รายงานวิจัยฉบับสมบูรณ์

โครงการ คุณลักษณะของมอเตอร์อัลตราโซนิคเมื่อกระตุ้นด้วยตัวทำงานเพียโซอิเล็กทริกแบบบางส่วน

โดย รศ.ดร. พฤทธิกร สมิตไมตรี และคณะ

กรกฎาคม 2555

สัญญาเลขที่ MRG5380183

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สนันสนุนโดย

สำนักงานคณะกรรมการอุดมศึกษา สำนักงานกองทุนสนับสนุนการทำวิจัย และ มหาวิทยาลัยสงขลานครินทร์

(ความเห็นในรายงานนี้เป็นของผู้วิจัย สกอ. สกว. และ ม.อ. ไม่จำเป็นต้องเห็นด้วยเสมอไป)

กิติกรรมประกาศ

งานวิจัยนี้สำเร็จลุล่วงลงได้ ด้วยการสนับสนุนทุนวิจัย (ทุนพัฒนาศักยภาพในการทำงานวิจัยของอาจารย์รุ่นใหม่) จากสำนักงานคณะกรรมการอุดมศึกษา สำนักงานกองทุนสนับสนุนการทำวิจัย และมหาวิทยาลัยสงขลานครินทร์ ผู้เขียนขอขอบพระคุณ คณะผู้บริหารและเจ้าหน้าที่ของ สกอ. สกว. และ ม.อ. ในทุกระดับชั้น ที่ได้ให้การสนับสนุนและช่วยเหลือในการทำงานวิจัยนี้

ผู้เขียนขอขอบพระคุณ รศ.ดร. นันทกาญจน์ มุรศิต ที่ปรึกษาให้กับโครงการวิจัยนี้ ซึ่งคำแนะนำและความช่วยเหลือที่มีให้นั้น ทำให้งานวิจัยนี้ดำเนินไปในทิศทางที่ถูกต้อง และกรรมการผู้ทรงคุณวุฒิผู้ประเมินผลงานของผู้เขียน ที่ได้ให้โอกาสในการทำงานวิจัยนี้

ผู้เขียนขอขอบพระคุณ อาจารย์ บุคลากร นักศึกษา ของภาควิชาวิศวกรรมเครื่องกล คณะวิศวกรรมศาสตร์ มหาวิทยาลัยสงขลานครินทร์ ที่ได้ให้ความช่วยเหลือในการทำงานหลายๆ ด้าน ซึ่งเป็นสถานที่ทำงานที่มีมิตรภาพและความอบอุ่นในการทำงานอย่างมาก

สุดท้ายนี้ ขอกราบขอบพระคุณ คุณพ่อ คุณแม่ ครู อาจารย์ ที่ได้ให้ชีวิต เลี้ยงดู อบรม และ สั่งสอน จนผู้เขียนมีวันนี้ได้ และ ขอขอบคุณภรรยาและลูกๆ สำหรับชีวิตครอบครัวที่อบอุ่น

รหัสโครงการ (Project Code): MRG5380183

ชื่อโครงการ (Project Title):

(ภาษาไทย) คุณลักษณะของมอเตอร์อัลตราโซนิคเมื่อกระตุ้นด้วยตัวทำงานเพียโซอิเล็กทริกแบบบางส่วน

(ภาษาอังกฤษ) CHARACTERISTICS OF THE ULTRASONIC MOTOR WITH THE PARTIALLY LAMINATED PIEZOELECTRIC ACTUATION

ชื่อนักวิจัย (Investigator):

รศ.ดร. พฤทธิกร สมิตไมตรี มหาวิทยาลัยสงขลานครินทร์

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ระยะเวลาโครงการ (Project Period): 2 ปี (2 years)

คุณลักษณะของมอเตอร์อัลตราโซนิคเมื่อกระตุ้นด้วยตัวทำงานเพียโซอิเล็กทริกแบบบางส่วน

บทคัดย่อ

งานวิจัยนี้ได้ศึกษาการออกแบบและทดสอบสมถรรนะมอเตอร์อัลตราโซนิคเชิงเส้นที่มีตัวทำงานเพียโซอิเล็กทริกแบบคู่ ระบบของมอเตอร์อัลตราโซนิคประกอบด้วย สเตเตอร์เชิงเส้น น้ำหนักกด และ คู่ตัวทำงานเพียโซอีเล็กทริกซึ่งติดอยู่ที่ตำแหน่งปลายทั้งสองข้างของสเตเตอร์ เมื่อตัวทำงานเพียโซอิเล็กทริกถูกกระตุ้นด้วยสัญญาณฮาร์โมนิคจะสามารถสร้างคลื่นเคลื่อนที่บนสเตเตอร์ได้ ผลการสั่นสะเทือนของสเตเตอร์ได้ถูกวิเคราะห์และเปรียบเทียบกันระหว่างผลการคำนวณด้วยวิธีไฟไนต์เอลิเมนต์กับผลการทดลอง พบว่ามีความสอดคล้องกัน รายงานนี้ได้นำเสนอผลการทดสอบสมรรถนะของมอเตอร์อัลตราโซนิค ในรูปของความสัมพันธ์ระหว่าง ความเร็วกับน้ำหนักกด ความเร็วกับศักย์ไฟฟ้ากระตุ้น แรงขับกับศักย์ไฟฟ้ากระตุ้น และ ความเร็วกับแรงขับ การออกแบบตัวกระตุ้นมอเตอร์อัลตราโซนิคด้วยตัวทำงานเพียโซอิเล็กทริกแบบคู่นี้ ทำให้โครงสร้างง่ายต่อการผลิตเพราะใช้ตัวทำงานน้อยลง และสเตเตอร์มีความแข็งน้อยลงเพราะพื้นที่การยึดติดตัวทำงานน้อยลง เมื่อเปรียบเทียบกับการติดตัวทำงานแบบเดิมที่ติดวัสดุเพียโซอเล็กทริกแบบเต็มสเตเตอร์

คำสำคัญ: มอเตอร์อัลตราโซนิค, ตัวทำงาน, เพียโซอิเล็กทริก, คลื่นเคลื่อนที่

Characteristics of the Ultrasonic Motor with the Partially Laminated Piezoelectric Actuation

Abstract

Design and performance testing of an ultrasonic linear motor with dual piezoelectric actuator patches are studied. The motor system consists of a linear stator, a pre-load weight, and two piezoelectric actuator patches. The piezoelectric actuators are bonded with the linear elastic stator at specific locations. The stator generates propagating waves when the piezoelectric actuators are subjected to harmonic excitations. Vibration characteristics of the linear stator are analyzed and compared with finite element and experimental results. The analytical, finite element and experimental results show agreement. In the experiments, performance of the ultrasonic linear motor is tested. Relationships between velocity and pre-load weight, velocity and applied voltage, driving force and applied voltage, and velocity and driving force are reported. The design of the dual piezoelectric actuators yields a simpler structure with a smaller number of actuators and lower stator stiffness compared with a conventional design of an ultrasonic linear motor with fully laminated piezoelectric actuators.

