated on PLGA substrates (Figure 4.7). During this study, bending of the PLGA pillars due to machining forces which caused dimensional errors was observed. MMT vibrations which alter the machining forces could be the reason of bending of pillars. Thus, it was suggested to investigate MMT vibrations to improve the output quality of the process

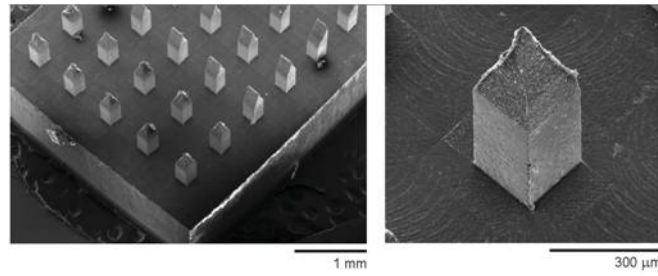


Figure 4.7: PLGA micro needle array with three different taper geometries. Right: Four taper needle with $w=200 \times 200 \mu\text{m}$, total $h=800 \mu\text{m}$ and taper angle for all sides $\sim 28^\circ$.

In conclusion, the micro-machining study performed on PMMA and PLGA polymers concluded that PLGA has better machinability than PMMA. The parametric study showed that 50,000 rpm spindle speed gave better results than 100,000 rpm spindle speed for both burr formation and surface roughness. The $20 \mu\text{m}/\text{flute}$ feedrate led to the least amount of burr formation, and the feedrate of $5 \mu\text{m}/\text{flute}$ resulted in minimum surface roughness. High repeatability values were observed for PLGA machining with 50,000 rpm spindle speed. Machining trials on the developed MMT has shown that the developed MMT was capable of manufacturing micro needles having different geometries from PMMA and PLGA polymer materials. Using the machining parameters of 50,000 rpm spindle speed and $20 \mu\text{m}/\text{flute}$ feedrate, micro needles were successfully manufactured from PMMA and PLGA polymers to demonstrate the capabilities of the developed miniature machine tool. Furthermore, it was observed that further improvements can be achieved by improving the machining strategy and investigating the MMT vibrations.

Chapter 5

Investigation of MMT Dynamics

The geometric and surface quality of precision parts manufactured on a MMT are highly dependent on the dynamic performance of the miniature machine tool, which is determined by the interrelated dynamics of machine tool mechanical structure and cutting process. Machine tool vibrations led to tool-workpiece relative displacements play an important role in determining the dynamic performance of miniature machine tools.

Of the key components described in chapter 3, spindle side is the most important structural loop in the designed miniature machine tool [66]. Spindle includes the flexible bearings and holds the micro-cutting tool with relatively reduced stiffness. Due to flexibility of these parts, when subjected to the cutting forces during the machining process, expected vibrations on the spindle will be higher than those of precision stages side. Therefore, the dynamics of micro-machining processes and the vibration generated during micro-machining are directly affected by the spindle side dynamics.

In this chapter, the dynamics of spindle side of a 3-axis miniature machine tool are investigated experimentally using runout measurements and experimental modal analysis techniques. The obtained results are compared with three dimensional simulations performed in chapter 3.

The runout characteristics of the miniature ultra high speed spindle is investigated at different spindle speeds by using one of the effective non-contact measurement techniques which utilizes laser doppler vibrometers (LDVs) to measure the runout motions while the spindle is rotating. Dynamics of the mechanical structures at the spindle side is obtained at different spindle speeds in the form of frequency response functions (FRFs) using experimental modal analysis. Based on these two experimental investigation methods, the accurate dynamic characteristics of the spindle side are obtained.

5.1 Runout characteristics of ultra-high speed miniature spindles for micromachining

Accurate rotational motions of micro tools affect the size and form accuracy, as well as surface roughness, of features created during micromachining. Therefore, micro-tool runouts, arising from the spindle error motions, the tool centering errors and the vibrations of the structural loop must be characterized to determine its effects on micro-machining accuracy.

This section discusses and adapts an experimental facility available in the literature to the developed MMT for measuring runout motions of ultra-high-speed spindles using a non-contact measurement technique [82, 29]. Two laser Doppler Vibrometer (LDV) systems attached to a metrology frame are used for simultaneous measurement of radial motions of the micro-cutting tool in two mutually orthogonal directions. These measurements enable assessing synchronous runouts, which are periodic with the spindle frequency and its harmonics, and asynchronous runouts, which occur at non-harmonics of the rotational speed.

The methodology available in the literature uses a precision artifact with optically smooth surface and provides the dynamic runouts of an UHS air-bearing air-turbine spindle. In the scope of this thesis, the runout motions of ultra-high-speed ceramic bearing electrical spindle are measured because the finite element simulations indicate that most of the critical natural frequencies are in the operating frequency range of the electrical spindle. During the experiments, a 2-fluted micro-cutting tool is used to investigate the possibility of taking measurements on the micro-cutting tools.

First, the experimental facility developed for measuring runout motions of ultra high speed spindles is described. Next, the procedure for aligning each pair of laser beams mutually perpendicularly with respect to the spindle is outlined. In addition to the steps in the available methodology, a well-known image processing technique to check the angle between laser beams after alignment procedure is presented. Finally, the experimental facility developed to measure the runout motions of the miniature spindles are used to investigate the speed dependent dynamics of UHS ceramic bearing electrical spindle.

5.1.1 Experimental Set-up

The experimental facility developed for non-contact measurement of runout motions of UHS spindles during micro-machining is shown in Figure 5.1. The entire set-up was constructed on the breadboard and the breadboard was placed on a vibration isolation table (Newport RS 4000 with tuned damping) with laminar flow isolator legs.

An extruded-aluminium frame using the Bosch Rexroth aluminium profiles with 45x45 mm and 45x90 mm cross-section area was constructed around the miniature machining center to allow the attachment of the lasers. Focus length of the lasers for both relative and absolute measurements, 204mm and 267mm respectively, were considered to specify the length of the profiles and overall dimensions of the frame [4].

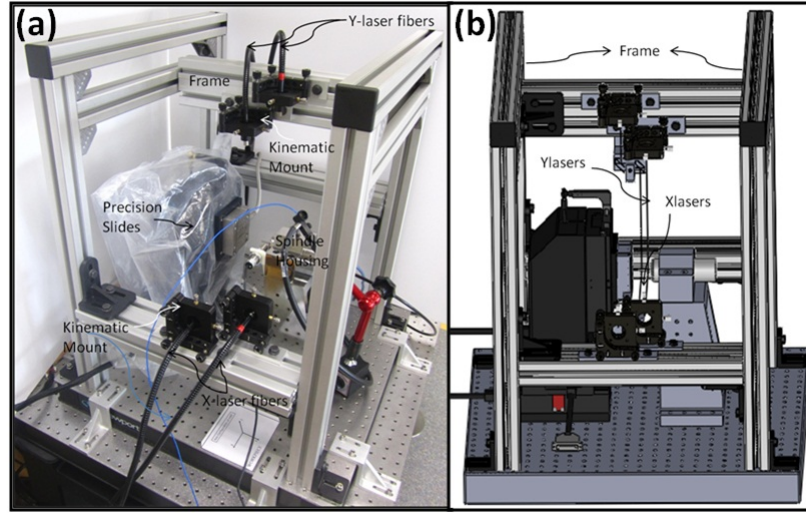


Figure 5.1: Experimental facility for runout measurement (a) The measurement set-up for vibration measurements (b) A 3D model of the experimental set-up

To be able to achieve simultaneous measurements in two radial directions, two differential laser Doppler vibrometer systems (Polytec Fiber Optic Vibrometer Sensor Head OFV 552 along with a Polytec Vibrometer Controller OFV-5000) were used for the runout measurements. Each system has two laser beams which are splitted by a fiber-optic cable. One of the two laser beams are labelled as black and it is used for measurment. Another one which is labelled as red is used for reference. Absolute measurements can be conducted by using one of the two laser beams (black labelled beam). A mirror cap is placed to the other laser beam during absolute measurements (see Figure 5.3 (b)). On the other hand, relative measurements can be conducted by using both reference and measurement beams simultaneously.

Each laser was fixed to a Thorlabs 6 degree-of-freedom (DOF) kinematic mount to obtain required orientation and position of the lasers. Kinematic mounts were attached to the measurement frame. As shown in Figure 5.1, two kinematic mounts were used in each plane, vertical (Y) plane and horizontal (X) plane, to enable absolute and relative measurements in two radial directions simultaneously. Accurate translational and angular positioning within $\pm 1\text{mm}$ and ± 5 degrees ranges, respectively can be achieved by using these kinematic mounts.

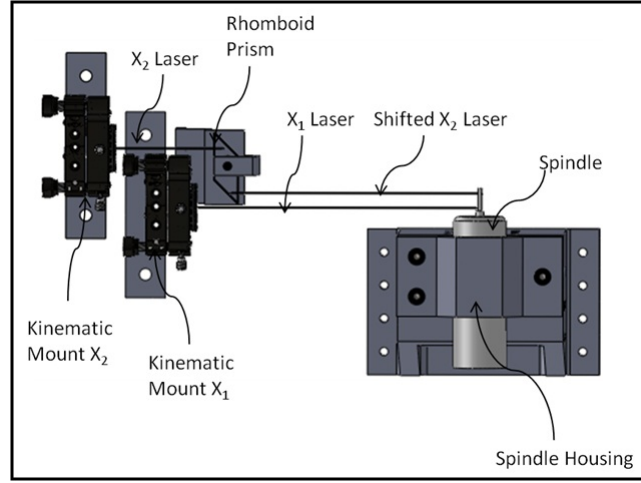


Figure 5.2: Staggered laser arrangement with a rhomboid prism to reduce the laser separation by laterally shifting the X_2 laser for relative measurement

Relative measurement of the vibration requires measuring the vibration from two axial positions of the cutting-tool. However, the minimum axial distance between two lasers on the same plane is limited to 45 mm because of the size of the kinematic mounts and laser objectives. This axial distance is larger than the preferred tool-overhang length. To enable LDV system conducting relative measurements, a rhomboid prism (with VIS 0 anti-reflective coating) was placed on each plane and the lasers were axially staggered using rhomboid prisms as shown in Figure 5.2. The minimum axial distance between two lasers was reduced to 10 mm by using rhomboid prisms.

In summary, an experimental set-up for comprehensive investigation of dynamic runout characteristics of miniature ultra-high speed spindles have been constructed. It is possible to conduct relative and absolute measurements by using this experimental facility. This thesis demonstrates the absolute measurements. However, relative measurements have to be performed for more detailed analysis.

5.1.2 Alignment of the lasers

Alignment of the lasers especially their mutually-perpendicular set-up is critical for enabling accurate measurement of the radial motions. A procedure developed at Carnegie Mellon University by Dr. Filiz et al was applied to accurately align the lasers [38]. The procedure is mainly based on the fact that two lasers are parallel to one another in the three dimensional space when they are normal to the same (reflective) place.

Since the maximum strength of the reflecting light can only be obtained when a surface is perpendicular to the incident light, it is crucial to check the perpendicularity of the lasers. First, perpendicularity of the lasers were assessed by checking the LDV strength indicator. Then, it was realized that BNC signal output of the controller gives more accurate results than strength indicator. The higher the output voltage is, the more accurate results are obtained. Although full strength indicator graph was obtained when the signal output was around 2 V, it was also possible to obtain signal output voltage of 3 V which provides more accurate results. In this section, full strength indicator means 3 V signal output.

This section explains the procedure for the perfect alignment of the lasers. For simplicity, alignment of only one set of lasers is introduced, but the simultaneous alignment of both sets can be completed by following steps included in this section.

The first step illustrated in Figure 5.3 is to attain a rough alignment/positioning of the lasers. The cutting tool for measuring vibrations is attached to the spindle. Since the surface quality of the cutting tool directly affects the measurement accuracy, many trials on harvey and seco tools concluded that each tool has different surface characteristics and it is not possible to obtain accurate measurement on all micro-cutting tools.

To be able to obtain accurate measurements on all cutting tools, different coating processes with different materials such as aluminum and silver have been tried. Although the surface quality of the shank section has been increased by using thermal evaporator and e-beam evaporator operations, these coatings caused imbalances of the cutting tool, which prevents accurate measurements. In this thesis, as a result of many trials, a 2-fluted seco micro-cutting tool with $400\text{ }\mu\text{m}$ diameter were used during the experiments (see Figure 5.3 (c)).

Subsequently, each of the four lasers or each of the measurement lasers, for relative and absolute measurements respectively, is aligned in both angular and axial directions using the kinematic mounts until the full laser strength (100 percent) is obtained (see Figure 5.3 (d)). In this step, it is more accurate to check the signal output of the each controller to have voltage output of 3 V rather than using only strength indicator. This step (see Figure 5.3) guarantees that each laser is perpendicular to the surface of the cutting tool.

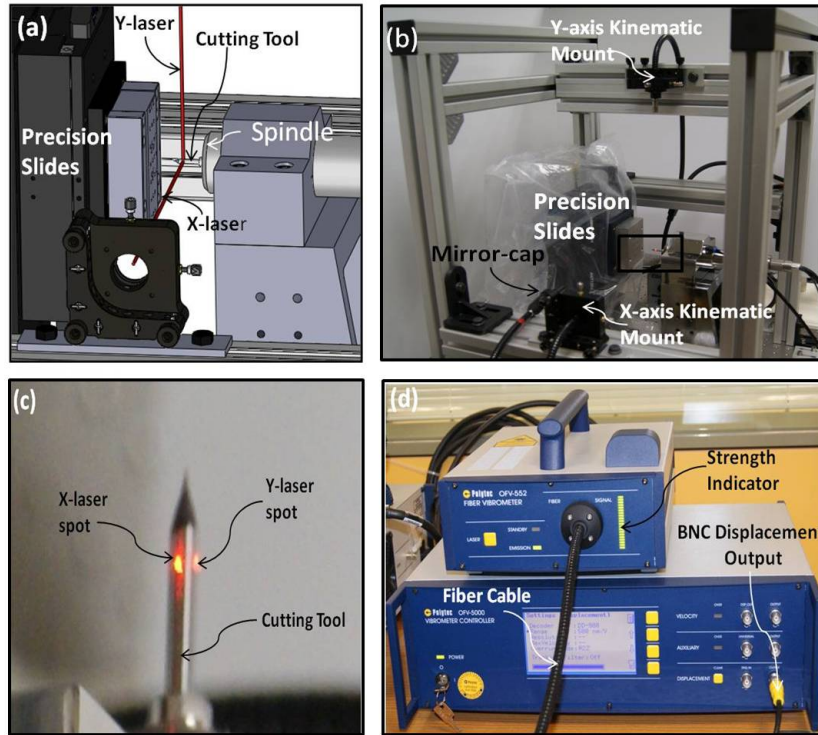


Figure 5.3: Rough alignment of the lasers on the cutting tool (a) 3D model of the rough alignment (b) Rough alignment of the lasers on the mMT (c) Zoomed on cutting tool (d) OFV-552 Vibrometer and OFV-5000 Vibrometer Controller.

Next, the fine alignment of the X laser (see Figure 5.4) was completed using a flat, aluminium-coated fused-silica mirror (25.4 mm diameter, $\lambda/10$ flatness at $\lambda = 633$ nm wavelength, and 10/5 scratch/dig), which is attached on a two-axis goniometer and a pentaprism (BK7 material, with MgF₂ anti-reflective coating on the entrance and exit faces, and aluminium coating on the reflective faces). As shown in Figure 5.4 (b), the pentaprism is attached to precision slides (Aerotech ANT130-XYZ, three-axis slides with 2 nm resolution) with designed clamp which is manufactured from ABS material using rapid prototyping machine.

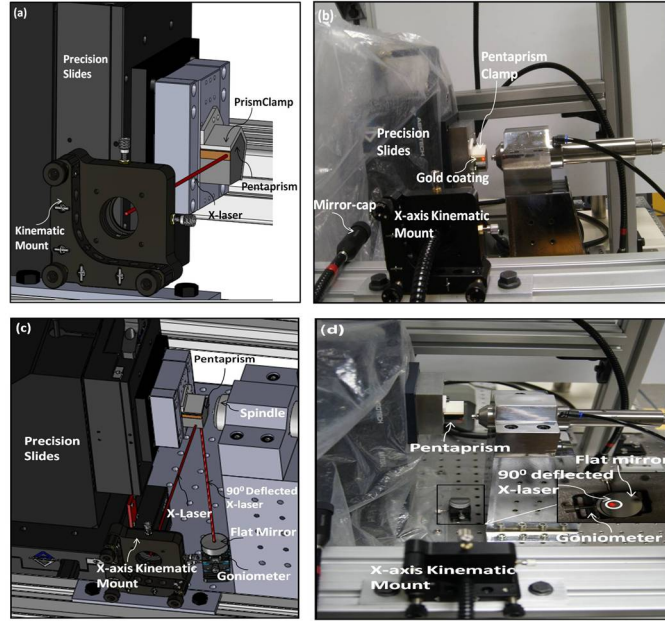


Figure 5.4: Fine alignment of the X-laser (a) 3D model of the focusing X-laser on the gold coating (b) Focusing X-laser on the gold coating on the MMT (c) 3D model of the 90° deflection of the X-laser (d) Deflection of the X-laser on to the flat mirror placed on a goniometer.

As seen in Figure 5.4 (c), the X-(horizontal) laser was turned on and targeted to the entrance face of a pentaprism. The pentaprism deflects the incoming light by 90 degrees with less than 1 arc-min tolerance, provided that the incoming light is normal to the entrance face. To enable the perpendicularity of the X-laser to the entrance face of the pentaprism, a portion of the entrance face is coated with gold approximately 50 nm thickness using thermal evaporator coating method. To achieve gold coating on BK7 material, first, 3nm chromium is coated on related surface. Then, laser was shined on the gold-coated surface.

Subsequently, angular adjustments were made to the laser using the kinematic mounts until the full strength was obtained from the strength indicator of the LDV, thereby establishing the perpendicularity of the laser to the entrance face. After this step, flat mirror attached to a two-axis goniometer was placed on the base and the precision slides were moved upwards (in Y direction) to allow the laser to shine on the uncoated portion of the pentaprism's entrance face (see Figure 5.4 (c)). The 90-degree deflected light is now incident on the surface of the flat mirror. The goniometer was then used to adjust the orientation of the mirror until the full strength is read from the strength indicator. Therefore, the 90-degree deflected X-laser became normal to the flat mirror.

The fine alignment of the Y-laser was completed next (see Figure 5.5). First, the pentaprism was moved away using the precision slides, enabling shining the Y-laser onto the flat mirror (see Figure 2.4 (d)). The kinematic mounts that control the Y-laser was adjusted until the LDV strength indicators showed the maximum strength, making the Y-laser perpendicular to the flat mirror. Therefore, since the Y-laser and the 90-degree deflected X-laser were perpendicular to the same surface, each pair of laser was mutually orthogonal.

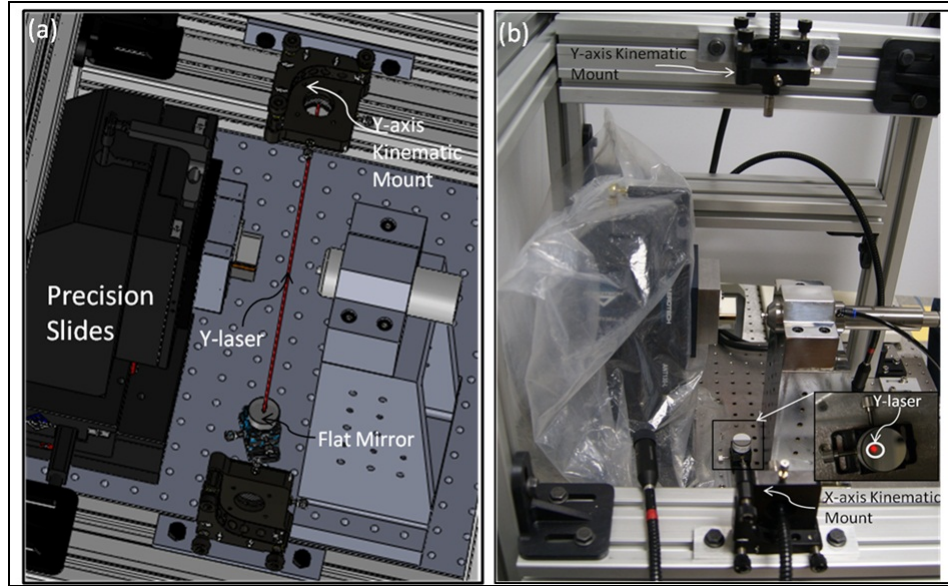


Figure 5.5: Fine alignment of the Y-laser (a) 3D model of the focusing Y-laser on the flat mirror placed on a goniometer (b) Focusing Y-laser on flat mirror on the MMT.