Keywords: Ultrasonic motor, Actuator, Piezoelectric, Traveling wave.

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1. ชื่อโครงการ (PROJECT TITLE):

(ภาษาไทย) คุณลักษณะของมอเตอร์อัลตราโซนิคเมื่อกระตุ้นด้วยตัวทำงานเพียโซอิเล็กทริกแบบบางส่วน

(ภาษาอังกฤษ) CHARACTERISTICS OF THE ULTRASONIC MOTOR WITH THE PARTIALLY LAMINATED PIEZOELECTRIC ACTUATION.

รหัสโครงการ (Project Code): MRG5380183

2. คณะผู้วิจัย (RESEARCH TEAM) :

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3. สาขาวิชาที่ทำการวิจัย ULTRASONIC PIEZOELECTRIC MOTOR

4. งบประมาณทั้งโครงการ 480,000 บาท

5. ระยะเวลาดำเนินงาน 2 ปี

6. ความสำคัญและที่มาของปัญหา (IMPORTANCE AND MOTIVATION OF THE RESEARCH)

A structronic system synergistically integrates smart materials, electronics, sensor/actuator, control with precision structures and machines, which is a structural application of the mechatronic systems. Structronic systems are used in many applications: adaptive wings, sensors or actuators in vibration control systems, variable-geometry structures, MEMS, NEMS, etc. An ultrasonic piezoelectric motor is also one of structronic actuator applications. This research is to develop a new ultrasonic piezoelectric motor and to evaluate its electro-dynamic behavior with the reduced number of actuators based on the new structronics technology.

There are many advantages of the ultrasonic motor over the traditional (electromagnetic) motor such as producing a high torque at a low speed with a high efficiency; the high torque produced as compared with its weight - since the inertia of the moving part can be made very small, the position control characteristic at start and stop is well controlled (Toyama et al., 1995 and 1996). There is no need for gears since the large torque can be produced. Precise positioning is possible because there is no error due to the gear backlash. The existing position can be maintained even when the electrical power supply is cut off because of the frictional force between contact areas. It has silent operation since speed-reduction gears are not required (Ueha et al, 1993; Uchino, 1998) and it has no magnetic field (Hemsel and Wallaschek, 2000). For these reasons, the ultrasonic motors are attractive for many industrial or special applications, for example, robot actuators, drive mechanism for auto-focus lenses, precise positioning devices, miniaturized machines, actuators for space applications, material conveyors (Ueha et al., 1993).

The traveling wave generated at the stator of the ultrasonic motor driving the rotor is a key design factor governing the overall motor performance; note that the traveling wave is also often referred to as the propagating wave. Unlike vibration in ultrasonic piezoelectric circular disk motors (Sashida and Kenjo, 1993; Ueha et al., 1993), boundary conditions of the finite length media (such as circular arc, beam and plate) reflect the waves when those generated waves hit the boundaries. This may generate undesirable standing waves.

The ultrasonic piezoelectric motor can be used in many applications, e.g., drive mechanism micro positioning, wave transport, material conveyer and movable structure. The piezoelectric actuator patterns for generating traveling waves have been recently studied (Smithmaitrie, 2007). The results show that partially laminated piezoelectric actuators are also possible of generating traveling waves, offering an alternative solution to the fully laminated piezoelectric actuators on the stator (Smithmaitrie et. al., 2008). The research methodology and knowledge are key information for design and development to improve performance of finite length ultrasonic motors.

Since, production cost and complication of piezoelectric motors depend on number of piezoelectric actuators used in the system, then, reducing the number of the actuators implies reducing production cost and system simplification. This is attractive to practical applications and industrial production.

2. วัตถุประสงค์ (OBJECTIVES OF THE RESEARCH)

The objectives of this research can be summarized as follows:

1) To analyze the vibration behavior of the ultrasonic motor when the motor is excited by the partially laminated piezoelectric actuators.
2) To determine characteristic and performance of the ultrasonic motor that is actuated by partially bonding piezoelectric actuators.

3. ระเบียบวิธีวิจัย

A methodology is developed to study the electromechanical characteristics of ultrasonic piezoelectric motor with partially laminated piezoelectric actuators. In that methodology, the finite element model is developed to determine the vibration characteristic of the motor and the operating frequency that yield stable traveling waves. After that, a prototype of the ultrasonic motor is built to according the design in the finite element analysis. Then, experiment of the ultrasonic piezoelectric motor is tested to determine the motor characteristics. Finally, the experimental result is analyzed and compared with the finite element results.

4. แผนการดำเนินงานวิจัย (RESEARCH PLAN)

Phase	Year 0.5	Year 1	Year 1.5	Year 2
Develop the finite element model of the ultrasonic piezoelectric stator with partially laminated actuators.	▬			
Study the vibration characteristic of the system with partially laminated actuators by using finite element method and determine the operating frequency		▬		
Order electronic equipments, materials, actuators and sensors.		▬		
Build electronic circuit, data interface system.		▬		
Build a prototype of the motor, and setup the experiment.			▬	
Perform the experiment and determine the characteristic of the motor.				▬
Analyze and compare experimental result with FE results				▬
Write reports/manuscripts	▬	▬	▬	▬

5. ผลงานตีพิมพ์ในวารสารวิชาการระดับนานาชาติ (OUTPUT)

Smithmaitrie, P., Suybangdum, P., Laoratanakul, P. and Muensit, N., (2012), "Design and Performance Testing of an Ultrasonic Linear Motor with Dual Piezoelectric Actuators," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 59(5), pp. 1033-1042. DOI 10.1109/TUFFC.2012.2289 **(JIF2011: 1.462) (รายละเอียดตามภาคผนวก)**

รายชื่อคณะผู้วิจัยในโครงการ

คณะผู้วิจัย (RESEARCH TEAM) :

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(ภาษาอังกฤษ) : Assoc. Prof. Dr. PRUITTIKORN SMITHMAITRIE

ตำแหน่งวิชาการ : รองศาสตราจารย์

ระยะเวลาดำเนินงาน : **2 ปี**

เวลาทำงานวิจัยในโครงการประมาณสัปดาห์ละ **19 ชั่วโมง**

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CHAPTER 1
RESEARCH INTRODUCTION

1.1 ชื่อโครงการ (PROJECT TITLE)

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(ภาษาอังกฤษ) CHARACTERISTICS OF THE ULTRASONIC MOTOR WITH THE PARTIALLY LAMINATED PIEZOELECTRIC ACTUATION.

รหัสโครงการ (Project Code): MRG5380183

1.2 RESEARCH AREA: ULTRASONIC PIEZOELECTRIC MOTOR

1.3 IMPORTANCE AND MOTIVATION OF THE RESEARCH

A structronic system synergistically integrates smart materials, electronics, sensor/actuator, control with precision structures and machines, which is a structural application of the mechatronic systems. Structronic systems are used in many applications: adaptive wings, sensors or actuators in vibration control systems, variable-geometry structures, MEMS, NEMS, etc. An ultrasonic piezoelectric motor is also one of structronic actuator applications. This research is to develop a new ultrasonic piezoelectric motor and to evaluate its electro-dynamic behavior with the reduced number of actuators based on the new structronics technology.

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Since, production cost and complication of piezoelectric motors depend on number of piezoelectric actuators used in the system, then, reducing the number of the actuators implies reducing production cost and system simplification. This is attractive to practical applications and industrial production.

1.4 OBJECTIVES OF THE RESEARCH

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1) To analyze the vibration behavior of the ultrasonic motor when the motor is excited by the partially laminated piezoelectric actuators.
2) To determine characteristic and performance of the ultrasonic motor that is actuated by partially bonding piezoelectric actuators.

1.5 LITERATURE REVIEW

Piezoelectric ultrasonic motors have been continuously developed over a decade (Sashida and Kenjo, 1993; Ueha et al, 1993). The principle of ultrasonic motors is to utilize ultrasonic oscillations (or waves) generated by piezoelectric actuators to create forces driving the rotor by friction at the contact surface as illustrated in Figure 1.1. Most of ultrasonic vibration sources are based on piezoelectric materials bonded with the motor structure.

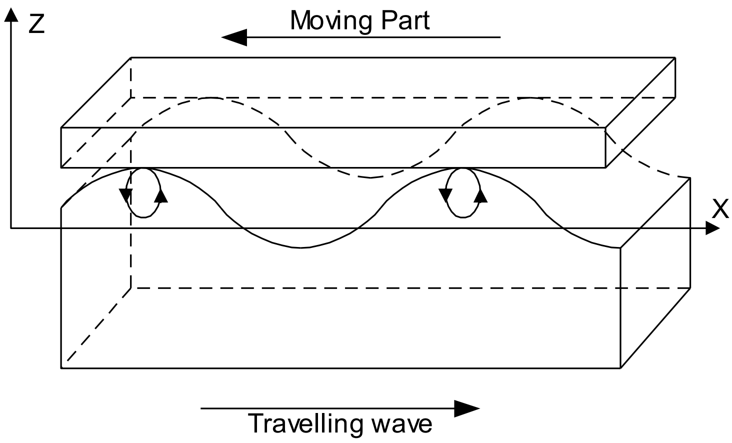

Figure 1.1 Principle of propagating-wave type motor.

An ultrasonic motor system usually consists of a stator and a rotor. The traveling wave generated at the stator driving the rotor is a key design factor governing the overall motor performance (Note that the traveling wave is also often referred to as the propagating wave). Unlike vibration in ultrasonic piezoelectric circular disk motors (Sashida and Kenjo, 1993; Ueha et al. 1993), boundary conditions of the finite length structure (e.g., arc, beam and plate) reflect the waves when those generated waves hit the boundaries. This may generate undesirable standing waves. There are techniques to generate traveling waves in finite length media. One technique is to use two actuators with one vibrator at one end to generate the vibrations and one absorber at the other end to absorb those vibrations as shown in Figure 1.2 (Kuribayashi et al., 1985). This technique generates only one-way traveling waves.

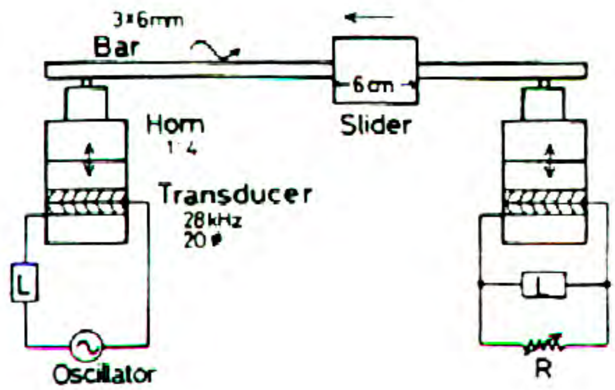

Figure 1.2 Ultrasonic linear motor using two transducers (Kuribayashi et al., 1985).

Another technique is to use two vibrators at the opposite ends generating traveling waves by superposing two standing waves with different phases as shown in Figure 1.3 (Higuchi, 1995). This technique is capable of generating either forward or backward traveling waves by the pair of vibrators operating in the appropriate phases.

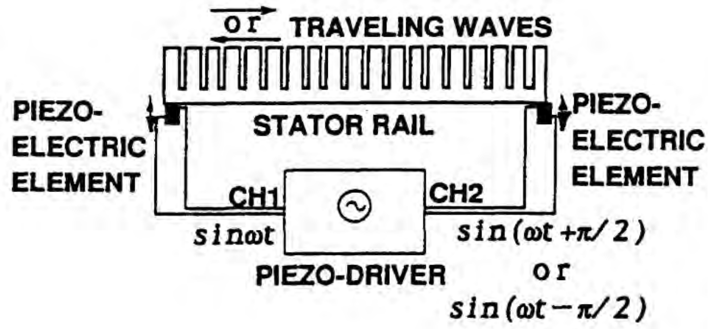

Figure 1.3 The straight finite length rail linear motor (Higuchi, 1995).