To ensure that two lasers are on the same (Z) plane (co-planar), the flat mirror/goniometers was replaced by a camera. The position of the Y -laser on the camera was first determined. The pentaprism was then brought back into position to enable reflecting the 90-degree deflected X-laser onto the camera. The Y -laser and 90-degree deflected X-laser were then shined onto the camera. Axial adjustments to the kinematic mounts were made until the lasers were shining on the same pixels of the camera. Therefore, the co-planarity of the lasers were established.

In this thesis, after performing the procedure described above an image processing technique was applied to obtain the angle between two lasers. First, the image of the lasers shining on a paper was obtained using a camera. Then, the image was loaded into MATLAB (see Figure 5.6) .

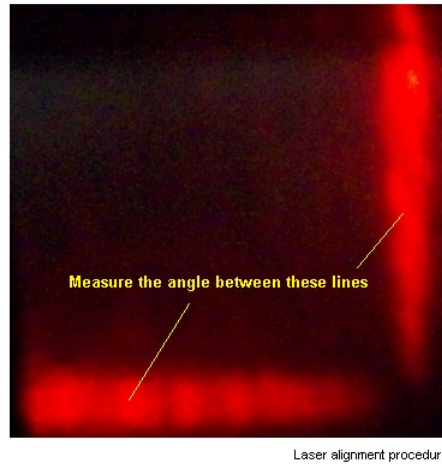


Figure 5.6: Image of the two lasers after alignment

Next, the image was converted into to black and white (see Figure 5.7 (a)) for subsequent extraction of the angle between them. Figure 5.7 (a) identifies the objects of interest and indicates them as black. To be able to obtain angle between these beams a line for each laser is fitted (see Figure 5.7 (b)) .

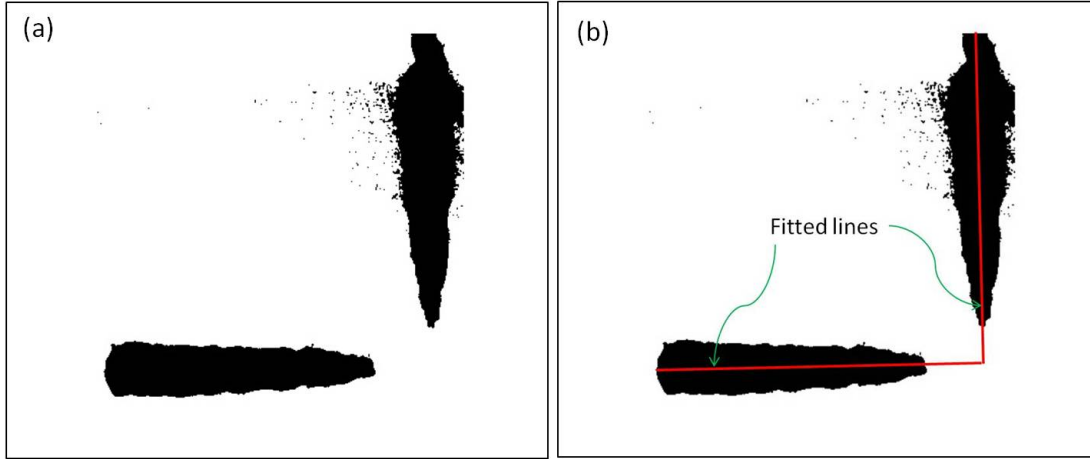


Figure 5.7: Line fitting on the laser images (a) Black and white image (b) Fitted lines on the pixels

Finally, the hough function available in image processing toolbox were used to obtain angle between lines (see Figure 5.8) . Fundamentally, the hough function implements the Standard Hough Transform (SHT) which uses the parametric representation of a line given in equation 5.1. In this equation, rho is the distance from the origin to the line along a vector perpendicular to the line and theta is the angle of the perpendicular projection from the origin to the line measured in degrees clockwise from the positive x-axis.

$$\rho = x * \cos(\theta) + y * \sin(\theta) \quad (5.1)$$

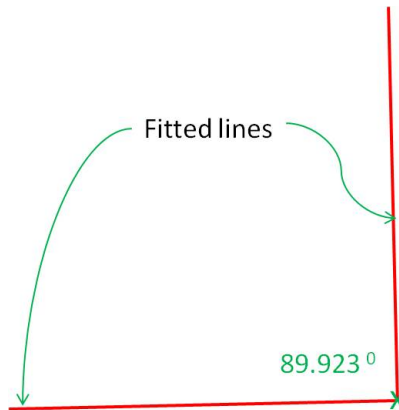


Figure 5.8: Image processing result for the angle between two lasers

5.1.3 Runout measurements

A miniature UHS ceramic bearing electrical spindle with a maximum speed of 50,000 rpm was tested in this section. The constructed experimental facility and the laser alignment procedure discussed in the previous part were applied during the experiments. The runouts were determined for speeds from 1,000 to 50,000 rpm at 5,000 rpm intervals to study the effect of spindle speed. For simplicity, only absolute measurements were conducted. Measurement lasers (black ones) were used and reference lasers (red ones) were placed in the mirror-caps. Each measurement laser was first aligned using the approach outlined above. The spindle was then rotated at the required spindle speed. During the initial operation, to ensure the thermal effects are minimized, the spindle was run for 10 minutes before the measurements are conducted. The 3 runout measurements were conducted for 10 mm overhang length to show the repeatability of the process.

To obtain accurate measurements at the rotational frequency and its harmonics, the measurement system must possess a high frequency bandwidth (commonly above 100 kHz). To enable accurate measurements and provide a virtual environment for the further advanced experiments which require very high sampling frequency and faster processing time, field-programmable Gate Array (FPGA) technology was adapted to the designed MMT. National Instruments PXI-7854R data acquisition card which is FPGA programmable with the LabVIEW FPGA Module was used during the experiments. It has 750 kHz sampling frequency and simultaneous measurement capability.

To be able to use FPGA technology, it is necessary to build a virtual data acquisition card which provides connection between computer and devices. Using this virtual data acquisition card, a host.vi which processes real experiments can be run. In this thesis, two types of virtual data acquisition card were prepared. First, a virtual environment which only gathers data from the devices was prepared (see Figure A.1). Then, a general virtual data acquisition card which includes both analog inputs and outputs was built (Figure A.1). It is suggested to use the first one if there is no analog outputs during the experiments because in the case of latter virtual data acquisition card, a portion of the capacity of

the card is allocated for the outputs, which affects the analog input portion adversely in terms of process time. Therefore, during the runout experiments the first virtual data acquisition card was used.

Subsequently, host.vis for both data acquisition card was prepared. Figure A.3 shows the data acquiring host.vi and Figure A.4 shows a general block diagram for both analog inputs and analog outputs. It is important note that FPGA module processes integer binary data. Therefore, while preparing the general block diagrams for analog input and analog output, it is significant to convert binary data into voltage and voltage into binary data for analog inputs and analog outputs, respectively. Since runout measurement requires only acquiring data, the first host.vi shown in Figure A.3 were used during the experiments.

After preparing the general data acquiring block diagram, the experimental block diagram for acquiring runout motions in two radial directions was build by adding some additional blocks to the general data acquiring block diagram (see Figure B.1). The front panel of this block diagram (see Figure B.2) was also designed for the users. In this block diagram, the constant 0.5 represents the sensitivity of the displacement decoder. 500 nm/V was selected during the measurements. To be able to obtain results in terms of microns, the coming voltage was multiplied with 0.5. During the experiments, the sampling frequency was specified as 500 kHz. Finally, the X and Y runouts (see Figure 5.9) were obtained using the designed block diagram which uses FPGA technology.

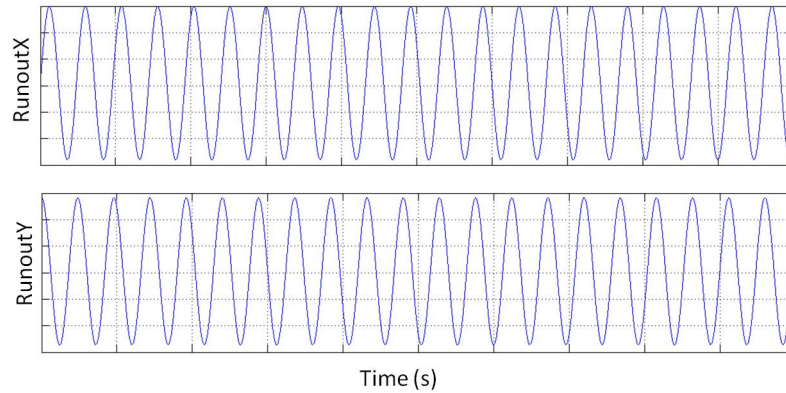


Figure 5.9: Raw X and Y runouts from the lasers

The average of the measured data depends on the reset time of the lasers, and therefore is not necessarily equal to zero. Furthermore, it is necessary to use same number of revolutions (100 revolutions) for different spindle speeds during data analysis, so the x-axis limit is determined by the spindle speeds.

Subsequently, the data analysis of the raw data was conducted. First, these runout measurements were combined to create the polar plot given in Figure 5.10. It is clear that this polar plot is not a centered plot because the average of the measured data is not zero.

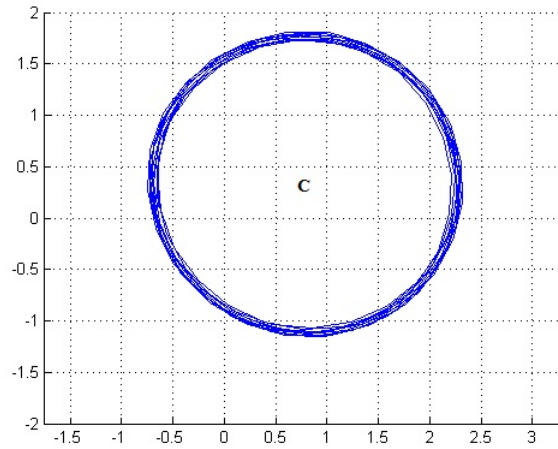


Figure 5.10: Data converted to polar coordinates

Next, frequency domain analysis were conducted to obtain centered total runout, synchronous runouts, which are periodic with the spindle frequency and its harmonics, and asynchronous runouts, which occur at non-harmonics of the rotational speed. During the frequency domain analysis, fast fourier transformation (fft) function of the MATLAB was used to obtain frequency domain representation of each X and Y runout and, inverse fast fourier transformation function (ifft) of the MATLAB was used to reform new time domain signals based on the frequency domain representation of each X and Y runout. Total runout errors (see Figure 5.11 (a)) including both synchronous and asynchronous runouts were obtained by eliminating the DC component obtained in the frequency domain. Since the DC component in the frequency domain is the reason of shifting the measurements and having non-zero mean signals, the new signals eliminating the

DC component was formed using IFFT function, which enables to obtain centered total runouts. Similarly, synchronous runouts shown in Figure 5.11 (b) were obtained using only spindle frequency and its harmonics and asynchronous runouts shown in Figure 5.11 (c) were obtained using non-harmonics of the rotational speed.

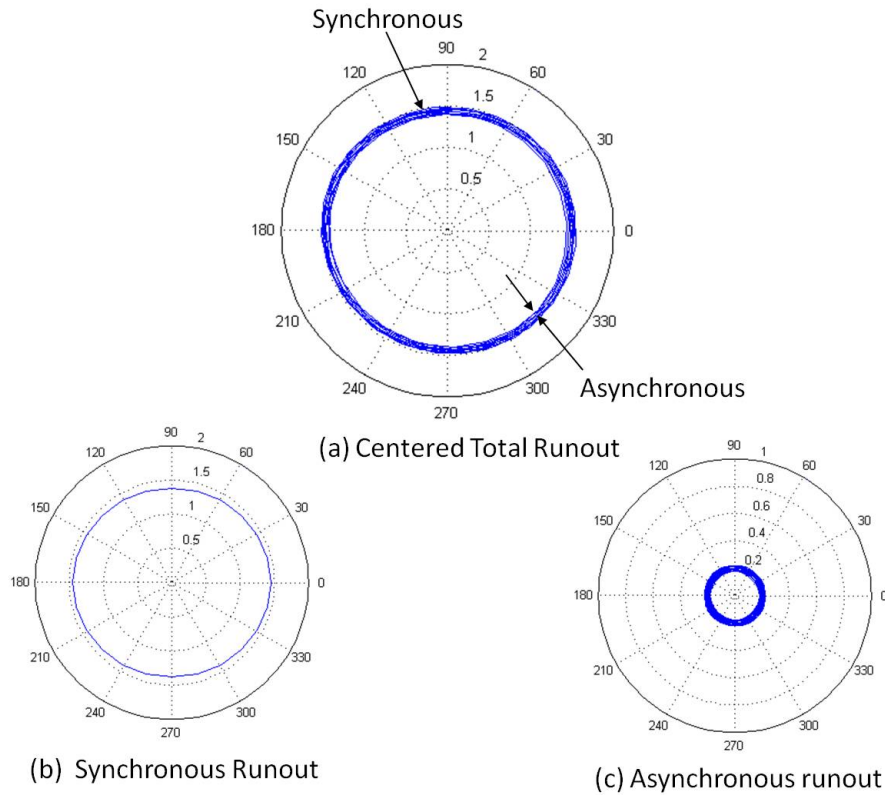


Figure 5.11: Steps in frequency domain analysis (a) Centered data in polar coordinates (b) Synchronous runout calculated by using spindle harmonics (c) Asynchronous runout calculated using non-harmonics of rotational speed

Data analysis described above uses both time domain and frequency domain analysis to obtain accurate runout motion characteristics. So, following the alignment procedure developed at Carnegie Mellon university and data analysis described above runout motion errors of the miniature ultra high speed ceramic bearing electrical spindle were obtained. Figure 5.12 - 5.14 give the polar plots of the total and synchronous runouts at three different spindle speeds and all runout measurement results for one measurement are presented in Appendix C.

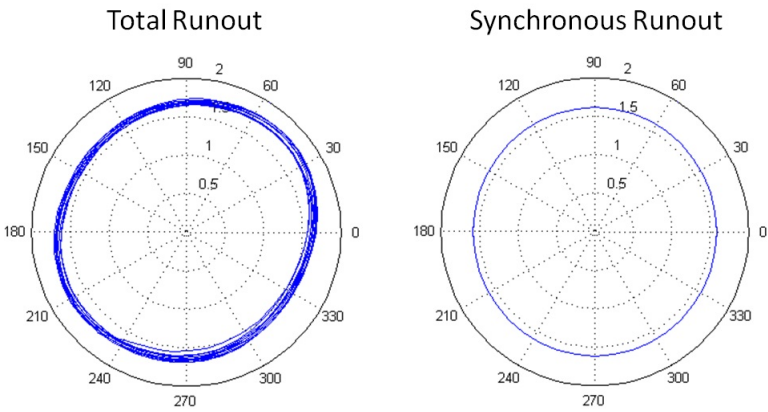


Figure 5.12: Radial runout results for 15,000 rpm

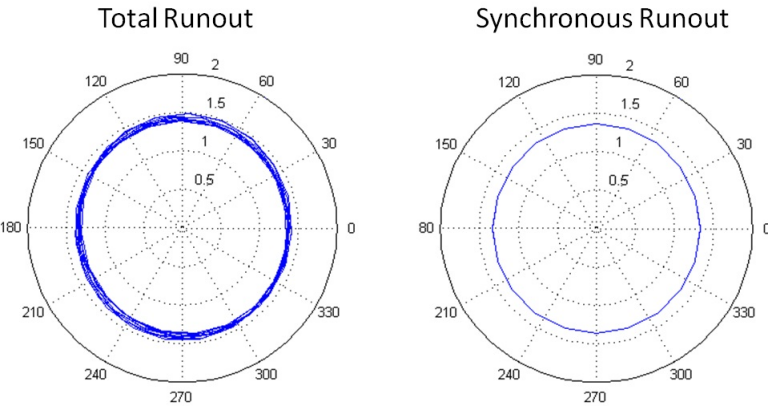


Figure 5.13: Radial runout results for 30,000 rpm

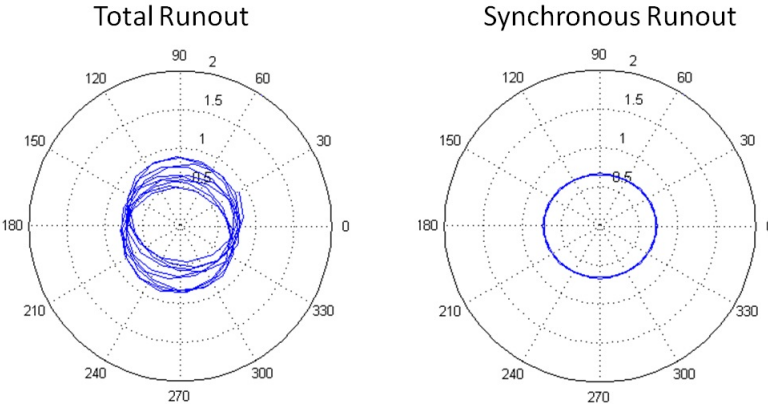


Figure 5.14: Radial runout results for 45,000 rpm

The runout measurement results show that nature of runout motions changes considerably with the spindle speed in terms of both magnitude and shape. The possible reason for this behaviour is speed-dependent characteristics of ceramic bearings and mechanical structures.

To ensure that the results are accurate and , the described alignment method and data analysis procedure are repeatable, three different measurements on the same cutting tool with same overhang length were obtained. Figure 5.15 illustrates the results of repeatability measurements and gives the average synchronous runouts as a function of spindle speed. It is seen that the average synchronous runout reaches a peak of $1.62 \mu\text{m}$ at about 15,000 rpm spindle speed. The minimum runout of $0.5 \mu\text{m}$ was seen at 50,000 rpm. Although these results seem to be very low, it is because the spindle under test was unused. Knowing these values provide great advantage for checking the performance of the spindle in the future. Similar experiments can be conducted in the future and the results can be compared with the results obtained in this thesis to decide on the failure of the spindle. Furthermore, these synchronous runouts are important to obtain accurate vibration and force models for micro-machining. Since there is a coupling effect between machining forces and machining vibrations, these runout motions must be taken into account for more accurate models.

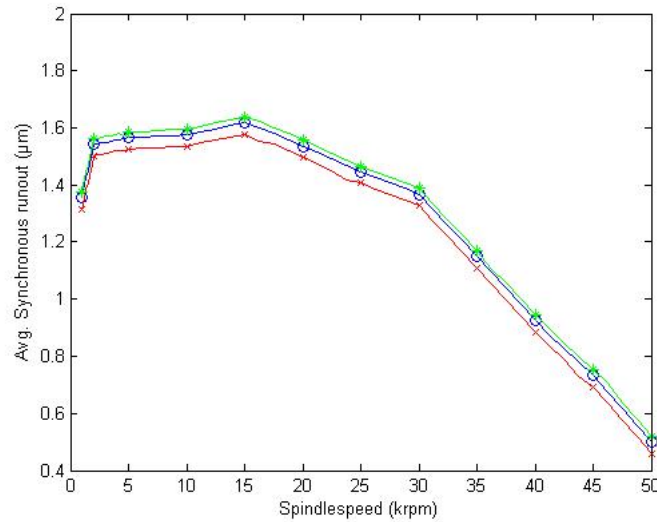


Figure 5.15: Spindle speed average synchronous runout errors relationship

Repeatability measurements show that the maximum variation is 2 % of the average synchronous runout and the measurements are highly repeatable. It is also important to note that during these three measurements 89.923° , 90° and 89.867° angle between lasers was obtained as a result of image processing. The interesting thing was that the last angle was obtained just after the rough alignment procedure and the rest of the procedure was not followed except the last step which includes only translational motions to ensure that lasers are coplanar, so it can be said that image processing can be used not only to verify the alignment procedure but also to check whether the angle between lasers is in the acceptable range in the first step of the alignment procedure, which may save many time and effort.

In addition to synchronous runout and spindle speed relationship, asynchronous runout stemming from non-harmonics of the rotational motion was obtained as a function of spindle speed. Figure 5.16 gives the speed-dependent asynchronous runout.

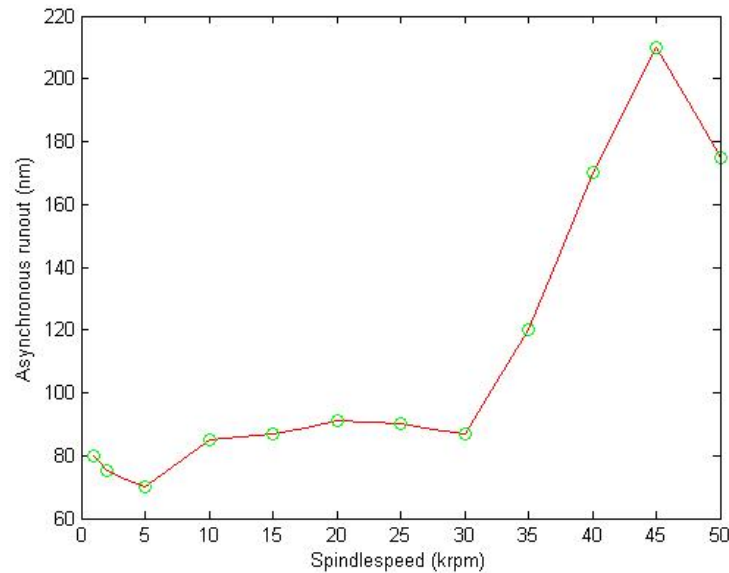


Figure 5.16: Spindle speed asynchronous runout errors relationship

It is seen that the magnitude of asynchronous runout increases considerably at high speeds and becomes very important between 40,000 rpm and 50,000 rpm, where the synchronous runout error is minimum. It is also clear in Figure C.10-

C.12 that the thickness corresponding to asynchronous runout increases too much between 40,000 rpm and 50,000 rpm and reaches to maximum (210 nm) at 45,000 rpm.

Finite element analysis conducted in chapter 3 indicated that the mechanical structures are critical between 40,000 and 50,000 rpm since they have natural frequencies at these rotational speeds. Runout measurements showed that asynchronous runouts become significant between 40,000 and 50,000 rpm. Considering both finite element simulations and runout measurements, it may be concluded that the reason for increasing asynchronous runout is the fundamental vibration frequencies of the mechanical structures and their speed-dependent characteristics. In order to verify this conclusion and investigate the speed dependent dynamics of mechanical structures, experimental modal analysis is required. Following chapter presents experimental modal analysis of the mechanical structures.

5.2 Experimental Modal Analysis

The natural frequencies of the mechanical structures were identified numerically during the design stage. However, since computer programming alone cannot determine the complete dynamic behaviour of structures, to better understand a structural vibration problem, it is also necessary to characterize the resonance of a structure experimentally [60]. Experimental modal analysis is the common method to identify the dynamic characteristics of a mechanical structure.

In this section, the dynamics of the mechanical structures is acquired at different spindle speeds in terms of frequency response functions. Since it is known that dynamic response of the spindle changes with spindle speed, to accurately determine the baseline dynamics of the machine, first, it is necessary to obtain the dynamics of the mechanical structures in its steady-state. Experimental modal analysis based on impulse testing is conducted to obtain the inertance-ratio of output acceleration to input force (A/F)- FRFs of the mechanical structures both in steady-state and at different spindle speeds.

5.2.1 Experimental Set-up

To perform the impact testing of the structures designed in Chapter 3, impulse excitations are supplied to the mechanical structures using a 086C03 model PCB impact hammer which has 2.288 mv/N sensitivity. In the experimental modal analysis, a 352C68 model accelerometer was used to measure response at a single fixed point. Both impact force application and vibration measurements were conducted on top of the clamp.

The frequency content of the energy applied to the mechanical structures is a function of the stiffness of the contacting surfaces and, to a lesser extent, the mass of the hammer. The stiffness of the contacting surfaces affects the shape of the force pulse, which in turn determines the frequency content. It is not feasible to change the stiffness of the test object, therefore the frequency content is controlled by varying the stiffness of the tip of the hammer. The harder the tip, the shorter the pulse duration and thus the higher the frequency content. It is better to have higher frequency range excitations especially for micro-machining since higher rotational speeds are acquired. Therefore, during the experiments the steel tip which has the highest stiffness among the tips that are available was utilized.

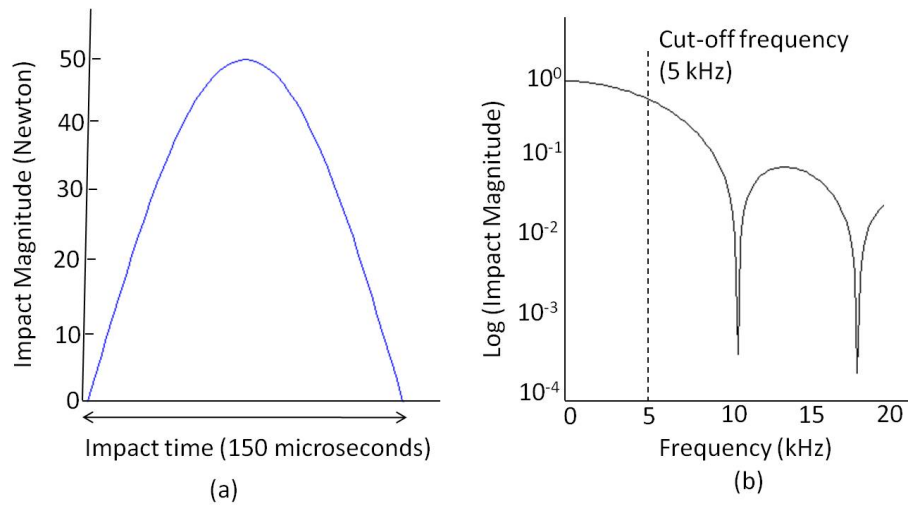


Figure 5.17: Cut-off Frequency (a) Impact force time history (b) Frequency spectrum of a typical impact

To ensure the effectiveness of hammer impact tests, the frequency range of impact must be examined. Figure 5.17 shows a impact data obtained using the 086C03 model PCB impact hammer in the time domain and frequency domain. It is seen that an excitation bandwidth of 5 kHz can be attained through impact hammer tests.

Next, PXI-7854R data acquisition card and LABVIEW 2010 were used to acquire time domain input and response measurements. The block diagram shown in Figure B.3 was used to obtain time domain signals. As shown in impact test block diagram, the sampling frequency was selected as 500 kHz and sensitivities of the instruments were not considered in the block diagram. During the post-processing, the acquired force and acceleration measurements in terms of voltage were multiplied by their sensitivities to transform them into newton and m/s^2 , respectively and frequency domain calculations were done in MATLAB.

5.2.2 Frequency Response Function Calculations

The FRF describes the input-output relationship between two points on a structure as a function of frequency, as shown in Figure 5.18 (b). Since both force and motion are vector quantities, they have directions associated with them. Therefore, an FRF is actually defined between a single input DOF and a single output DOF. It is a fundamental measurement that isolates the inherent dynamic properties of a mechanical structure. Experimental modal parameters (natural frequencies, damping constants and mode shapes) are also obtained from a set of FRF parameters using convenient curve fitting processes.

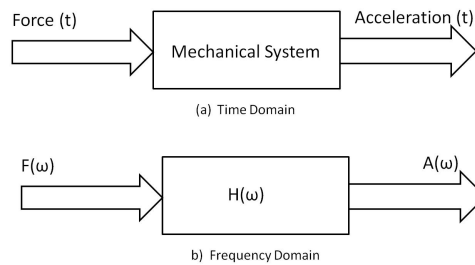


Figure 5.18: Block Diagram of an FRF (a) Time Domain (b) Frequency Domain

Mathematically, as indicated in Figure 5.18 (b), FRF is defined as the ratio of Fourier Transform of an output response to ($A(\omega)$) the Fourier transform of the input force ($F(\omega)$) (see equation 5.2).

$$H(\omega) = \frac{A(\omega)}{F(\omega)} \quad (5.2)$$

Time domain measurements shown in Figure 5.18 (a) are significant to obtain accurate FRFs. It is necessary to obtain input force and response (acceleration) in a suitable manner to ensure that the calculations in the frequency domain will not be affected from the errors stemming from time domain measurements. Therefore, after the time domain measurements are obtained, they cannot be used directly.

Most commonly, exponential windowing is applied to eliminate the leakage in the response function. However, in this research, since the time record length is sufficiently long enough to capture the complete response time history of the response signal, there is no necessity for exponential windowing. Optimally, the response channel time history should decay to zero at the end of the analyzer's time record. This is preferred because no special signal processing windows need to be applied to the response channel. This results in a very accurate measurement that has no leakage errors or distortion caused by signal processing. Impact force results should be also examined to guarantee that there is no double impact measurement and it is almost zero just after having half sinus impact. Consequently, in the time domain, the impact force (see Figure 5.19 (a)) and acceleration (see Figure 5.19 (b)) were acquired accurately.

Then, to check the quality of the measurements, the magnitude of squared coherence between input and output were calculated using the equation 5.3. The magnitude squared coherence estimate is a function of frequency with values between 0 and 1 that indicates how well input corresponds to output at each frequency and it is a function of the power spectral densities (P_{FF} and P_{AA}) of force and acceleration and the cross power spectral density (P_{AF}) of force and acceleration. If coherence value is less than 0.8 for any frequency, it was indicated

as poor coherence and those measurements were not used during the experiments.

$$C_{AF} = \frac{|P_{AF}|^2}{P_{FF}P_{AA}} \quad (5.3)$$

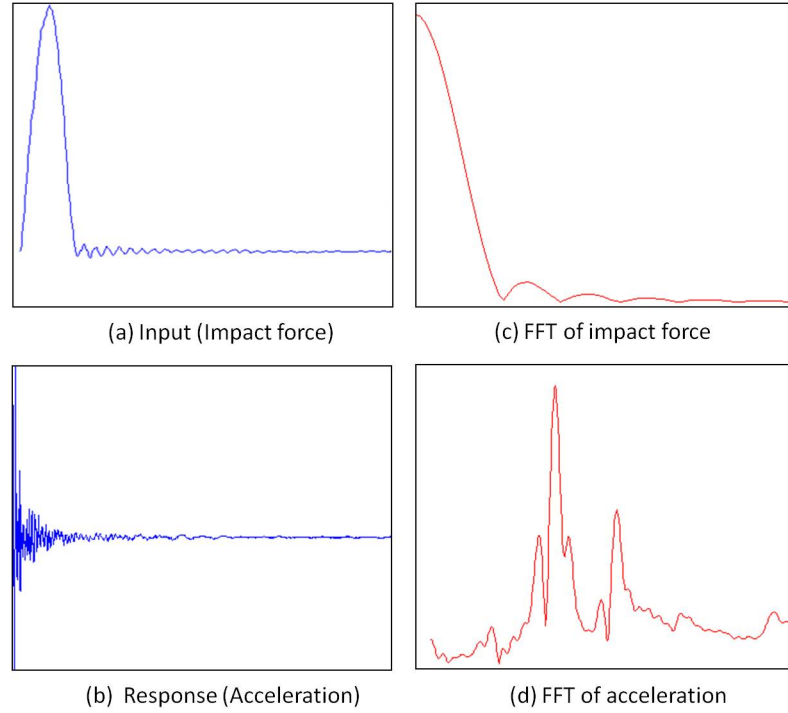


Figure 5.19: Dataprocessing (a) Impact force time history (b) Acceleration Time History (c) Impact force frequency domain magnitude (d) Acceleration frequency domain magnitude

Getting the accurate time domain input and output data makes the process ready for frequency domain analysis. In the frequency domain, first, fast fourier transformations of impact force ($F(\omega)$) (see Figure 5.19 (c)) and acceleration ($A(\omega)$) (see Figure 5.19 (d)) are obtained. Both $F(\omega)$ and acceleration $A(\omega)$ are complex functions with real and imaginary components. Next, using the real and imaginary components of input and output, real (equation 5.4) and imaginary (equation 5.5) parts of frequency response function are calculated.

$$FRF_{real} = \frac{Real[(A(\omega))]}{Real[F(\omega)]} \quad (5.4)$$

$$FRF_{imag} = \frac{Imag[A(\omega)]}{Imag[F(\omega)]} \quad (5.5)$$

Using the imaginary and real parts of the frequency response functions, magnitude (equation 5.7) and phase (equation 5.7) of the frequency response function can be calculated.

$$Magnitude = \sqrt{FRF_{real}^2 + FRF_{imag}^2} \quad (5.6)$$

$$Phase = \tan\left(\frac{FRF_{imag}}{FRF_{real}}\right) \quad (5.7)$$

Using the procedure described above, the frequency response functions are represented in terms of magnitude and phase. Next section presents the experimental investigations of natural frequencies of the mechanical structures when they are in the steady-state and compares the results with the finite element simulations conducted in Chapter 3.

5.2.3 Natural Frequencies (Experimental and Numerical)

The measured FRFs, obtained from multiple tests (10), were averaged to obtain the dynamics of the mechanical structures at steady-state. The averaging process is necessary to reduce the statistical variance of the measurement and also reduces the effects of nonlinearities. Figure 5.20 presents the frequency response function of the mechanical structures in terms of logmagnitude and phase in the operating frequency range (0-2,500 Hz) to determine the critical frequencies where a small amount of input force can cause a very large response. This is clearly evident from the narrow peaks in the FRF. When a peak is very narrow and high in value, it is said to be a high resonance.

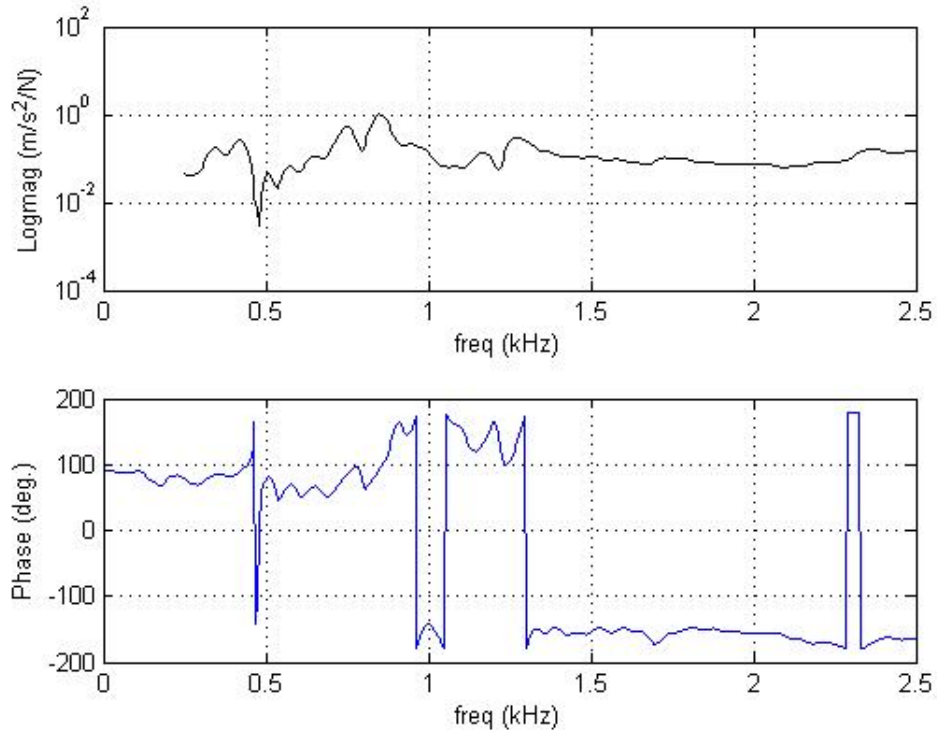


Figure 5.20: Average frequency response function measurements for 2500 Hz frequency range

The steady state frequency response function measurement indicate that the the fundamental corresponding frequencies occur around 845 Hz where the magnitude is maximum. However, since the peaks are not very narrow to identify clearly, linear scale frequency response function was plotted for the mechanical structures. Figure 5.21 represents the magnitude of the frequency response function as a function of the spindle speed. It is seen that there are 2 critical rotational speeds in the frequency of interest 45,000 rpm (750 Hz) and 51,000 rpm(850 Hz). On the other hand, finite element simulations have indicated those first two frequencies as 699.59 kHz and 827.91 kHz. The difference between simulations and experiments are significantly less when the rigid structure assumption in the simulations are considered. When both experiments and simulations are considered it can be said that the rotational speeds between 40,000 rpm and 50,000 rpm should be avoided during machining.

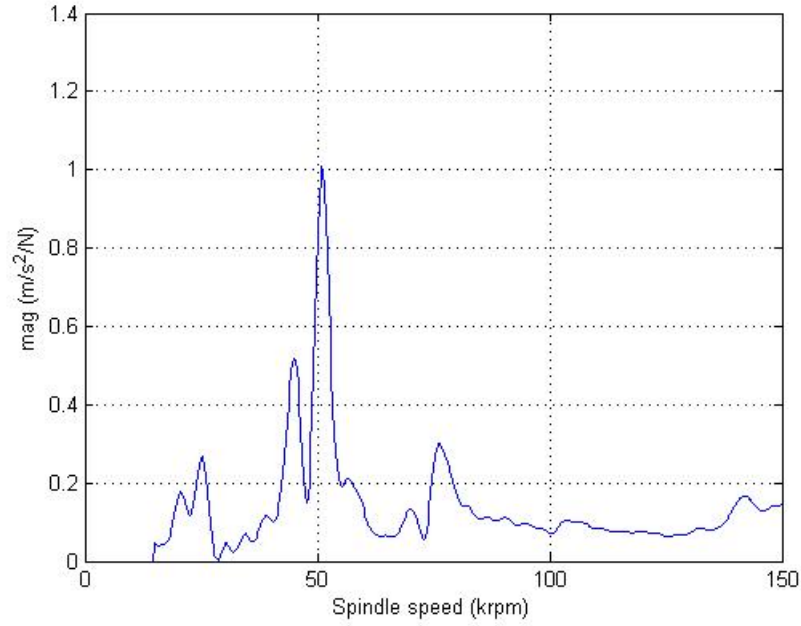


Figure 5.21: Steady state frequency response magnitude in linear scale

Calculated FRFs can be used to obtain modal parameters using a convenient curve fitting method. Since omitting higher frequency modes during curve fitting does affect the accuracy of the modal fit, particularly the real part of the FRF, it is necessary to obtain frequency response measurements up to the cut-off frequency. Figure 5.22 presents the steady state frequency response function measurement of the mechanical structures up to 5 kHz frequency range.

When the frequency response measurement for larger frequency range is investigated, it is seen that narrower and higher magnitude peaks are between 3000 Hz and 3750 Hz. It was also concluded as a result of the finite element simulations. 3195 kHz, 3419 kHz and 3635 kHz are the three fundamental frequencies of the mechanical structures that were acquired as a result of finite element simulations. It is clear that both simulations and experiments suggest to avoid same frequency range of 3000 Hz and 3750 Hz, which can be important when two-fluted cutting tool is used.

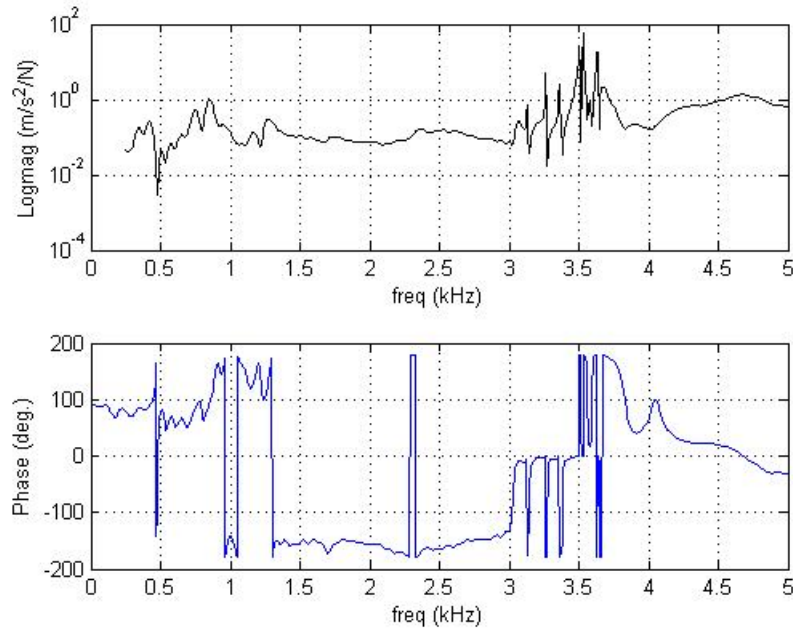


Figure 5.22: Average frequency response function measurements for 5000 Hz frequency range

5.2.4 Speed Dependent FRFs

The dynamic behaviour of spindles has significant effect in quality and stability (against chatter) of machining operations, so it is also necessary to observe the stiffness and damping characteristics of spindles with varying spindle speed. It is not possible to take into spindle rotation account during the finite element simulations. On the other hand, impact testing can be conducted while spindle is rotating at different spindle speeds to investigate the effect of rotation on the dynamics of the mechanical structures.

In this section, speed dependent characteristics of the mechanical structures were acquired from 2,000 to 50,000 rpm at 2,000 rpm intervals. The similar FRF calculations procedure described in the previous section was applied but the only difference was the acquired time domain response. As shown in Figure 5.23, the response has a part stemming from the rotating mass imbalance of the rotating spindle parts. In order to investigate the effects of this part, frequency response

functions of the mechanical structures were obtained at different spindle speeds and the results are presented in Appendix D.