The other technique is to use the piezoelectric patches bonded with an elastic medium, producing traveling waves by superposing two standing waves. Figure 1.4 shows a pattern of piezoelectric patches designed so that they can generate two sinusoidal waveforms at different time and location phases (Ueha et al., 1993; Roh et al., 2001). External vibrators are no longer needed in this setup, since the waves are generated by bonded actuator patches. This motor construction is relatively simple and flexible. However, wave reflection at the boundaries is prohibited because this can interfere and distort the pattern of traveling waves. In practice, damping materials are attached to the boundaries to prevent wave reflection. Ultrasonic motors made of a finite length medium (e.g., plates and beams) laminated with piezoelectric actuators have been reported (Tomikawa et al., 1989; Kosawada et al., 1992; Roh et al., 2001; Ming et al., 2005), but those are only designed for linear translational motions.

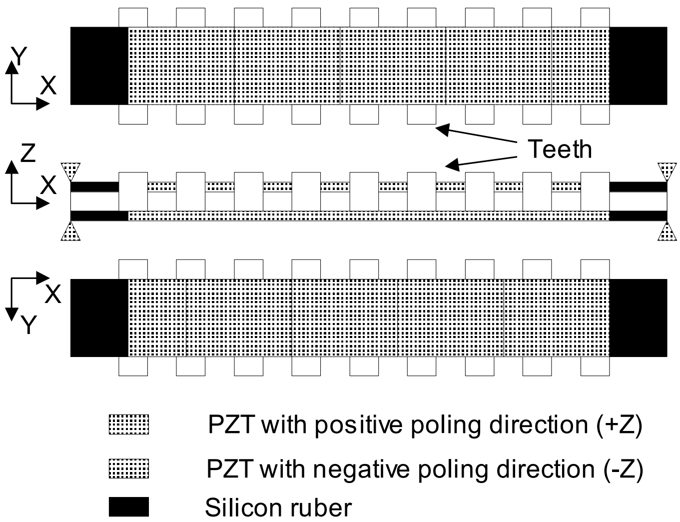

Figure 1.4 Straight finite length beam linear motor (Roh et al., 2001).

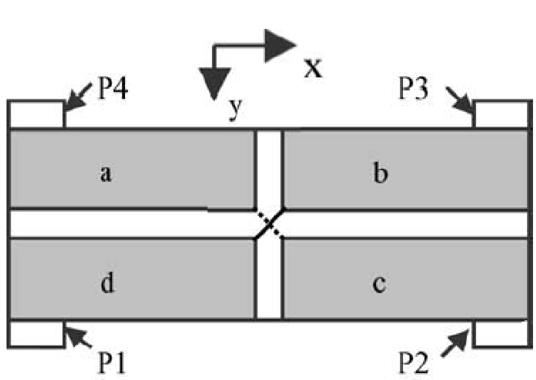

Figure 1.5 Patterns of Electrodes on the piezoelectric plate linear motor (Ming et al., 2005).

A new design of piezoelectric curvilinear arc motor has been proposed as illustrated in Figure 1.6 (Smithmaitrie, 2005). In addition, analysis and mathematical model of piezoelectric actuator laminated on the piezoelectric curvilinear arc stator has been developed as illustrated in Figure 1.7 (Smithmaitrie et al., 2007). The design of the actuator pattern for the curvilinear arc stator is developed based on those linear translational motors.

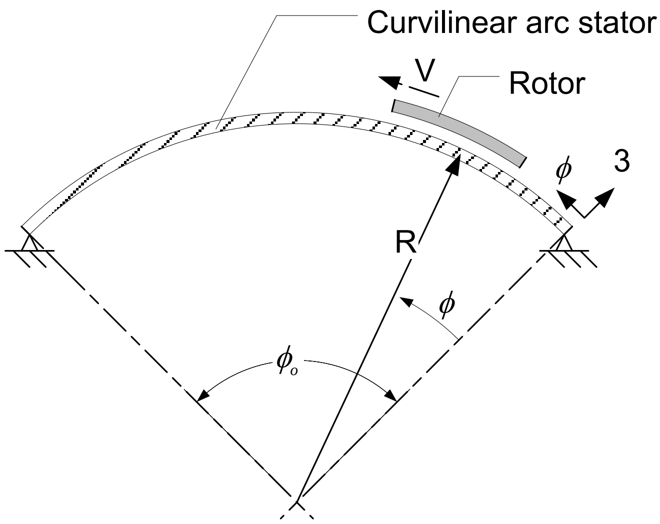

Figure 1.6 Schematic diagram of the curvilinear arc motor (Smithmaitrie, 2005).

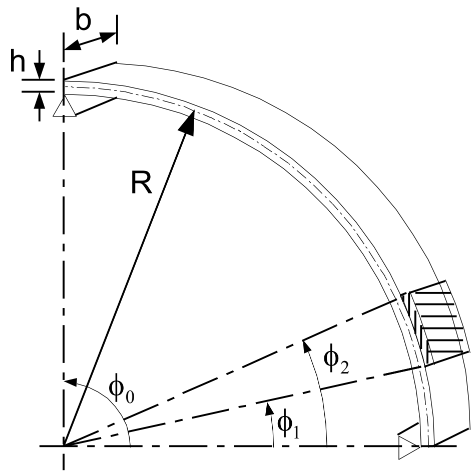

Figure 1.7 Analysis of a laminated piezoelectric actuator on the curvilinear arc stator (Smithmaitrie et al., 2007).

The effect of number of piezoelectric actuator patches has been investigated (Smithmaitrie et al., 2008). As a result of the research, the actuation characteristic of the piezoelectric actuators has been studied in order to find out the alternative actuator patterns for generating traveling waves (Smithmaitrie et al., 2008) as illustrated in Figure 1.8. The results show that partially laminated piezoelectric actuators are also capable of generating traveling waves, offering an alternative solution to the fully laminated piezoelectric actuators on the stator. The research methodology and knowledge yield crucial information for design and development to improve performance of the finite length ultrasonic motors.