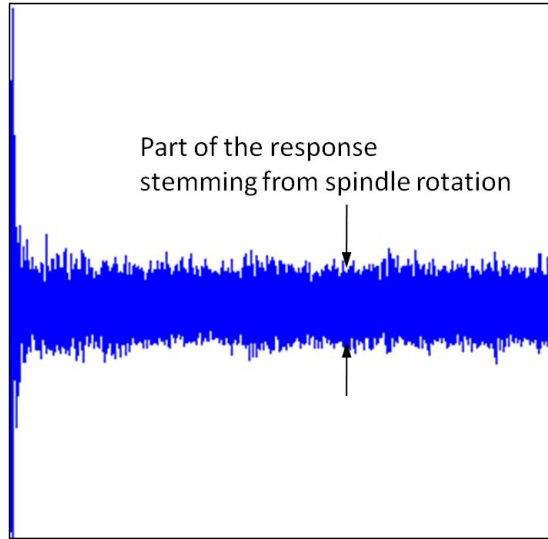


Figure 5.23: Typical response while spindle is rotating

The frequency response measurements indicate that the resonance peaks change while the spindle is rotating and the maximum peaks occur when the spindle speed is around 16,000 rpm (see Figure 5.24 (a)) and 45,000 rpm (see Figure 5.24 (b)).

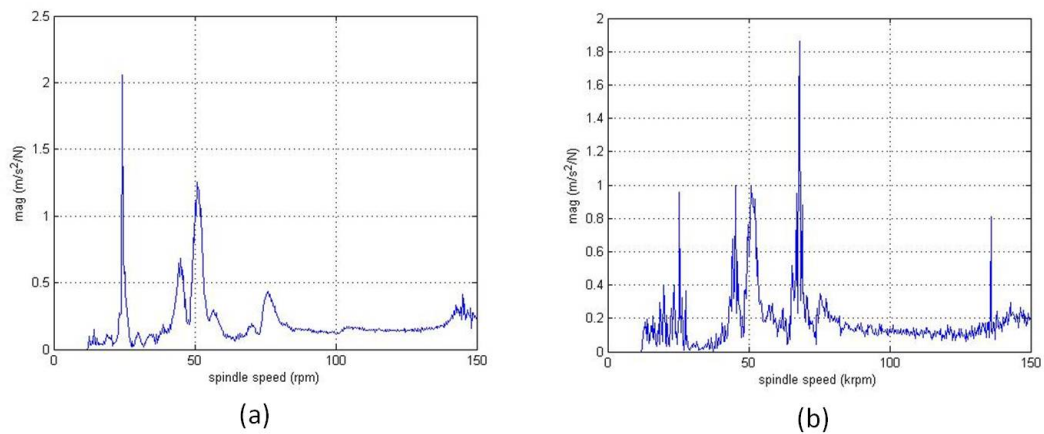


Figure 5.24: Linear frequency response functions for (a) 16,000 rpm (b) 45,000 rpm

According to runout measurements, the spindle has a natural frequency around 15,000 rpm which corresponds to 250 Hz. The speed-dependent FRFs showed that the maximum response of about $0.35 \mu\text{m}/\text{N}$ was obtained around 24,000 rpm (400 Hz) while the spindle is rotating at 16,000 rpm. The 150 Hz difference can be arising from the dynamics of mechanical structures. In addition, it was also clear that vibration amplitude of the mechanical structures grows between spindle speed of 40,000 and 50,000 rpm which is the primary reason for asynchronous runout shown in Figure 5.16.

In conclusion, like finite element simulations, experiments performed on spindle concluded that selection of the spindle operation frequency at certain speeds is challenging for miniature ultra high speed ceramic bearing electrical spindle. It was suggested to avoid two different spindle speed ranges (15,000- 25,000 rpm and 40,000-50,000 rpm) in order to prevent vibration related inaccuracies. This experimental data can be used as a machine operation frequency selection guide and further improvements can be achieved using this guide.

Chapter 6

Summary and Conclusions

This thesis demonstrates the development of a 3-axis miniature machining center, the performance evaluation of its micro-milling processes and characterization of its dynamic behaviour.

In this research, a 3-axis miniature machine tool testbed was designed and developed using precision three-axis positioning slides (2 micrometers positioning accuracy, 10 nanometers positioning resolution, 60 mm x 60 mm x 60 mm workspace), miniature ultra high speed spindles (a miniature UHS ceramic bearing electrical spindle with maximum 50,000 rpm and a miniature UHS air bearing air turbine spindle with maximum 160,000 rpm), a miniature force dynamometer, and a microscope. Based on the experimental study on the test-bed, performance evaluation of the developed MMT was achieved particularly focusing on its dynamic behaviour.

Micro-milling was proposed as a novel method for fabricating three dimensional PMMA and PLGA polymer micro-needles. Due to the lack of knowledge in micro-machinability of polymers, the micro-machinability of PMMA and PLGA polymers was investigated experimentally to study the parameters (cutting speed and feed) that influence the quality of the machined components. During the micro-machinability study, a group of 3 mm length and 100 μ m depth slots using 50,000 and 100,000 rpm spindle speeds with different feedrates (5, 10, 15, and 20

$\mu\text{m}/\text{flute}$) were machined. It was concluded that PLGA has better machinability than PMMA. A parametric study concluded that 50,000 rpm spindle speed gave better results than 100,000 rpm spindle speed for both burr formation and surface roughness. In addition, during PMMA machining, melting problem was observed at spindle speeds above 50,000 rpm. The 20 $\mu\text{m}/\text{flute}$ feedrate led to the least amount of burr formation, and the feedrate of 5 $\mu\text{m}/\text{flute}$ resulted in minimum surface roughness. Based on the parametric study, micro needles were machined using the 50,000 rpm spindle rotational speed and the 20 $\mu\text{m}/\text{flute}$ feedrate to minimize burr formation. Repeatable manufacturing PMMA and PLGA polymer micro-needles with different geometries were achieved to demonstrate the capabilities of the developed miniature machine tool. During this study, bending of the PLGA pillars due to machining forces, which causes dimensional errors, was observed. Thus, it was suggested to investigate the MMT vibrations which alter the machining forces to reduce these errors.

Dynamic characteristics of the developed MMT were investigated to address the deterioration of the output quality due to vibrations stemming from machining forces and high-speed-rotations. MMT vibrations particularly focusing on the spindle dynamics were investigated experimentally using runout measurements and experimental modal analysis techniques. The results were compared with those from the three-dimensional finite element simulations. Investigation of miniature ultra-high speed spindle dynamics concluded that the developed MMT is convenient for accurate applications of micro-machining using air-turbine air bearing spindle. However, the selection of the operation frequencies at certain spindle speeds for electrical spindle is challenging with this design because most of the critical natural frequencies of the developed MMT appear in the operating frequency range of electrical spindle (1-50,000 rpm).

Runout measurements performed on the miniature ultra-high speed ceramic bearing electrical spindle using two laser doppler vibrometer (LDV) systems showed that both magnitude and shape of the runout errors vary considerably with spindle speed. A peak of 1.62 μm synchronous runout was observed at 15,000 rpm. Asynchronous runout errors become significant between spindle speeds of 40,000 and 50,000 rpm and reach to maximum of 0.21 μm at 45,000 rpm. On

the other hand, experimental modal analysis using an impact hammer and accelerometer was conducted to obtain both the steady-state and speed dependent frequency response functions (FRFs) of the mechanical structures. Steady state FRFs indicated that 750 Hz and 850 Hz are two important natural frequencies for successful application of micro-machining. Compared to the three dimensional finite element simulations, there is 7 % difference for the first mode and 3 % difference for the second mode. Furthermore, experimental modal analysis conducted at different spindle speeds concluded that natural frequencies of the mechanical structures change significantly depending on spindle speed. Speed-dependent FRFs showed that the maximum response of about $0.35 \mu\text{m}/\text{N}$ is obtained while the spindle is rotating at 16,000 rpm but the peak occurs at 24,000 rpm (400 Hz). In addition, the vibration amplitude grows significantly between the spindle speed of 40,000 rpm and 50,000 rpm. In conclusion, experiments and finite element simulations provided a machine operation frequency selection guide. It was suggested to avoid two different spindle speed ranges (15,000- 25,000 rpm and 40,000-50,000 rpm) to prevent vibration related inaccuracies.

Overall, development of a 3-axis miniature machine tool was accomplished. Its performance evaluation was conducted by fabricating PLGA and PMMA polymer micro-needles with different geometries successfully. Dynamics of the developed MMT particularly focusing on the spindle side was investigated to provide experimental data for further improvements in the output quality of the process. The experimental investigation of MMT vibrations conducted in this thesis can also be used as a methodology for other researchers who work on micro machining vibrations.

Chapter 7

Future work

The developed MMT and experimental study performed on this MMT can be used for mechanical micro-machining research in the future. Optimization studies in micro-milling processes can be performed using the developed MMT. In addition, in order to prevent undesired effects of vibrations, stability studies and vibration control during micro-machining can be achieved using the experimental data obtained in this thesis.

The output quality of the final product manufactured on the developed MMT can be further improved based on the experimental data obtained in this thesis. The machining strategies for manufacturing micro-needles can be optimized to improve the dimensional stiffness and surface roughness of the machined parts. In addition, further improvements in micro-needle machining can be achieved by using electrical spindle and utilizing the operation frequency selection guide presented in this work. The presented guide can also be used to avoid vibration related inaccuracies during machining of any materials. Considering the dynamic analysis results, structural modification may also be performed to improve the performance of the developed MMT.

Experimental data obtained in this study can also be used in stability studies for micro-machining processes. Parameters for the highest productivity without causing instability can be selected using tool point dynamics in the miniature machine tools. Tool point dynamics of a machine tool is obtained by coupling the frequency response functions of the cutting tools and spindle side. Using the obtained frequency response functions of the spindle side in this thesis and 3D models of cutting-tools, the complete tool point dynamics of miniature machine tools can be obtained and stability limits of the machining processes can be investigated.

During the impact tests of the mechanical structures, it was realized that the maximum impact force may reach to 200 N peak value when a conventional hammer is used, which may damage the spindle when the tests are conducted on the spindle. Since the force is an impulse, the amplitude level of the energy applied to the structure is a function of the mass and velocity of the hammer. Since it is difficult to control the velocity of the hammer, the force level is usually controlled by varying the mass, which is not so effective method for impact testing of miniature spindles. Therefore, a mechanical set-up can be designed to control the velocity of the hammer.

The experimental modal analysis can be conducted on the cutting tool in x and y direction. Then, using the frequency response functions obtained as a result of impact tests, a convenient curve fitting method can be applied to obtain MDOF model of the miniature machine tool without needing receptance coupling substructure analysis (RCSA). Using the model predictions for specified cutting-tool and process parameters, a control action can be planned for avoiding the undesired effects of vibrations.

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Appendix A

Fpga Technology

This chapter presents the block diagrams to adapt FPGA technology to the designed MMT. NI PXI-7854R data acquisition card which has three connector blocks (CONNECTOR0, CONNECTOR1 and CONNECTOR2 for analog data, digital inputs and digital outputs, respectively) are used to provide FPGA technology.

A.1 Virtual Data Acquisition Card

In this section, designed and developed virtual data acquisition cards to enable host.vis working properly are presented. Since only analog data is interested in the scope of this thesis , CONNECTOR0 which has analog options are utilized. However, if digital data is necessary for any kind of experiment, similar procedure can be applied and same block diagrams having CONNECTOR1 (digital inputs) and CONNECTOR2 (digital outputs) can be prepared. The maximum sampling frequency in the virtual data acquisition cards is selected as 500 kHz. Furthermore, it can be increased up to 750 kHz. Once the block diagram under the FPGA is changed, it is necessary to compile it again. Therefore, to prevent waste of time due to compilation process, the virtual daqs are prepared so that they let the host.vis to control the sampling frequency without needing compilation.

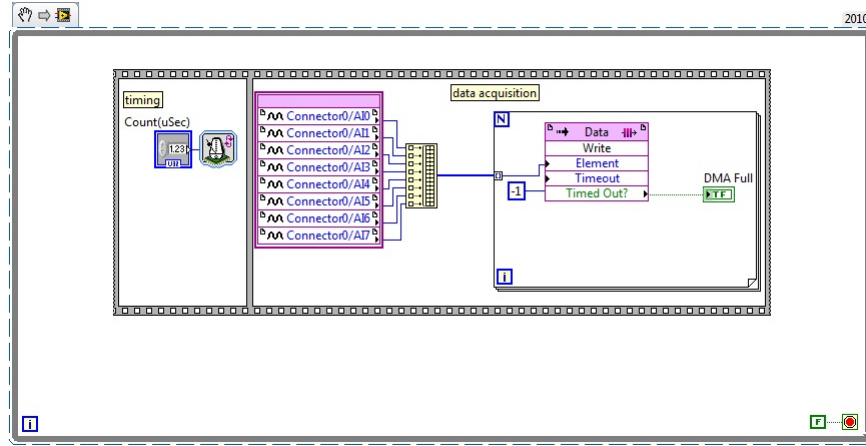


Figure A.1: Virtual DAQ environment for only analog input

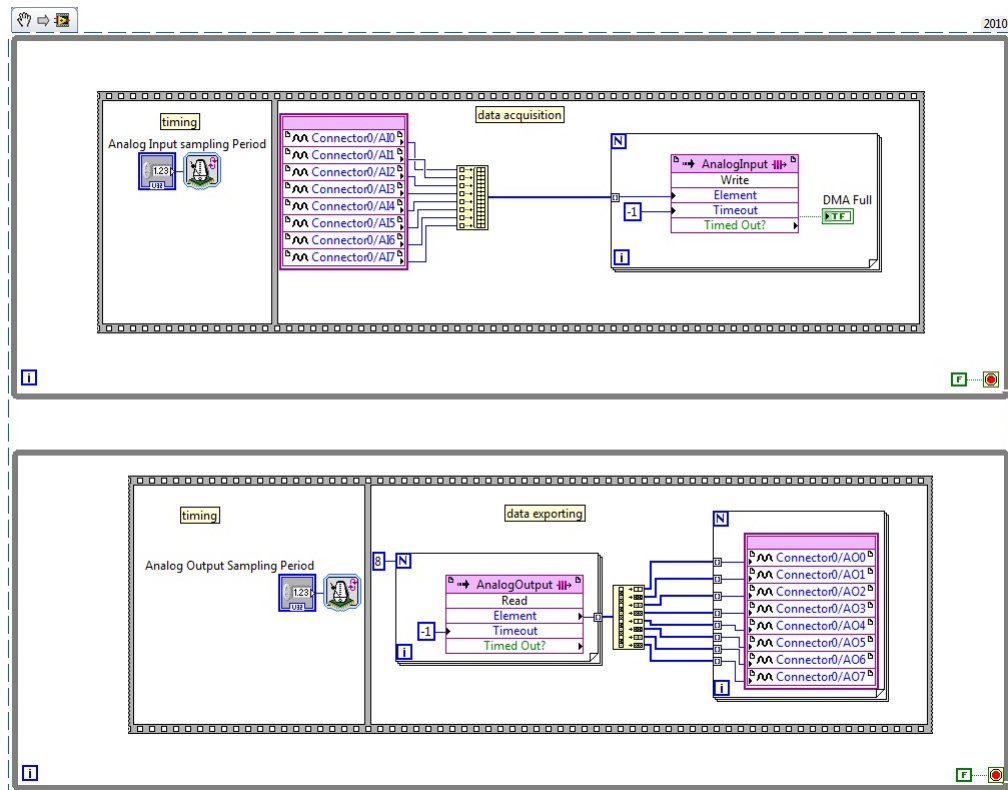


Figure A.2: Virtul DAQ environment for both analog input and analog output

A.2 Analog Input and Output Host.VIs

General host.vi block diagrams for both virtual data acquisition cards designed and developed in the previous section are given in this section, and they can be used to conduct experiments for both analog inputs and outputs.

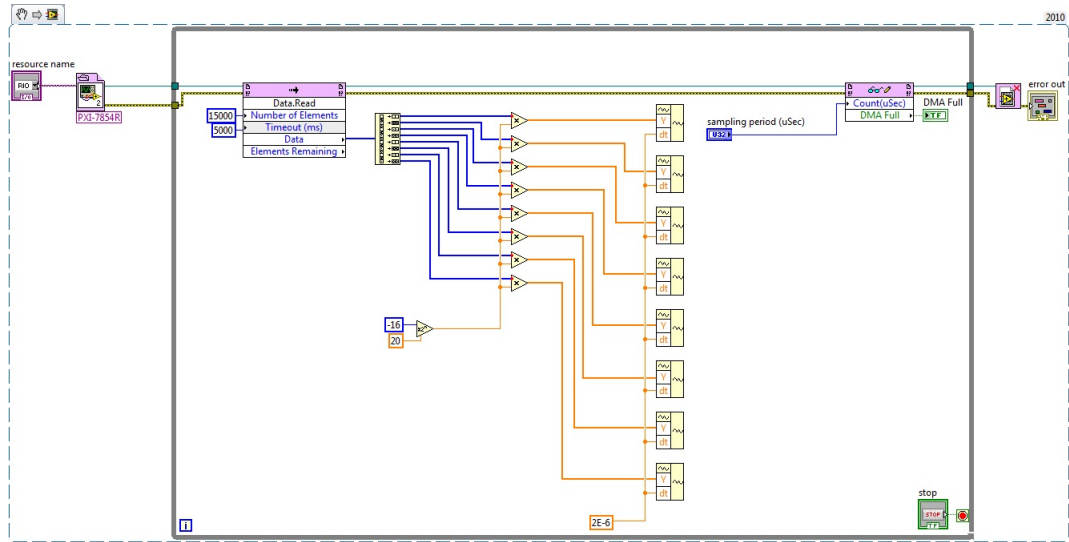


Figure A.3: Data acquiring Block Diagram

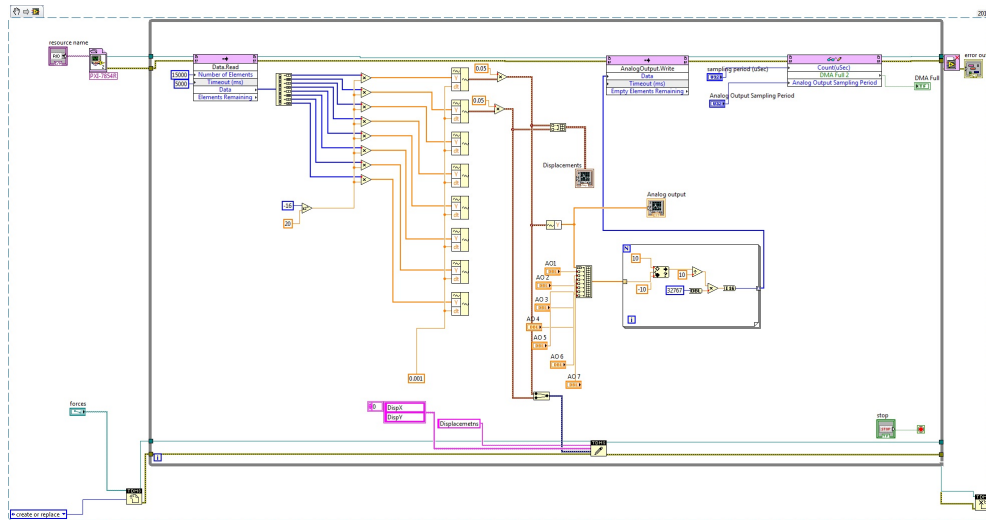


Figure A.4: An example of general host.vi for both analog inputs and outputs

Appendix B

Labview Environment for Experiments

This chapter presents a LABVIEW environment for basic experiments such as displacement measurement (see Figure B.1 and Figure B.2), impact test (see Figure B.3 and Figure B.4) and force measurement (see Figure B.5 and Figure B.6). Considering the structure in these block diagrams, many different block diagrams for any kind of experiments can be designed and developed.

All block diagrams given in this chapter is based on data acquiring so, general data acquiring host.vi given in the previous chapter is used and improved according to the purpose. It can be realized that data acquiring part of all block diagrams remains same for all experiments. In addition to block diagrams, front panels are designed and developed for each block diagram. Those front panels require only some basic informations such as sampling frequency and the location of the file that will store the data. They provide a significant advantages for the users particularly who do not understand block diagrams.

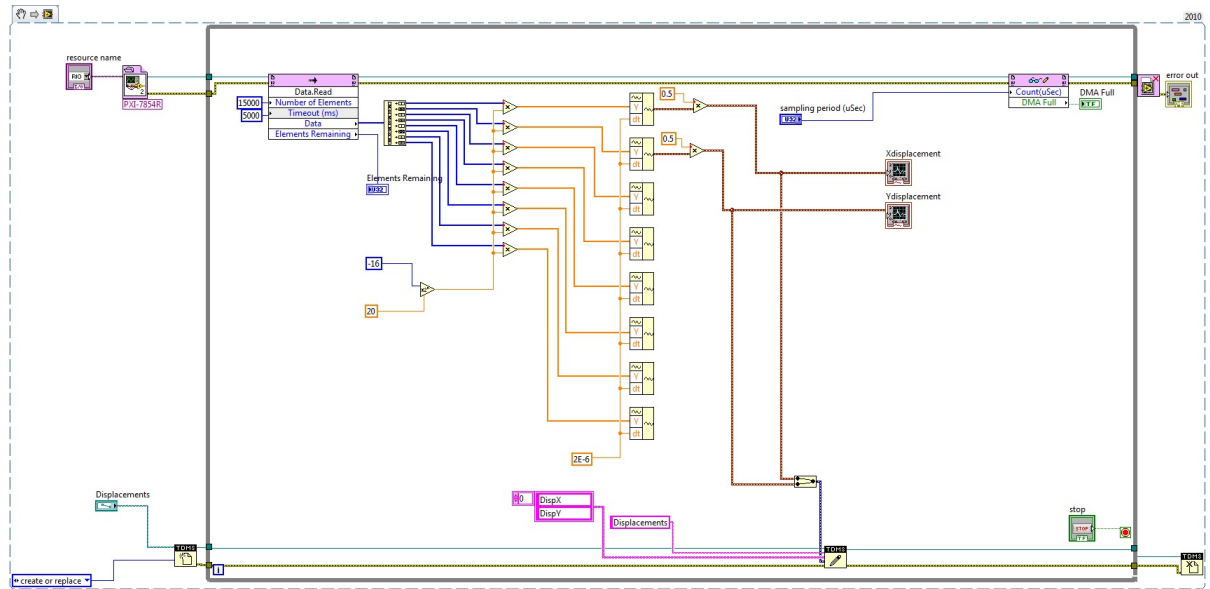


Figure B.1: Displacement Measurement Block Diagram

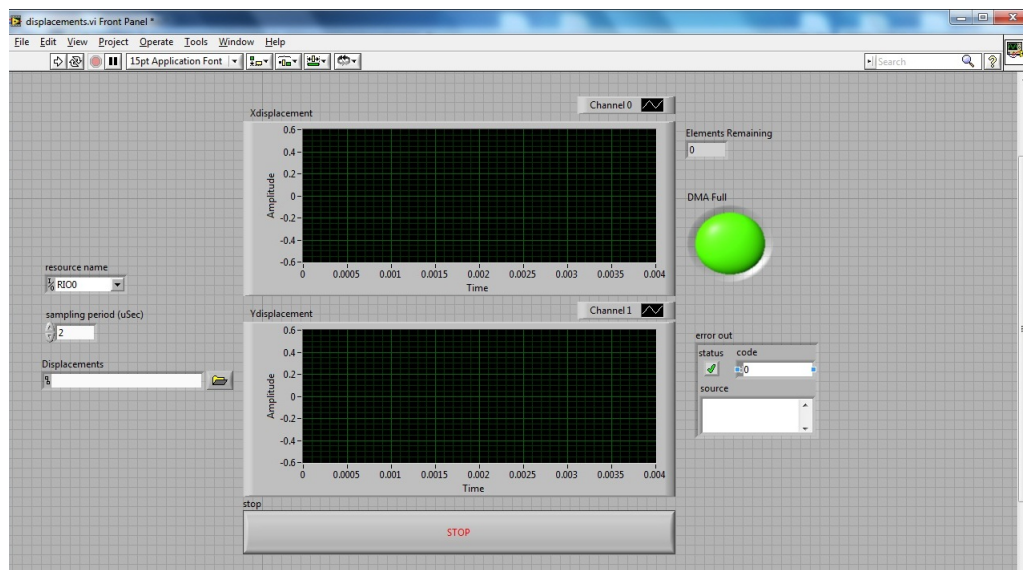


Figure B.2: Front Panel for Displacement Measurement

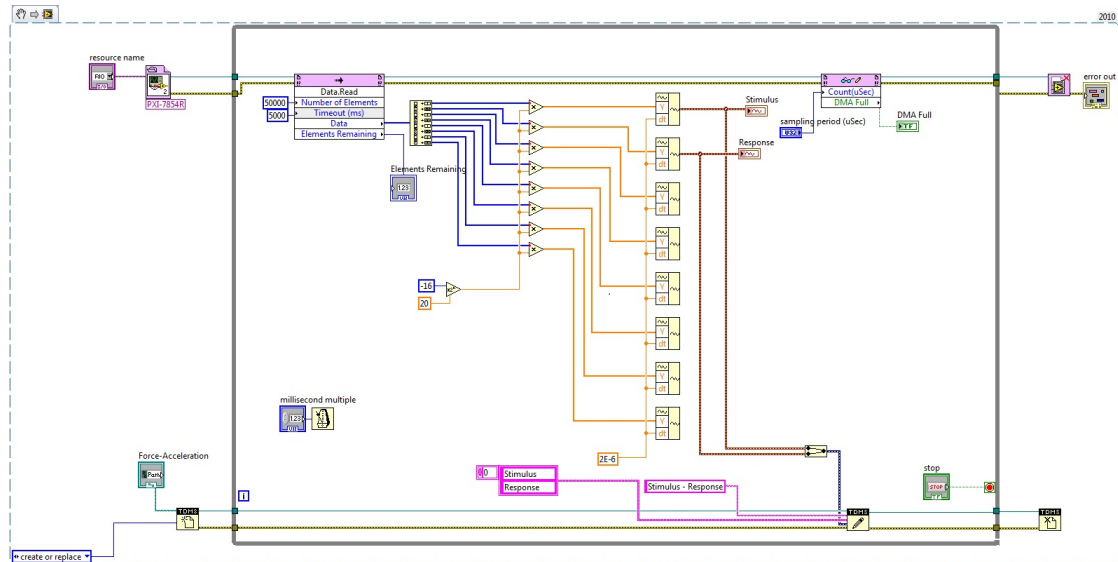


Figure B.3: Simple Impact Test Block Diagram

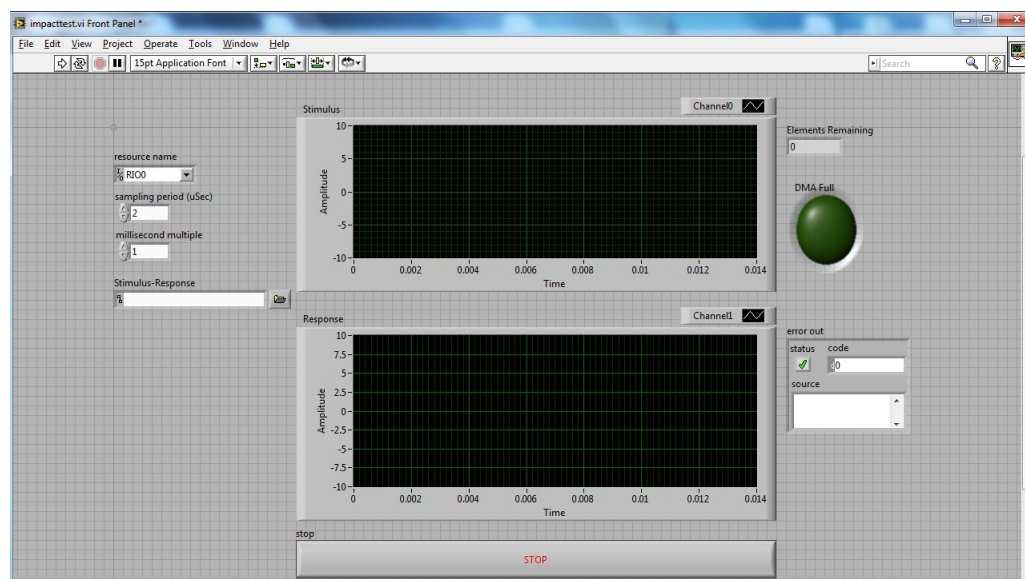


Figure B.4: Front Panel for Impact Test

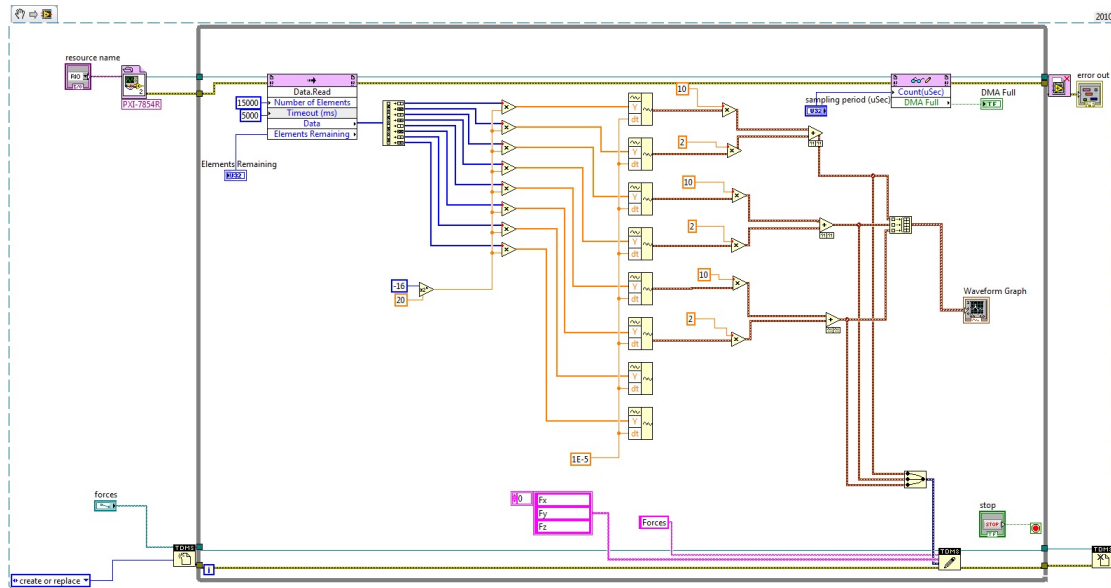


Figure B.5: Force Measurement Block Diagram

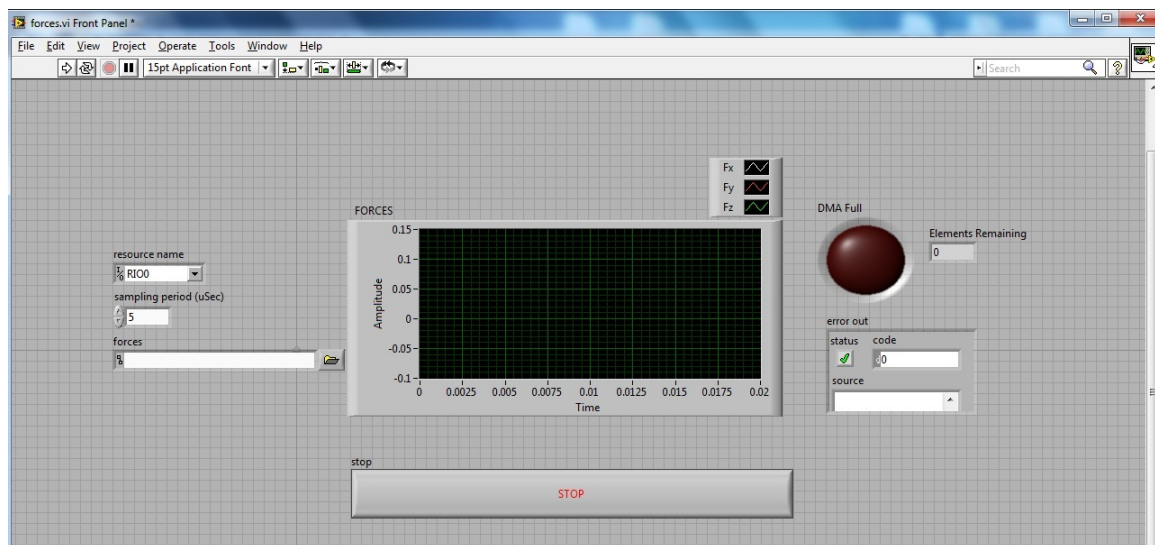


Figure B.6: Front Panel for Force Measurement

Appendix C

Runout Measurement Results

Runout error motions obtained from 1,000 to 50,000 rpm at 5,000 rpm intervals are presented in this chapter. Total runout motions including both synchronous and asynchronous errors, and synchronous errors which occur at the spindle frequency and its harmonics are given for different spindle speeds to obtain speed-dependent characteristics of the spindle.

Asynchronous runout errors which occur at the non-harmonics of the rotational speed can be identified by comparing total and synchronous runouts. Thickness of the total runout measurements fundamentally determines the asynchronous runout. Therefore, it can be seen that as the thickness of the total runout measurement increase, asynchronous runout errors increase. The certain values of the asynchronous runout errors as a function of the spindle speed is given in Figure 5.16.