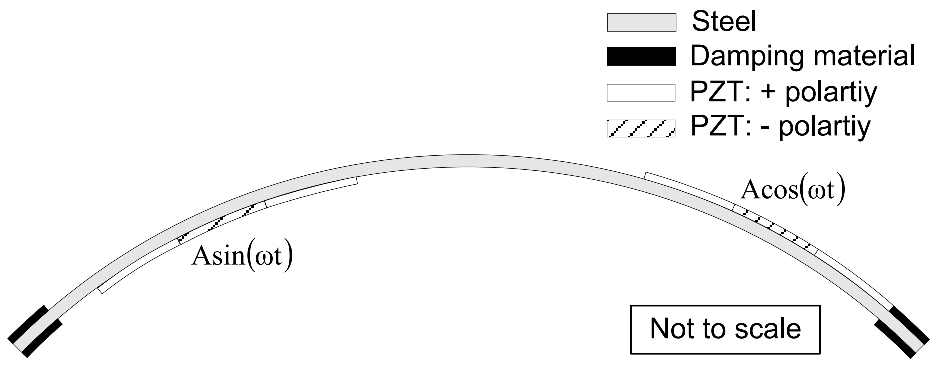

Figure 1.8 The partially laminated arc stator with piezoelectric actuators near the supports (Smithmaitrie et al., 2008).

After the knowledge of design the partially actuation ultrasonic motor has been thoroughly studied as earlier mention, the test of the motor characteristics, e.g., operating frequency, velocity and driving load should be conduct to evaluate the motor performance.

Hence, the main objective of this research is to build and test the ultrasonic motor with partially laminated piezoelectric actuators.

1.6 RESEARCH METHODOLOGY

A methodology is developed to study the electromechanical characteristics of ultrasonic piezoelectric motor with partially laminated piezoelectric actuators. In that methodology, the finite element model is developed to determine the vibration characteristic of the motor and the operating frequency that yield stable traveling waves. After that, a prototype of the ultrasonic motor is built to according the design in the finite element analysis. Then, experiment of the ultrasonic piezoelectric motor is tested to determine the motor characteristics. Finally, the experimental result is analyzed and compared with the finite element results.

1.7 SCOPE OF THE RESEARCH

The scope of this project is to study the vibration and characteristic of the ultrasonic piezoelectric motor that excited by the partially laminated piezoelectric actuators. Major tasks can be summarized as follows:

1) Design and develop the finite element model of the ultrasonic piezoelectric motor to determine operating frequency and vibration characteristic.
2) Build the ultrasonic motor with partially laminated piezoelectric motor.
3) Setup an experiment and test characteristic of the ultrasonic motor.
4) Analyze and compare the experimental result with the analytical and finite element results.

1.8 RESEARCH PLAN

Phase	Year 0.5	Year 1	Year 1.5	Year 2
Develop the finite element model of the ultrasonic piezoelectric stator with partially laminated actuators.				
Study the vibration characteristic of the system with partially laminated actuators by using finite element method and determine the operating frequency				
Order electronic equipments, materials, actuators and sensors.				
Build electronic circuit, data interface system.				
Build a prototype of the motor, and setup the experiment.				
Perform the experiment and determine the characteristic of the motor.				
Analyze and compare experimental result with FE results				
Write reports/manuscripts				

1.9 RESEARCH OUTPUT

International Journal:

Smithmaitrie, P., Suybangdum, P., Laoratanakul, P. and Muensit, N., (2012), "Design and Performance Testing of an Ultrasonic Linear Motor with Dual Piezoelectric Actuators," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 59(5), pp. 1033-1042. DOI 10.1109/TUFFC.2012.2289 **(JIF2011: 1.462) (รายละเอียดตามภาคผนวก)**

Reviewer of International Conference:

- The International Data Storage Technology Conference (DST-CON) (2011)

Reviewer of National Journal:

- Songklanakarin Journal of Science and Technology (2012)

Reviewer of International Journal:

- Journal of Intelligent Material Systems and Structures (2010, 2011)

1.10 RESEARCH CONCLUSIONS

An ultrasonic linear motor with dual piezoelectric actuators has been studied and tested in this work. The design deploys two piezoelectric actuators that are bonded with a linear stator, one actuator near each end of the support. Movement direction of the motor is controlled by alternating phase difference between two harmonic control signals. Analytical, finite element and experimental results of the natural frequency of the linear stator reveal positive agreement. The operating frequency resulted from the finite element analysis (29.2 kHz) is in good comparison with that from the experimental result (28.2 kHz). Based on the experimental testing, the suitable pre-load pressed on the motor is 101.5 g. The maximum velocity of the motor is 17.59 cm/s at an applied voltage of 59 V. The power consumption of the motor is 0.2 W.

The design of the ultrasonic linear motor with dual piezoelectric actuators exhibits a simpler structure with fewer actuators, thus yielding a low system structural stiffness in comparison with conventional ultrasonic linear motors with fully laminated actuators, even though the fewer piezoelectric actuators weaken the driving force. But, the dual piezoelectric motor is designed to operate near the resonance frequency. Thus, it has high vibration amplitude and low structural stiffness to partially compensate for the fewer number of actuators. The new design of the ultrasonic linear motor with dual actuators presented in this work has the least amount of piezoelectric material volume, yet it still performs the traveling wave motor task. Moreover, the design of the linear motor can be scaled down. This opens up an opportunity for many applications that require a tiny translation actuator.

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CHAPTER 2

CHARACTERISTICS OF THE ULTRASONIC MOTOR WITH THE PARTIALLY LAMINATED PIEZOELECTRIC ACTUATION

In this chapter, design and performance testing of an ultrasonic linear motor with dual piezoelectric actuator patches are studied. The motor system consists of a linear stator, a pre-load weight and two piezoelectric actuator patches. The piezoelectric actuators are bonded with the linear elastic stator at specific locations. The stator generates propagating waves when the piezoelectric actuators are subjected to harmonic excitations. Vibration characteristics of the linear stator are analyzed and compared with finite element and experimental results. The analytical, finite element and experimental results show agreement. In the experiments, performance of the ultrasonic linear motor is tested. Relationships between velocity and pre-load weight, velocity and applied voltage, driving force and applied voltage, velocity and driving force are reported. The design of the dual piezoelectric actuators yields a simpler structure with less number of actuators and lower stator stiffness compared with conventional design of ultrasonic linear motor with fully laminated piezoelectric actuators.