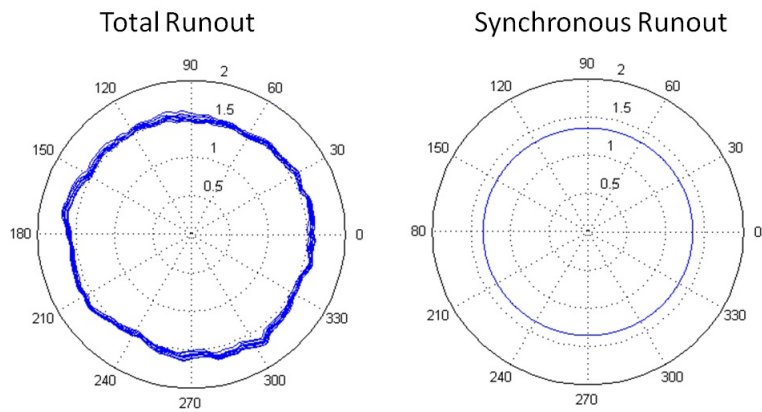


Figure C.1: Radial runout results for 1,000 rpm

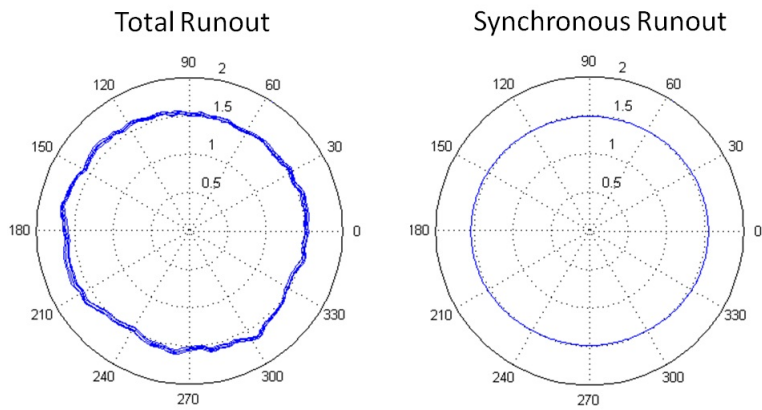


Figure C.2: Radial runout results for 2,000 rpm

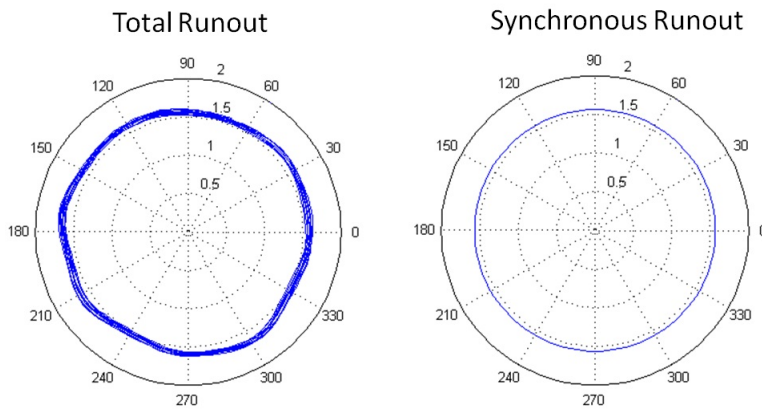


Figure C.3: Radial runout results for 5,000 rpm

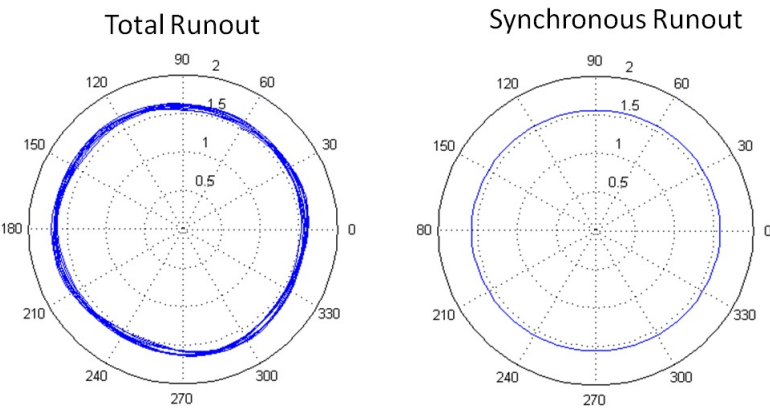


Figure C.4: Radial runout results for 10,000 rpm

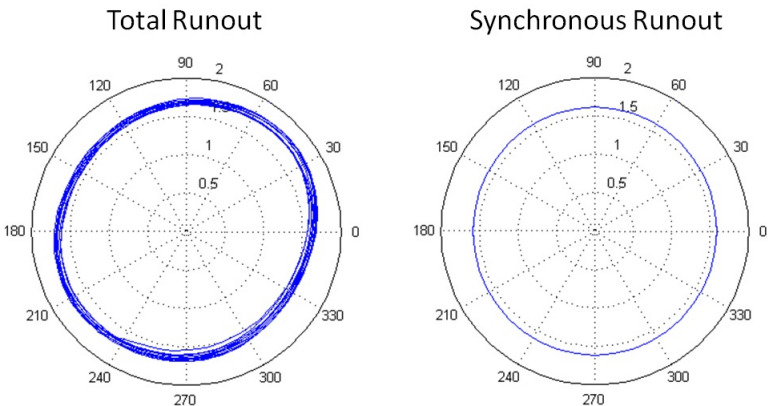


Figure C.5: Radial runout results for 15,000 rpm

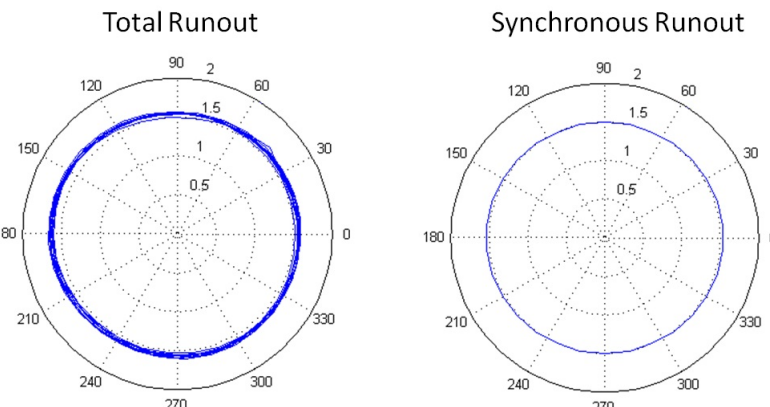


Figure C.6: Radial runout results for 20,000 rpm

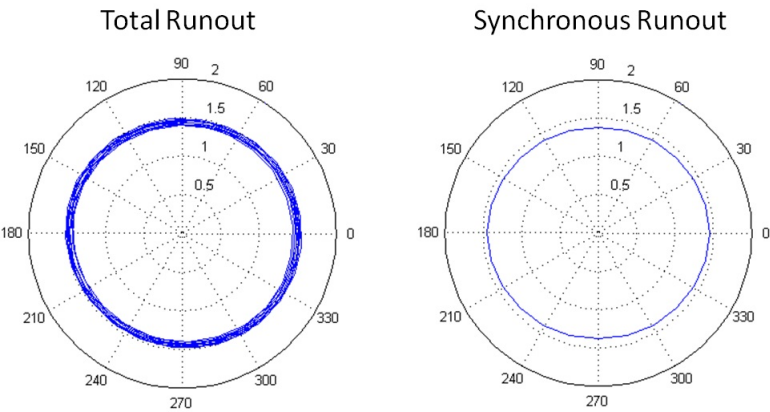


Figure C.7: Radial runout results for 25,000 rpm

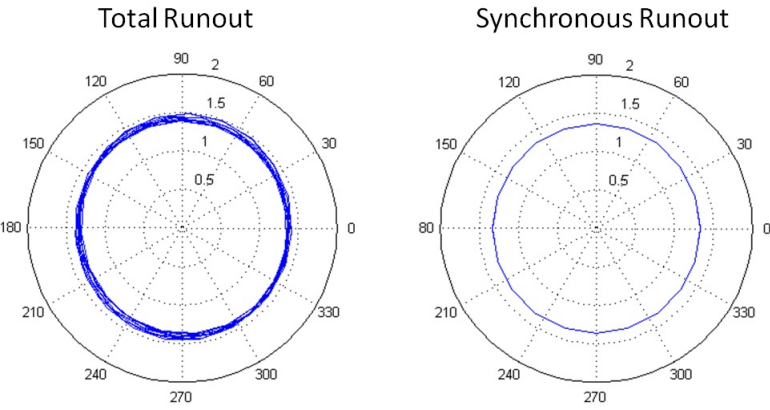


Figure C.8: Radial runout results for 30,000 rpm

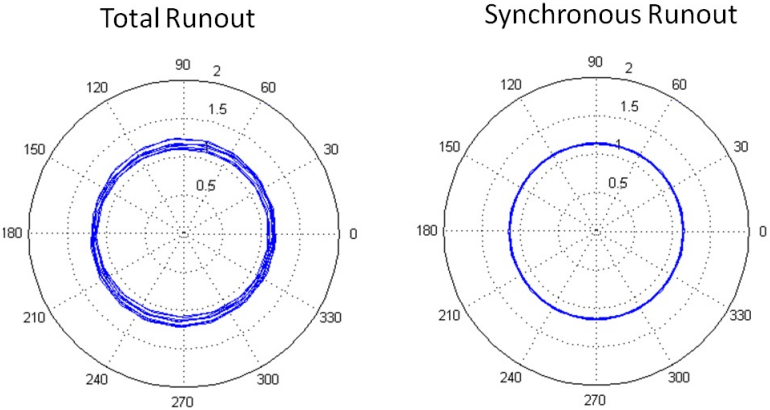


Figure C.9: Radial runout results for 35,000 rpm

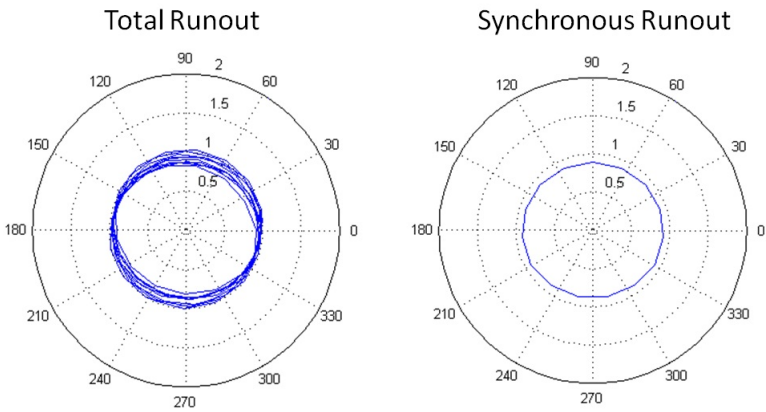


Figure C.10: Radial runout results for 40,000 rpm

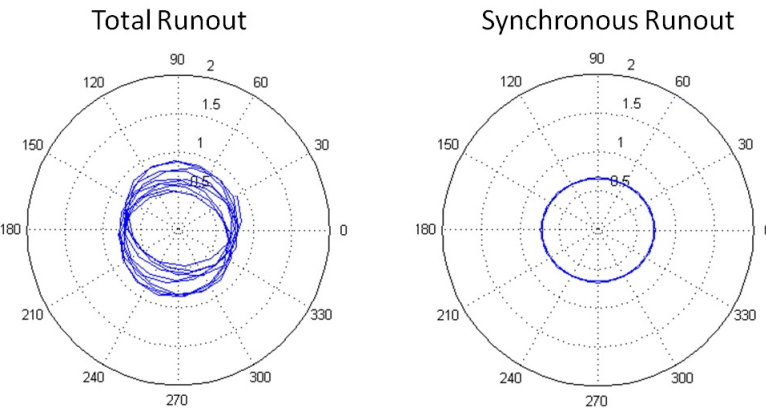


Figure C.11: Radial runout results for 45,000 rpm

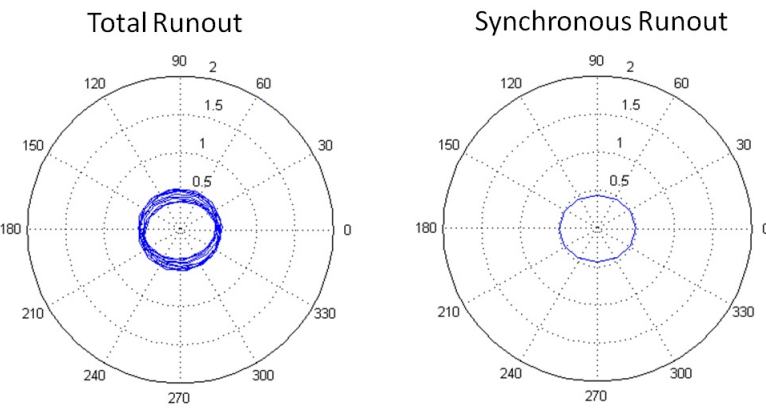


Figure C.12: Radial runout results for 50,000 rpm

Appendix D

Speed Dependent Frequency Response Functions

Experimental modal analysis was conducted to obtain speed-dependent dynamics of the MMT from 2,000 to 50,000 rpm at 2,000 rpm intervals. This chapter presents the obtained frequency response functions at different spindle speeds from 2,000 rpm to 50,000 rpm.

Since it gives more detailed information in terms of modal parameters, log-magnitude of the frequency response functions was presented and inertance (acceleration (A)/force (F)) results are given. It is possible to obtain receptance (displacement (X) /force (F)) directly using equation D.1.

$$\frac{X}{F} = -\frac{1}{\omega^2} * \frac{A}{F} \quad (\text{D.1})$$

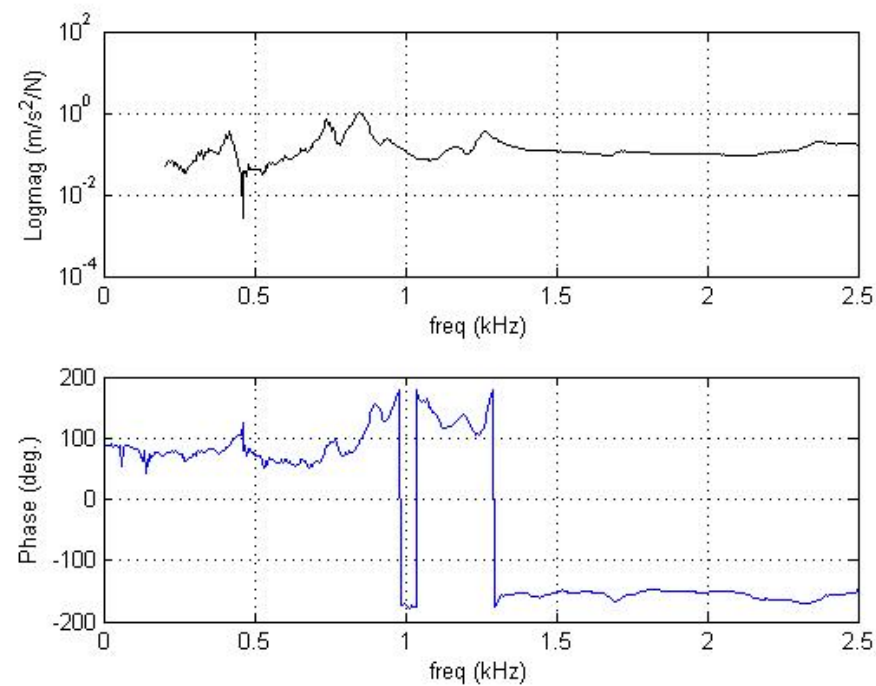


Figure D.1: Average frequency response function measurements for 2,000 rpm

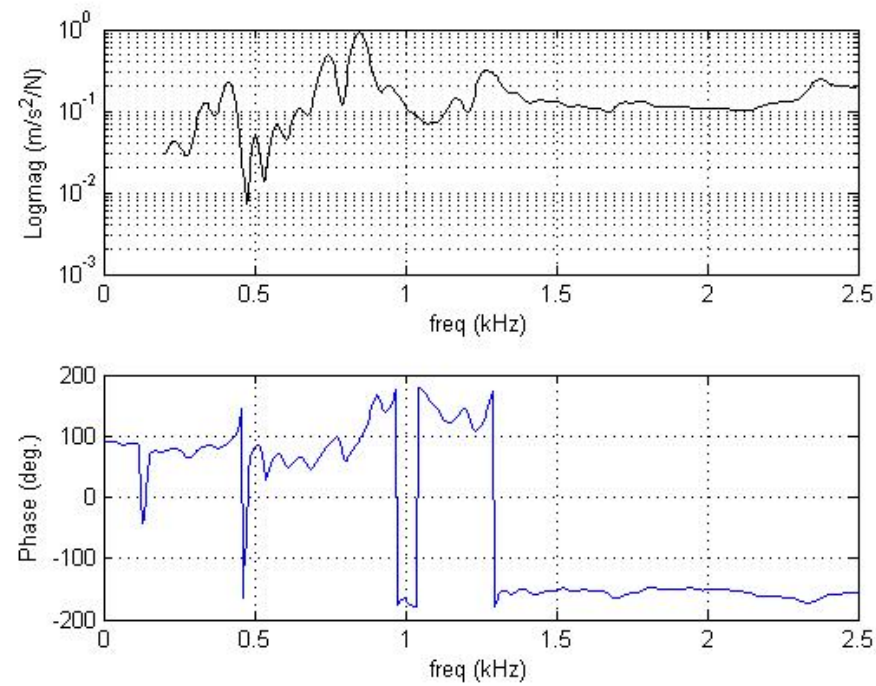


Figure D.2: Average frequency response function measurements for 4,000 rpm

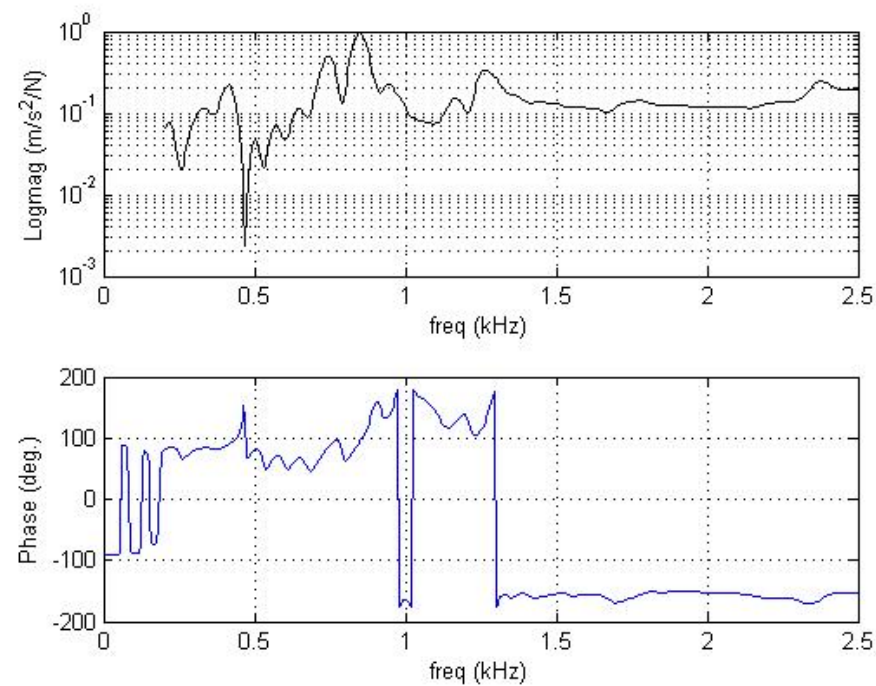


Figure D.3: Average frequency response function measurements for 6,000 rpm

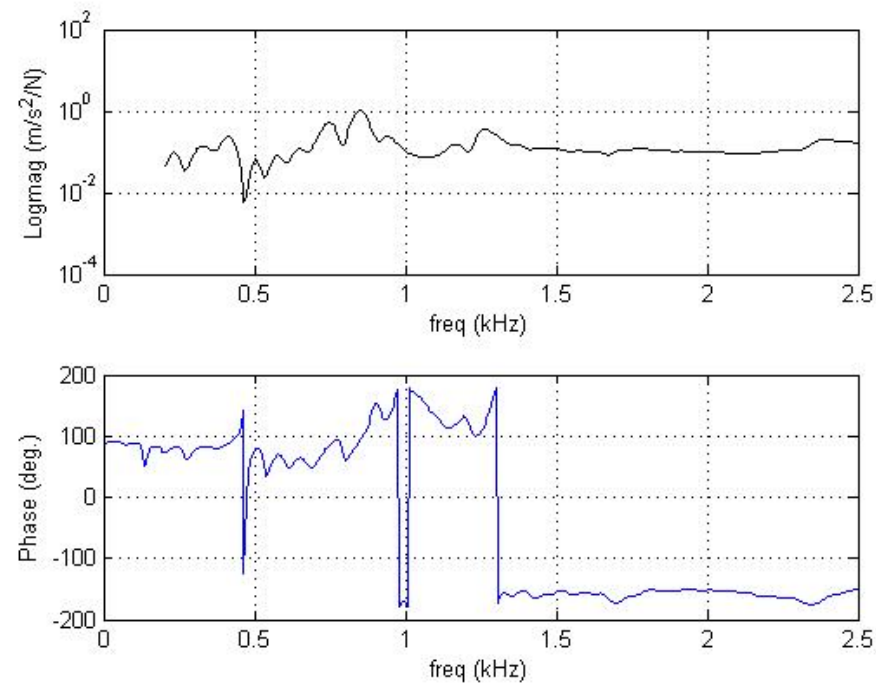


Figure D.4: Average frequency response function measurements for 8,000 rpm

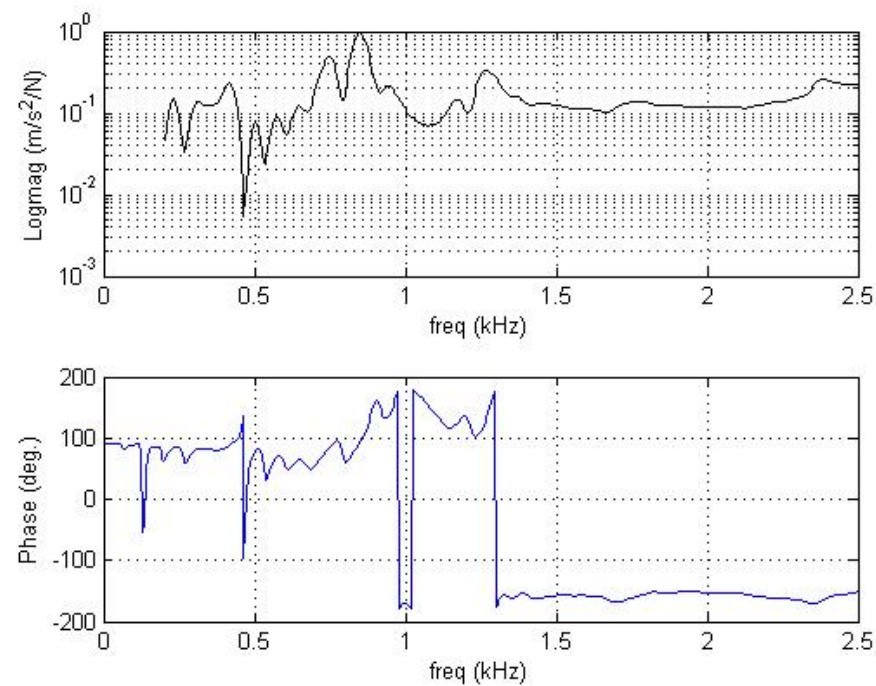


Figure D.5: Average frequency response function measurements for 10,000 rpm

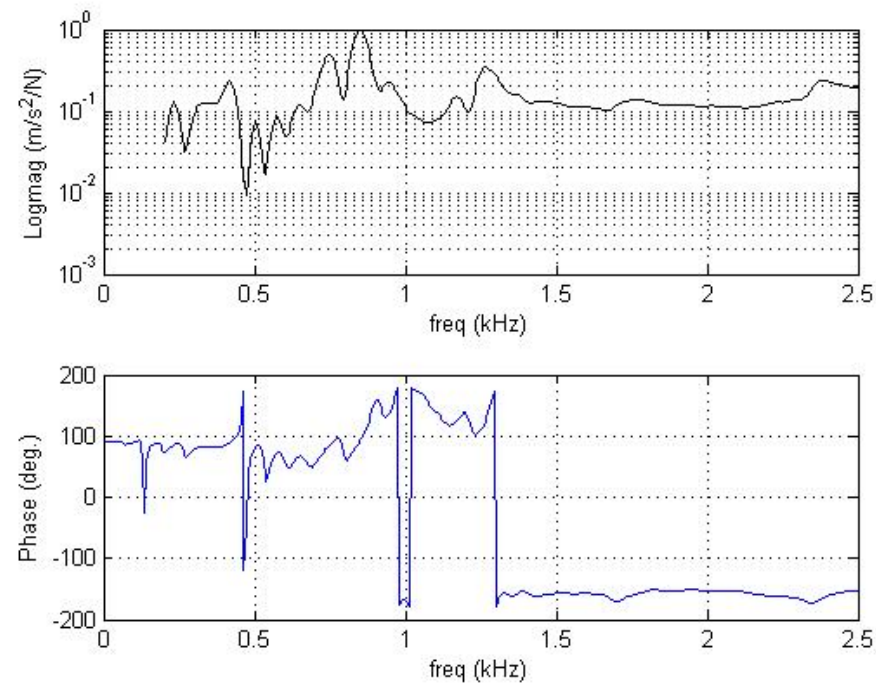


Figure D.6: Average frequency response function measurements for 12,000 rpm

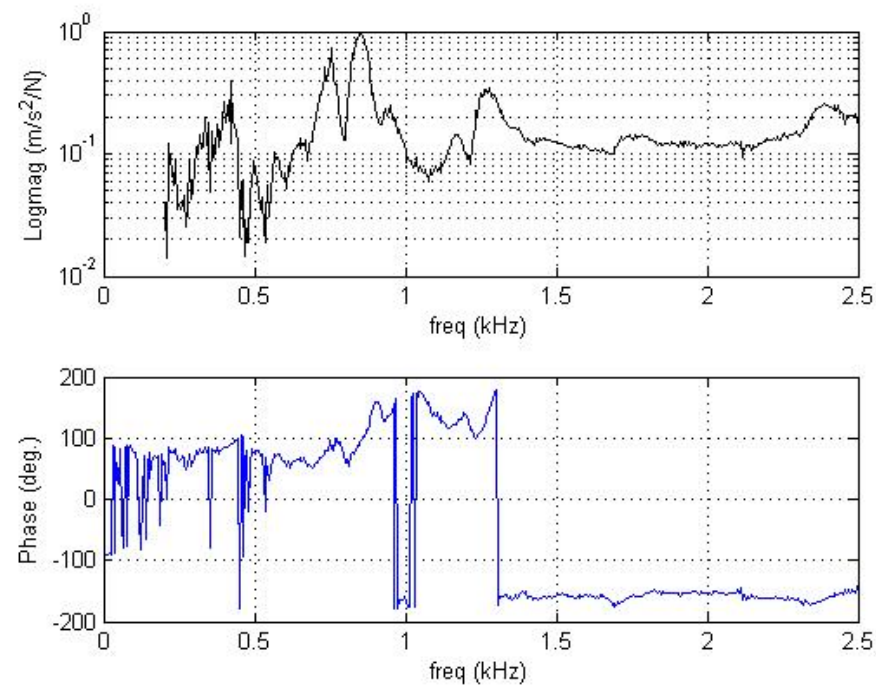


Figure D.7: Average frequency response function measurements for 14,000 rpm

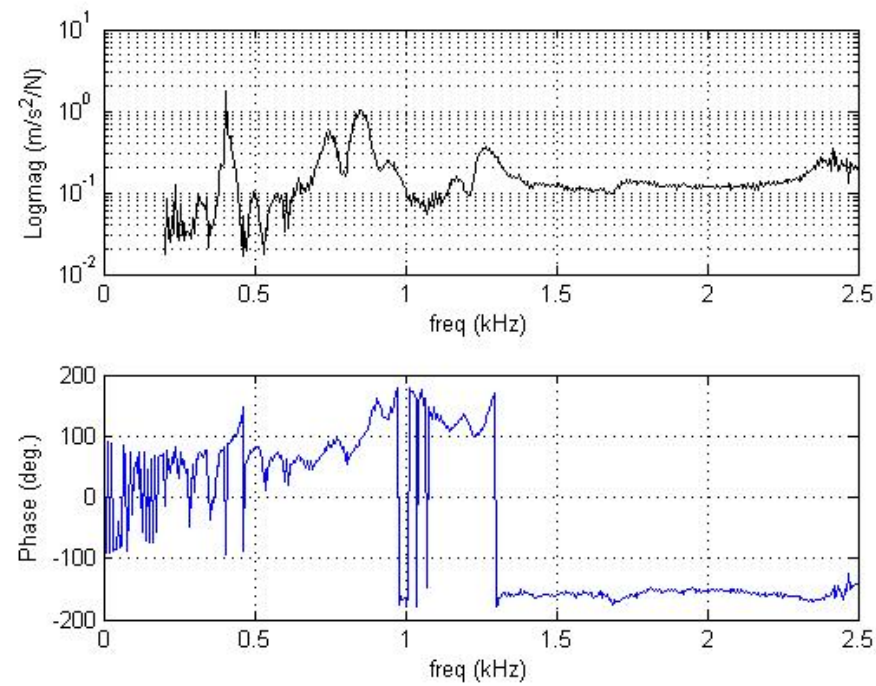


Figure D.8: Average frequency response function measurements for 16,000 rpm

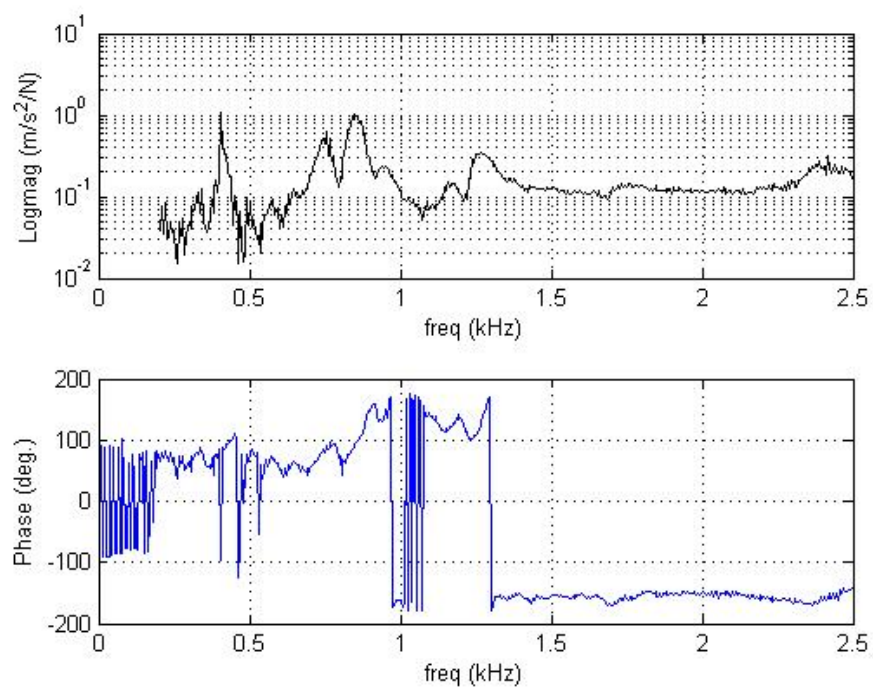


Figure D.9: Average frequency response function measurements for 18,000 rpm

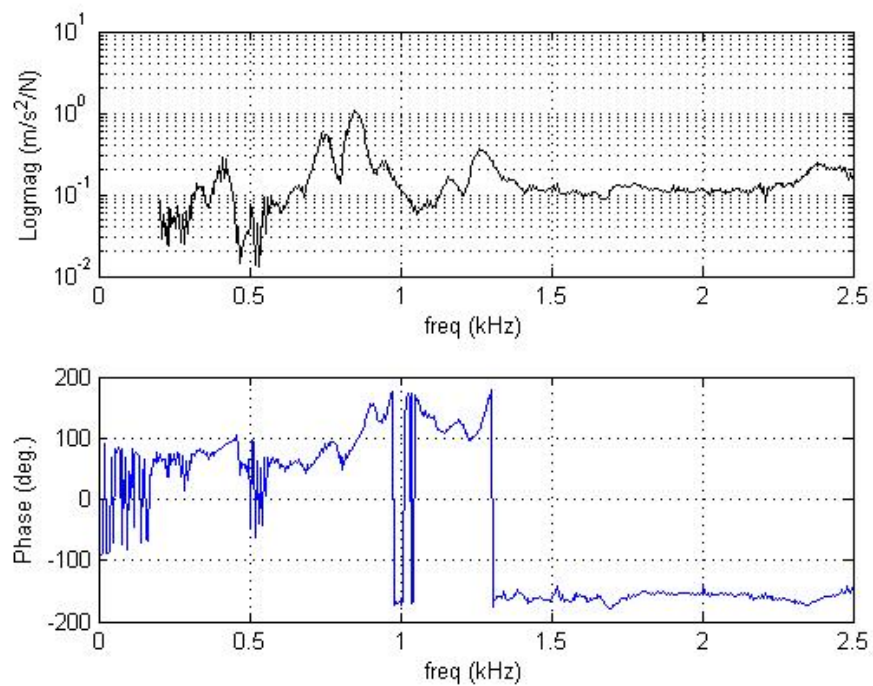


Figure D.10: Average frequency response function measurements for 20,000 rpm

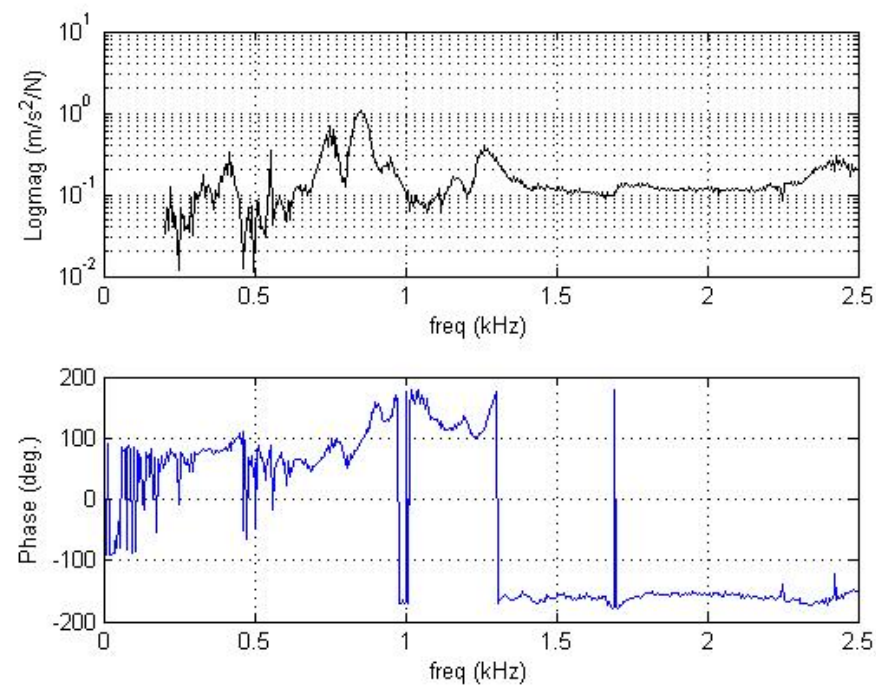


Figure D.11: Average frequency response function measurements for 22,000 rpm

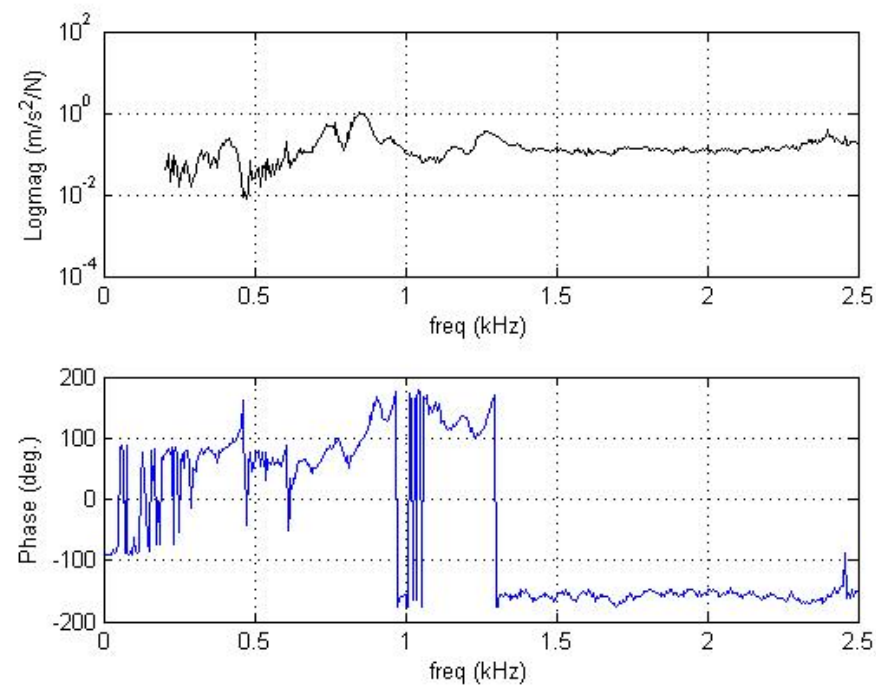


Figure D.12: Average frequency response function measurements for 24,000 rpm

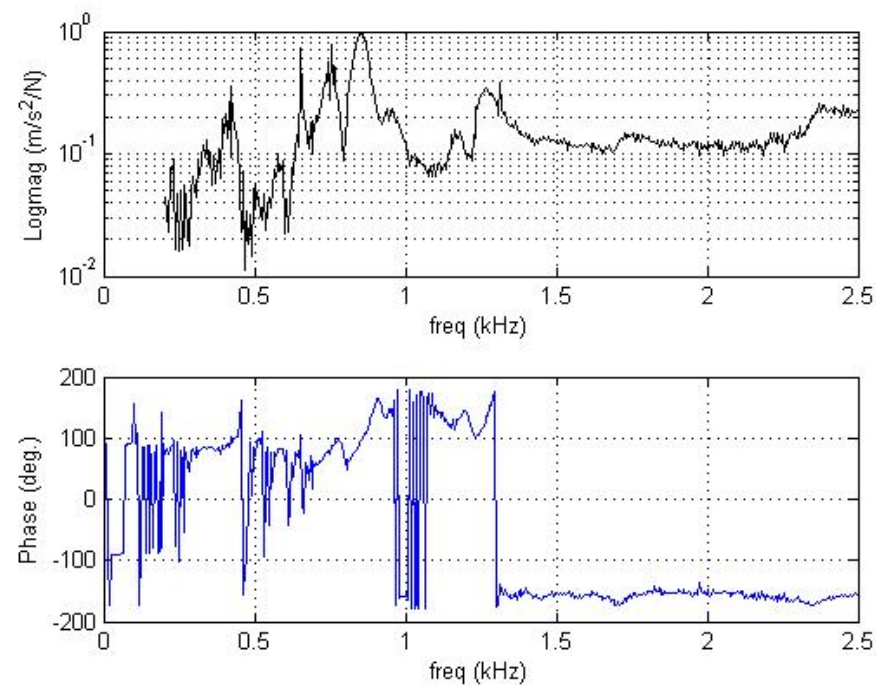


Figure D.13: Average frequency response function measurements for 26,000 rpm

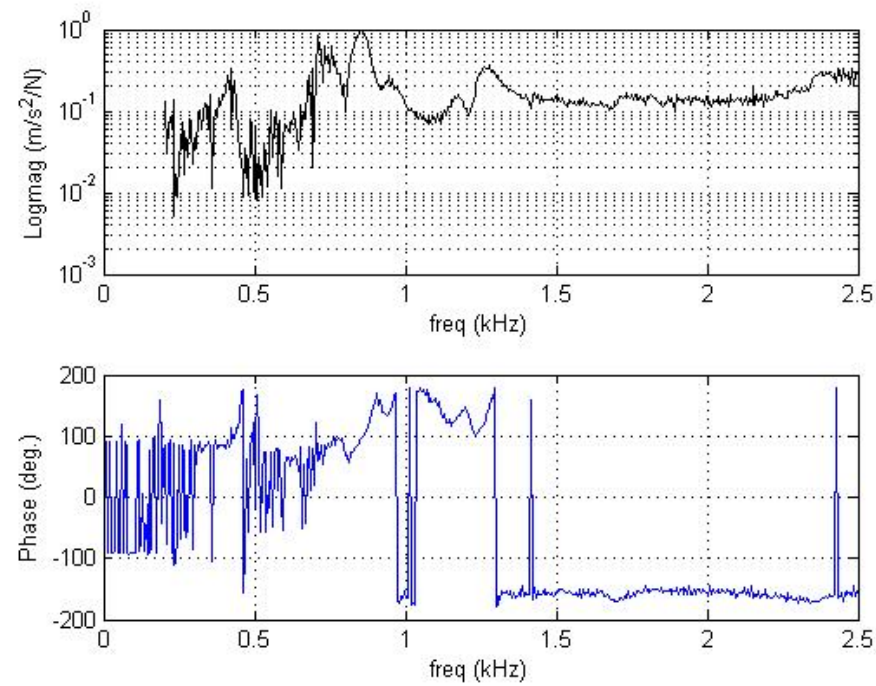


Figure D.14: Average frequency response function measurements for 28,000 rpm