2.1 INTRODUCTION

Ultrasonic motors can be classified into two major categories based on vibration characteristics: traveling wave motors and standing wave motors (Hemsel and Wallaschek 2000; Chen, Liu, and Zhou 2006). An ultrasonic motor usually consists of a stator and a rotor. The stator drives the rotor by means of mechanical waves at the contact area. The waves are generated by piezoelectric actuators which are bonded with the stator. The electrical excitation applied to the piezoelectric actuator induces deformation on the piezoelectric actuator and stator (Smithmaitrie et al. 2007; Smithmaitrie et al. 2008). There are many advantages of ultrasonic motors over conventional electromagnetic motors. For instance, ultrasonic motors have high driving force per body weight, high precision in order of nanometer (Lu et al. 2006), high torque at low speed without a gear mechanism (Chen, Liu, and Zhou 2006), no magnetic field working without restriction of induction (Roh, Lee, and Han 2001; Sun et al. 2009), high static friction holding-force without power supply (He et al. 1998; Chen, Liu, and Zhou 2006; Lu et al. 2006), ability to work in vacuum environment (Sashida and Kenjo 1993; Yoo et al. 2007), short response time, compact size, light weight and quiet operation. However, the ultrasonic motor still has noise in ultrasonic range which should be considered in some cases.

Types of ultrasonic linear motors are direct flexural waves, hybrid transducers, sandwich vibrators, multi-mode vibrators, surface acoustic waves, impact motors, π-shape transducers and the Paderborn rowing type. The direct flexural waves (Roh and Kwon 2004; Ming et al. 2005) have simpler structure and more flexibility. The hybrid transducers (Cheol-Ho Yun et al. 2001) have many advantages such as a large mechanical output, good performance and also give bidirectional motion. The sandwich vibrators (Kuribayashi Kurosawa et al. 1998) can achieve very high speed and large thrust. The multi-mode vibrators (Lu et al. 2006; Zhai et al. 2000; Hemsel et al. 2006) have a simple structure, but they require simultaneously excitation of two vibration modes at a specific synchronization of the two modes, which causes restrictions on design and fabrication. The surface acoustic wave motors (Sashida and Kenjo 1993; M. Kurosawa, Takahashi, and Higuchi 1996; Uchino 1998; M. K. Kurosawa 2000; Takasaki, Kuribayashi Kurosawa, and Higuchi 2000) have high energy density and tiny size. The impact motors (Chen et al. 2002; Jin and Zhao 2006; Ko et al. 2006; Lim et al. 2007) have a compact working unit. The advantages of π-shape transducers and Paderborn rowing type (Hemsel and Wallaschek 2000) are that they have low energy loss, high efficiency and vibration amplitude because they used the d_{33} effect instead of the d_{31} effect. There are many techniques to improve performance of motors such as using actuators that are made of multi-layer piezoelectric ceramics instead of single layer piezoelectric ceramics (Zhai et al. 2000) because it generated larger mechanical output for a given voltage, thus yielding the higher motor speed and driving load, replacing single driving foot with double driving feet to increase torque of the motor (Lu et al. 2006), using high efficiency friction materials (Uchino 1998; Ko et al. 2006), can generate maximum driving force at the contact area between the stator and the rotor.

Various designs of traveling wave ultrasonic motors have been reported. The traveling wave linear motor using a ring-type stator, designed by (Hermann, Schinköthe, and Haug 1998), was excited by a pair of orthogonal mode shapes at the same resonance frequency. This motor has high velocity and short time constant, but it has a large size stator. The surface acoustic wave motor, proposed by (M. Kurosawa, Takahashi, and Higuchi 1996; M. K. Kurosawa 2000), used the interdigital transducer with a high frequency electrical power source to generate the high frequency traveling wave on the media surface. This design yielded very high output force density with tiny size of stator. However, the system required the high voltage and high power supply to drive the transducer. The vibrator-absorber linear motor making use of the d33 effect, proposed by (Sashida and Kenjo 1993), generated high vibration amplitude resulting high velocity and trust force. But, the main drawback is its large size.

Ultrasonic motors are attractive devices for applications on automatic focusing device of digital camera and optical lens zooming operation in personal digital assistant (PDA) and mobile phone (Yoo et al. 2007; Lim et al. 2007; Paik et al. 2009), image processing (Ko et al. 2006), robot, aerospace, automatic control, military industry, medical instrument (Jin and Zhao 2006), chemical mixing process, pharmaceutical and food industries that demand an exact control of powder feeding (Mracek and Wallaschek 2005).

The design of the dual piezoelectric actuator is a kind of traveling wave ultrasonic motor. Even though efficiency of general traveling wave ultrasonic motors is low but there are a few advantages as well. One is that the driving structure can be integrated into a system. By design of the actuator bonded location, it can turn a continuous structure into a wave media. This is a different design concept rather than use of a separated driving system such as a contact driving motor. In addition, this work presents the use of only two piezoelectric patches for creating the traveling wave and capable of control the wave direction on a flat beam. The design is capable of scaling down the size. This could provide a linear translation on flat media as well, similar to the PCB motor giving the rotational motion (Ellesgaard et al. 2010). Other possible applications of this linear traveling wave driver are such as powder transport and linear translation on MEMs devices.

All these ultrasonic motors have been using certain numbers of active piezoelectric actuator to create mechanical vibration on the stator. A large number of piezoelectric actuators will cause both high energy consumption and undesired system stiffness, resulting in requirement of high applied voltage for the generation of effective vibration on the stator. In structural mechanics, the lower stiffness structure gives the larger vibration amplitude for the same amount of applied energy. Moreover, the ultrasonic motor should not be operated at too high frequency due to the limitation of the electrical power supply. At high frequency, the piezoelectric actuator consumes high electrical power. It is because the piezoelectric actuator acts as a capacitance load which its power consumption depends on frequency (Liang, Sun, and Rogers 1994; Brennan and McGowan 1997). Moreover, if the high applied voltage is acquired to achieve the high vibration amplitude, then this may lead to accumulate the heat due to the mechanical vibration which would raise the temperature of the system during operation. This could cause depolarization of the piezoelectric actuator because it operates at high temperature due to the heat from the mechanical strain under the active electrical field (Roh, Lee, and Han 2001). Furthermore, many ultrasonic linear motors are complicated in fabrication (Zhai et al. 2000). For this reason, one of the main objectives of this research is to reduce the number of piezoelectric actuators, so that it will be simpler for fabrication, require lower applied voltage and consume less energy. Even though, the fewer piezoelectric actuators weaken the driving force. However, the dual piezoelectric motor is designed to operate near the resonance frequency. Thus, it has high vibration amplitude and low structural stiffness to partially compensate the reduced number of actuators. Hence, a new design of ultrasonic linear motor with dual piezoelectric actuators is introduced in this work. The principle of operation of the ultrasonic linear motor is discussed. Vibration characteristics of the linear stator are investigated by using finite element method. In addition, the performance of the ultrasonic linear motor with dual piezoelectric actuators is assessed. Key relationships among performance parameters such as velocity, pre-load weight, applied voltage and driving force are reported. Topics of discussion are presented in detail in the following sections.

2.2 THE DESIGN AND THE PRINCIPLE OF OPERATION

An ultrasonic linear motor with dual piezoelectric actuators consists of a beam stator with rectangular teeth, damping material patches and two piezoelectric actuators bonded with the beam structure near both ends of the beam, as shown in Figure 2.1. The actuator design is that the length of the actuator is equal to the wave length (λ), the location phase shift between the two actuators is a half of the wave length ($\lambda/2$). Both actuators are bonded with the stator on the same surface and their piezoelectric domains point in the same direction, toward the teeth. The phase difference of the two harmonic excitations on the piezoelectric actuators is 90 degree, so that the rotor can be driven efficiently (Sashida and Kenjo 1993). The transverse vibration mode number of a beam, with fixed boundary conditions on both ends, is counted by the number of antinodes (Blevins 2001). That is, one wavelength has two antinodes. Hence, in this works, the operating frequency is occurred in between the 14^{th} and 15^{th} modes which are respectively corresponding to the 7 and 7-and-a-half wavelengths. Note that the actuator design proposed in this work is different from Roh's (Roh, Lee, and Han 2001) which has the $\lambda/2$ actuator length. In addition, on the same surface, Roh's actuators have no location phase shift and the piezoelectric domains point in opposite direction.

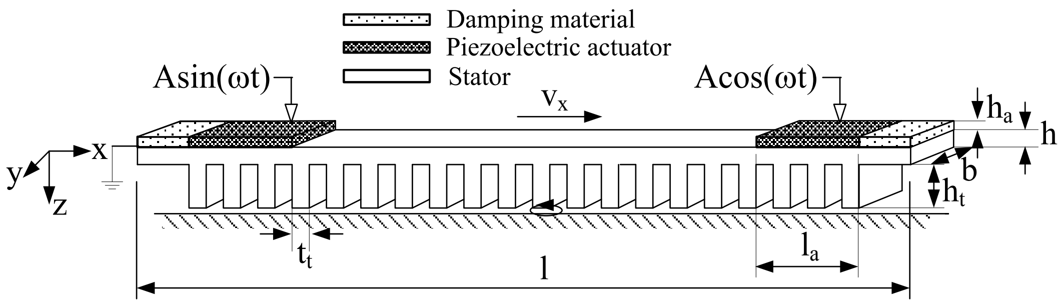

Figure 2.1. Design of the ultrasonic linear motor with dual piezoelectric actuators.

The stator generates traveling waves when the piezoelectric actuators are excited by harmonic excitations. The wave should propagate on the stator in one direction with consistency in wave amplitude. However, traveling waves reflect when they hit a physical boundary at the end of the stator. This distorts the pattern of the traveling waves. Accordingly, damping material patches are attached to the stator at both ends of the stator adjacent to the fixed supports in order to prevent wave reflections. The piezoelectric ceramic actuators are polarized in the thickness direction. The two harmonic excitations are Asin(ωt) and Acos(ωt) signals, where A is the signal amplitude, ω is the driving frequency and t is the time. The body of the stator is grounded. Direction of the traveling waves can be controlled by alternating the phase difference between the two control signals. Teeth on the stator are designed to expand the wave amplitude and to create elliptical motions at the tips of the teeth. The elliptical motions at the tips generate driving forces against the contact surface (Sashida and Kenjo 1993; Uchino 1998). Velocity of the motor can be controlled by adjusting the amplitude of excitation voltages on the piezoelectric actuators.

The stator is assumed to be a thin beam. Hence, vibration theory of the elastic thin beam is applicable to analyze the characteristics of the stator. The governing equation of a homogeneous isotropic solid beam (Fernandez and Perriard 2003), is expressed as follow:

$$\mathrm{YI}\frac{\partial^4 u_3}{\partial x^4} + \rho \mathrm{bh}\frac{\partial^2 u_3}{\partial t^2} = 0, \tag{1}$$

where Y is the Young's modulus, I = $bh^3/12$ is the area moment of inertia of the beam cross-section, b is the beam width, h is the beam thickness, u_3 is the transverse displacement, ρ is the mass density and bh represnts the cross-section area. The solution of the governing equation above is:

$$u_3(x,t) = A_z \sin(\omega t - kx), \tag{2}$$

where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength and A_z is the transverse wave amplitude. In addition to the transverse displacement, the longitudinal displacement of a tooth tip (u_{1_tip}) is given by:

$$u_{1\_tip}(x,z,t) = -a\frac{\partial u_3}{\partial x} = aA_z k\cos(\omega t - kx), \tag{3}$$

where a is the distance from the beam neutral surface to the teeth contact surface. Based on (2) and (3), the trajectory of a point at the tooth tip can be achieved:

$$\left(\frac{u_{1\_tip}}{aA_z k}\right)^2 + \left(\frac{u_3}{A_z}\right)^2 = 1. \tag{4}$$

Equation (4) shows that the trajectory of the point is elliptical. When the stator is pressed against the surface, the stator moves itself by the friction force exerting at the contact surface. The velocity in the x-direction is obtained by the derivate of (3):

$$v_x = -aA_z k\omega \sin(\omega t - kx). \tag{5}$$

Equation (5) represents the maximum speed reachable by the motor. The motor moves in opposite direction to the wave direction. Thus, the motor can move in another direction by reversing the wave direction. The natural frequency of the beam with fixed-fixed boundary condition (Blevins 2001) can be written as:

$$f_i = \frac{1}{2\pi L^2}\left(\frac{(2i+1)\pi}{2}\right)^2 \sqrt{\frac{YI}{m}}\ ; \quad \text{for } i > 5 \tag{6}$$

where L is the length of the beam and m is the mass per unit length of the beam. In the case study, the mass of the teeth on the linear stator is also included into the mass per unit length of the beam by approximation (Smithmaitrie et al. 2008). In order to verify the theoretical analysis, the ultrasonic linear motor with dual piezoelectric actuators is studied employing a finite element software package. The finite element model of the ultrasonic motor is discussed next.