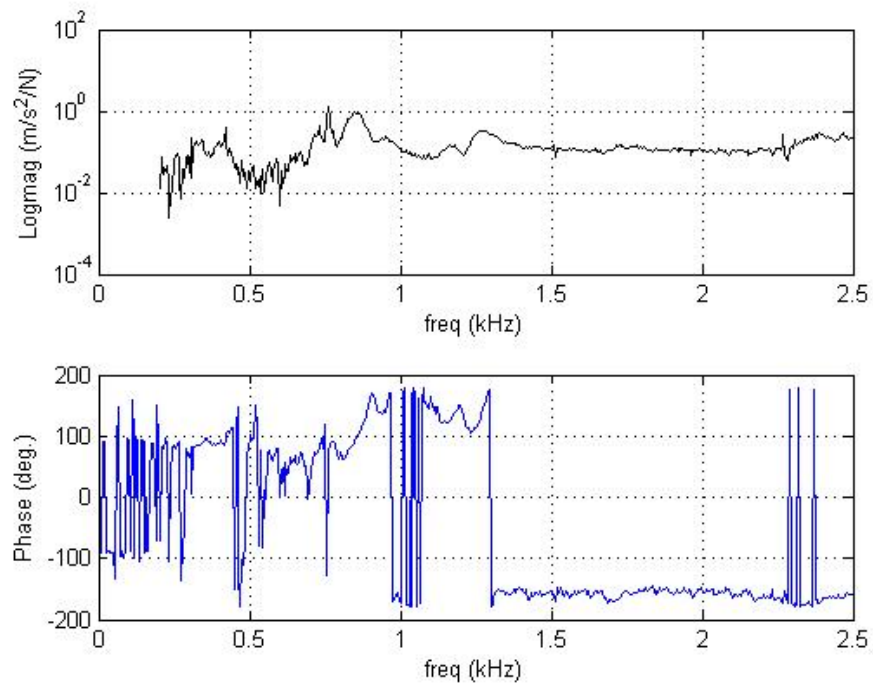


Figure D.15: Average frequency response function measurements for 30,000 rpm

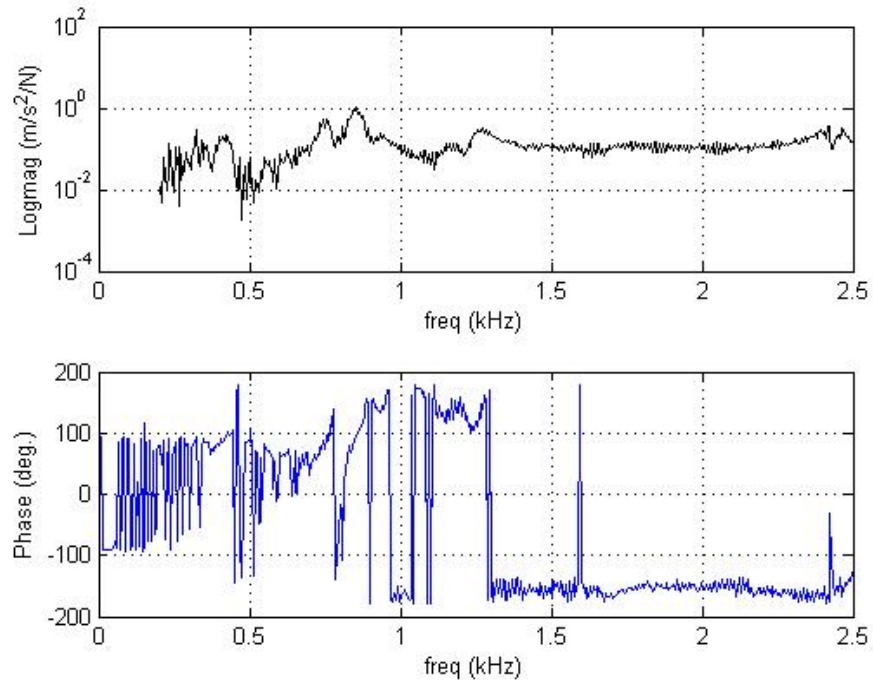


Figure D.16: Average frequency response function measurements for 32,000 rpm

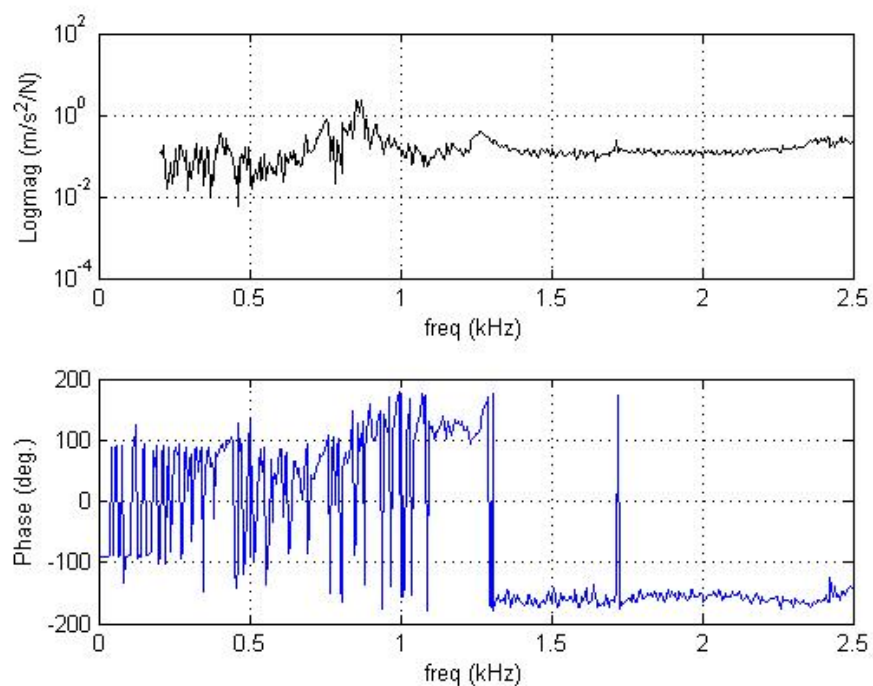


Figure D.17: Average frequency response function measurements for 34,000 rpm

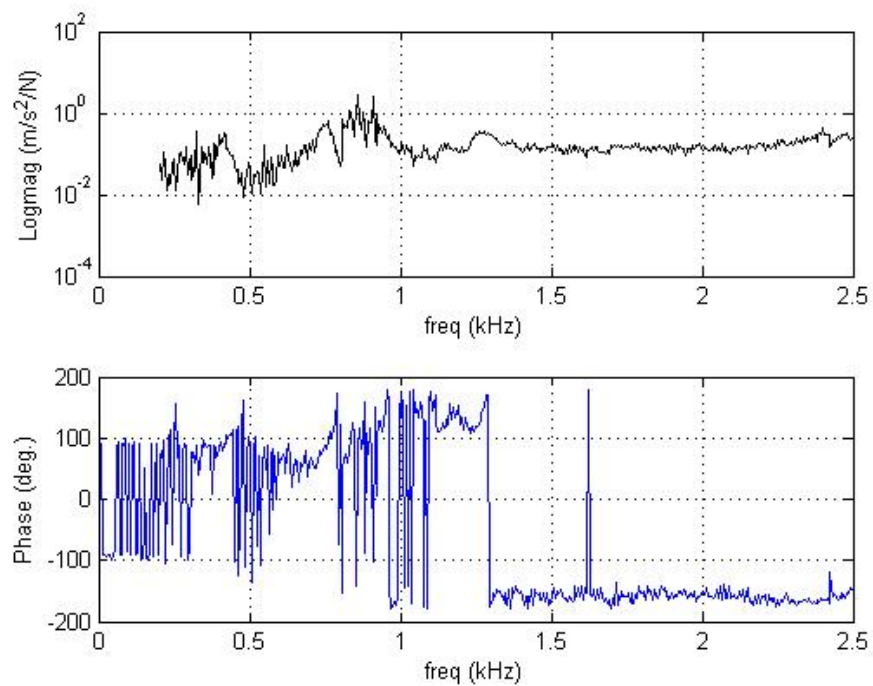


Figure D.18: Average frequency response function measurements for 36,000 rpm

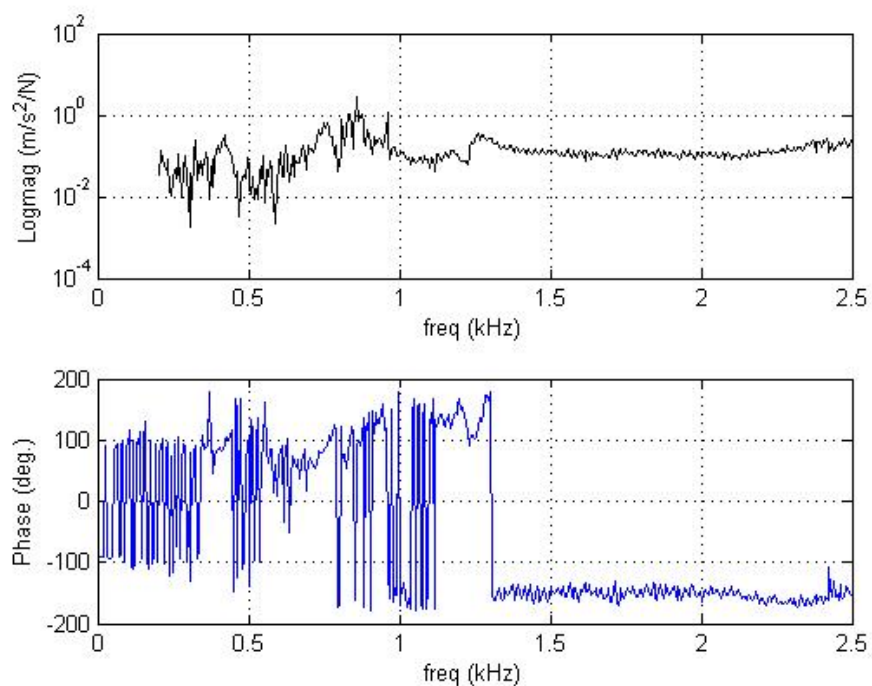


Figure D.19: Average frequency response function measurements for 38,000 rpm

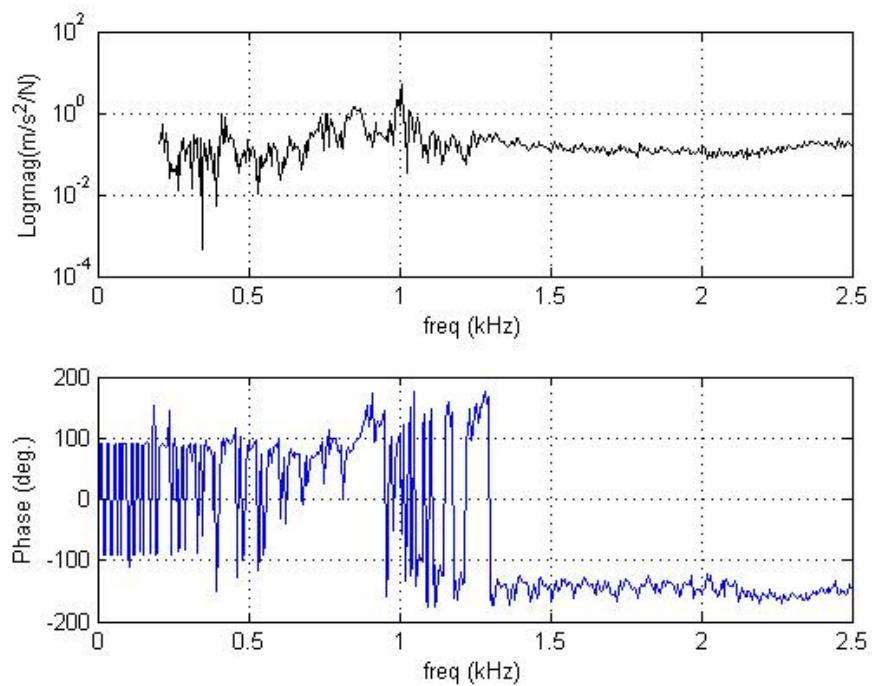


Figure D.20: Average frequency response function measurements for 40,000 rpm

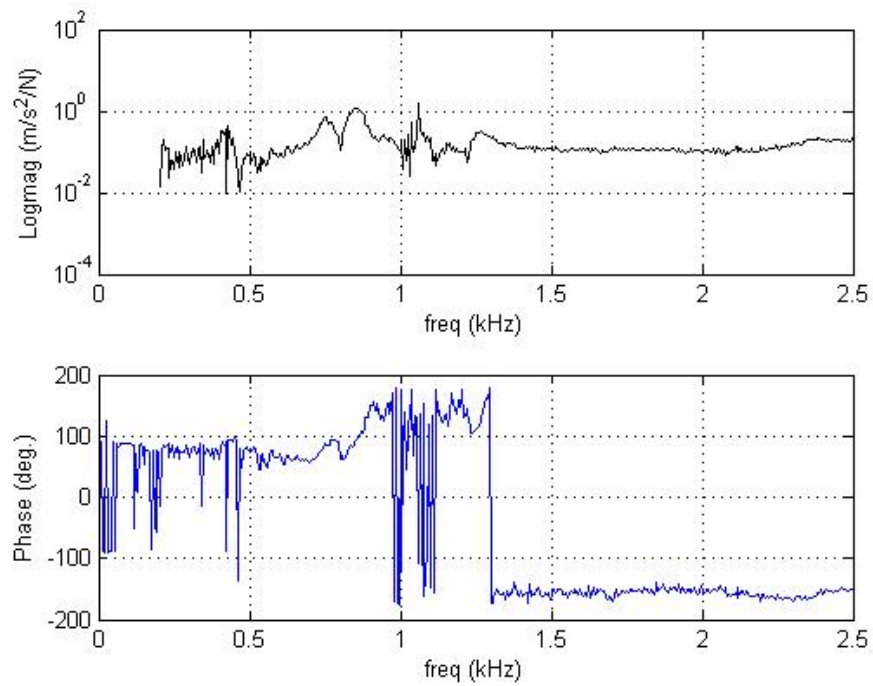


Figure D.21: Average frequency response function measurements for 42,000 rpm

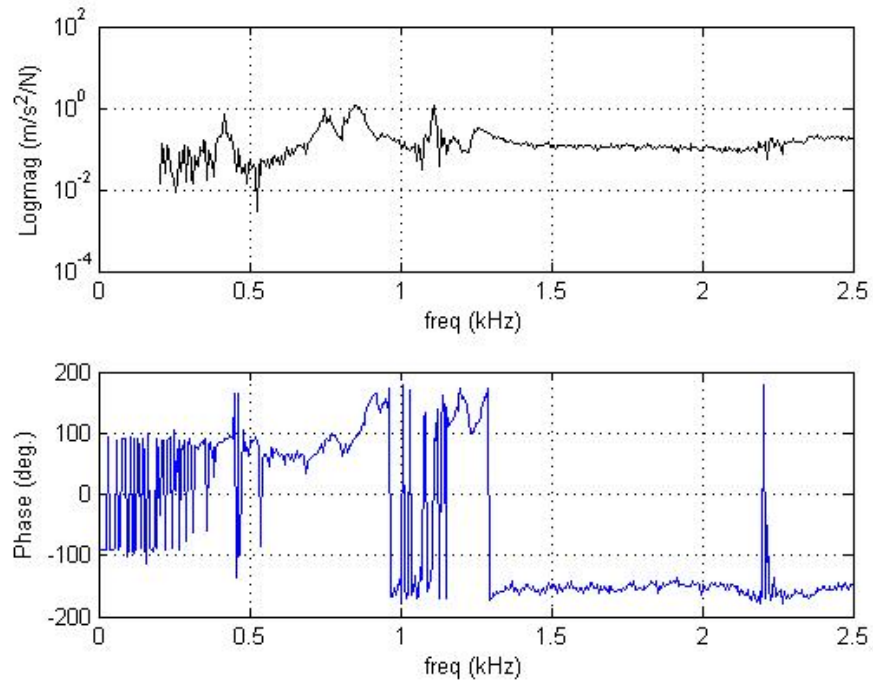


Figure D.22: Average frequency response function measurements for 44,000 rpm

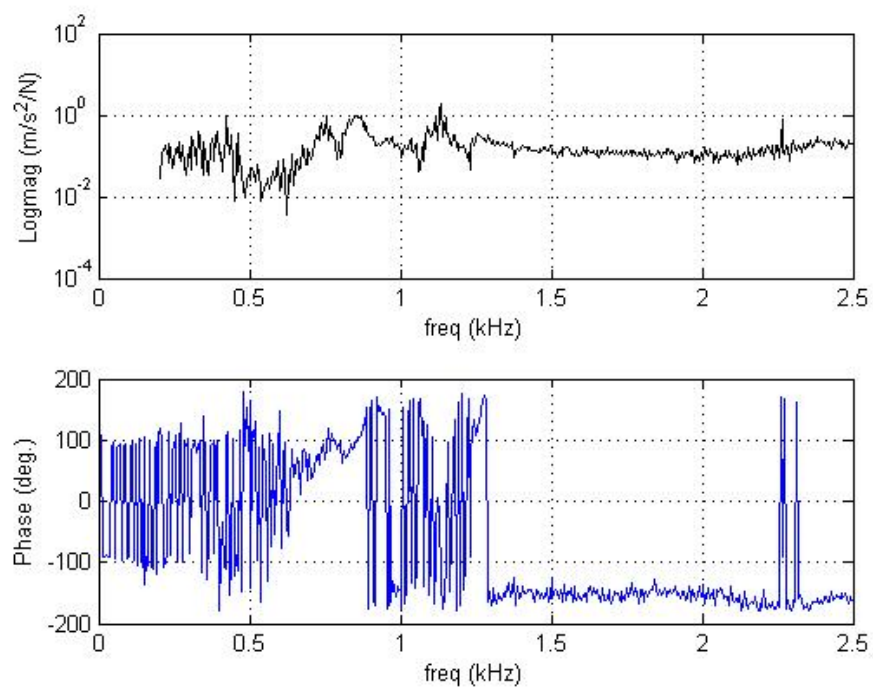


Figure D.23: Average frequency response function measurements for 45,000 rpm

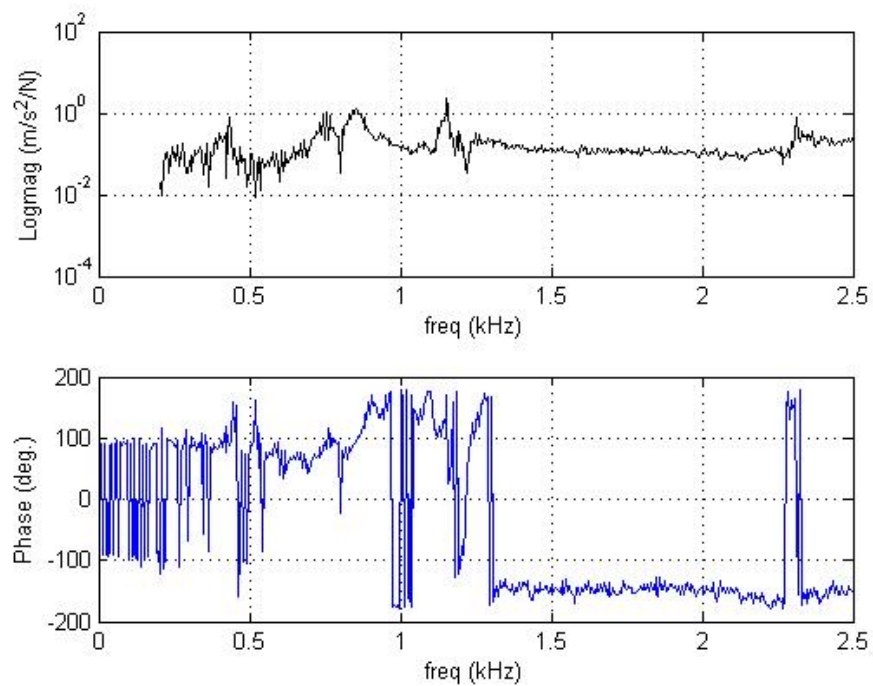


Figure D.24: Average frequency response function measurements for 46,000 rpm

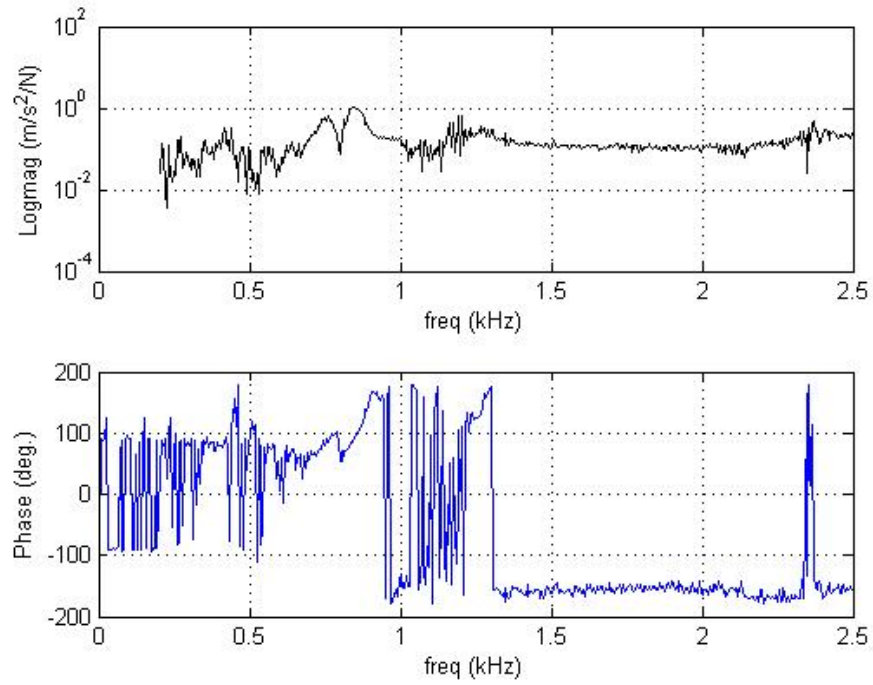


Figure D.25: Average frequency response function measurements for 47,000 rpm

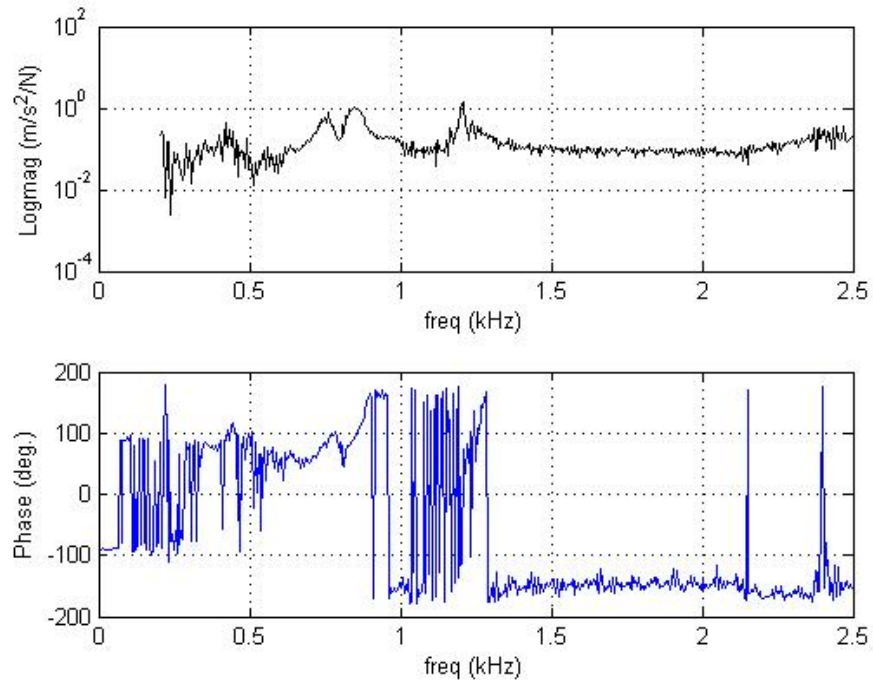


Figure D.26: Average frequency response function measurements for 48,000 rpm

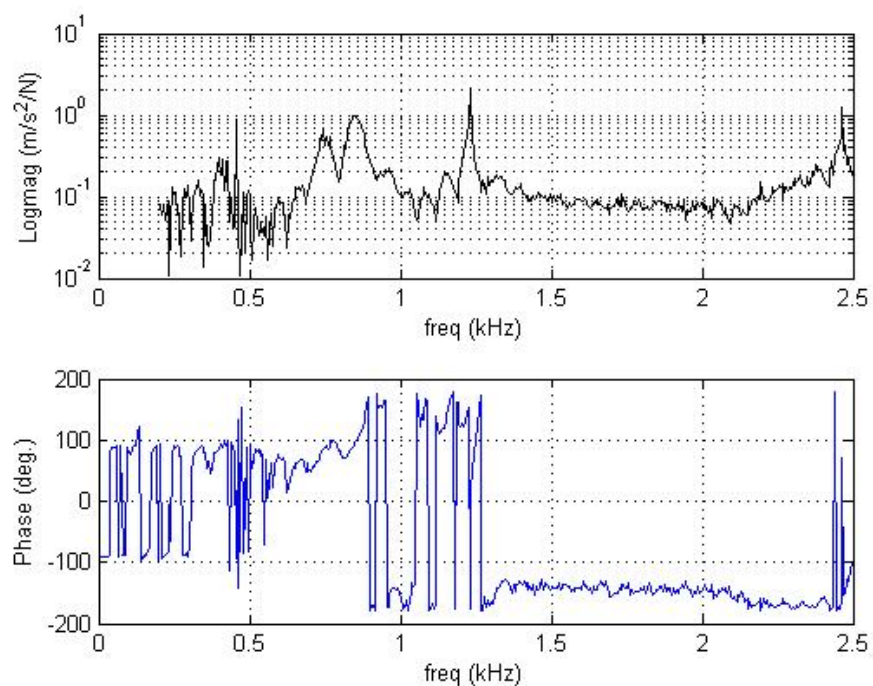


Figure D.27: Average frequency response function measurements for 49,000 rpm

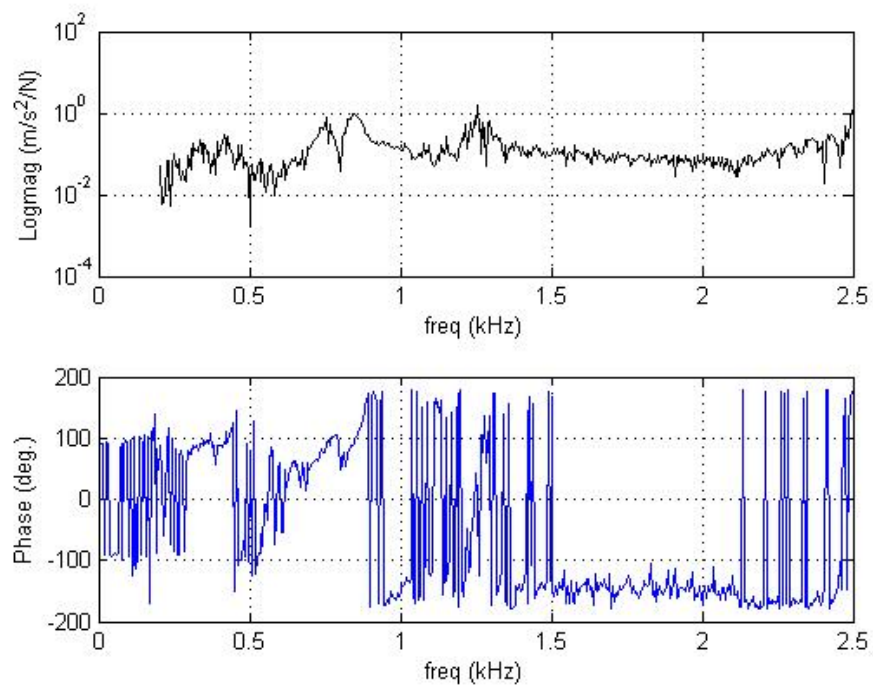


Figure D.28: Average frequency response function measurements for 50,000 rpm