2.3 FINITE ELEMENT MODEL OF THE ULTRASONIC LINEAR MOTOR WITH DUAL PIEZOELECTRIC ACTUATORS

According to the design described above, the stator of the ultrasonic linear motor is modeled to study the vibration characteristics, the frequency response and the local motion of the tooth tip. The linear stator is made of brass. The dimensions of the stator are: width b of 6 mm, length l of 85 mm and beam thickness h of 1 mm. The teeth dimensions are: height h_t of 3 mm, width b of 6 mm and thickness t_t of 1.5 mm. The teeth are used for amplifying the elliptical trajectory at the surface contact. The piezoelectric actuator is made of Lead Zirconate Titanate (PZT-4). The actuator dimensions are: length l_a of 10 mm, width b of 6 mm and thickness h_a of 0.5 mm, as shown in Figure 2.1. In this study, the length of the actuator is equal to the wave length of the 15^{th} mode. The two piezoelectric actuators are located one at each end of the stator. The actuators are excited by a pair of electrical signals, Asin(ωt) and Acos(ωt). Capacitance of the piezoelectric actuator is measured by using a LCR meter (GW Instek LCR-821). It is assumed that the piezoelectric actuator (PZT-4) is an orthotropic material. The related shear modulus can be calculated based on the given modulus of elasticity and Poisson’s ratio.

Properties of the piezoelectric material and its damping coefficient are provided by the manufacturer. Note that the common damping properties (Barron 2003) of the materials and real excitation amplitude are used in the finite element model in order to estimate the system response. The stator is made of brass because it is practical in manufacturing and processing. Other properties of the stator, the actuators and the damping materials are described in Table I.

TABLE I Material properties of the ultrasonic linear motor with dual piezoelectric actuators

	PZT-4 actuator	Brass stator	Silicon rubber damping material	Unit
Modulus of Elasticity	(Orthotropic)	(Isotropic)	(Isotropic)	
Y_{11}	79	96	4.2×10^{-3}	GPa
Y_{33}	66	96	4.2×10^{-3}	GPa
Density	7700	8400	1510	kg/m^3
Poisson's ratio	0.33	0.35	0.45	
Damping coefficient	0.0013	0.0005	0.05 (Barron	
Piezoelectric constant		(Barron	2003)	
e_{33}	17.56	2003)		C/m^2
e_{31}	-4.38		-	C/m^2
Permittivity	1.018×10^{-8}	-	-	F/m
Capacitance	2096	-	-	pF
		-	-	
		-		

To predict the experimental result, the stator is modeled and simulated by using a finite element software package: MSC.Marc. The finite element model of the linear stator with dual piezoelectric actuators is illustrated in Figure 2.2. The stator is bonded with damping material patches at supported boundaries to prevent wave reflections. The model is assumed to be a 2.dimensional plane strain problem. The plane strain assumption assumes that there is no change of strain in the depth direction (the y-direction in Figure 2.1). Thus, the strain in a cross-section of the x-z plane can be represented the deformation of the structure. The boundary conditions of the stator are stipulated to be fixed at both ends. The excitation voltages are $54\sin(\omega t)$ on one actuator and $54\cos(\omega t)$ on the other one. The excitation frequency is varied to determine the operating frequency that generates a traveling wave. All material properties and dimensions of the finite element model are assigned according to the previous descriptions.

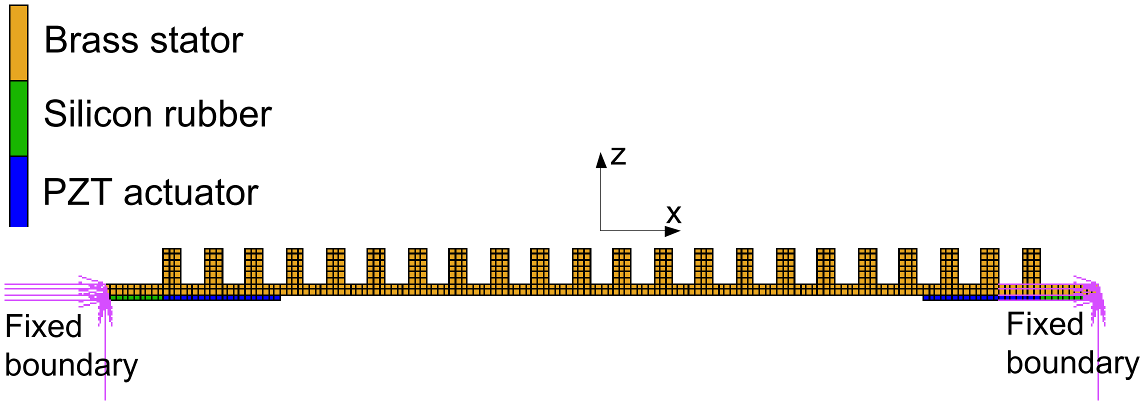

Figure 2.2. Finite element model of the stator with dual piezoelectric actuators.

2.4 VIBRATION CHARACTERISTICS OF THE STATOR

Analytical and finite element models of the stator with dual piezoelectric actuators are carried out and simulated to determine the system response based on the boundary conditions and excitations as operated. Details of the experimental testing are discussed in the next section. The modal analysis is conducted to study the free vibration characteristics of the system. Natural frequencies of the stator for the analytical, the finite element and experimental results are presented in Table II. The results of natural frequencies are observed at the higher modes because the operating frequency is expected near the 15th mode according to the actuator design. In Table II, the analytical results are quite different from the finite element and experimental results. The reason is that the analytical method has its own limitation due to the approximation of the geometry derivation. That is, the linear stator is assumed to be a simple beam. However, mass of the teeth on motor also induced the mass per unit length to the structure. In addition, the effective thickness of the beam has to be approximated to cover the effect of structural stiffness due to the teeth (Smithmaitrie et al. 2007; Smithmaitrie et al. 2008). Natural frequencies are obtained in the early range of ultrasonic frequency (just above 20 kHz). Reasons are to avoid causing audible noises at the lower frequency operation, and that a power amplifier circuit has a limited capability for generating signals at higher frequency operation.

TABLE II Natural frequencies of the ultrasonic linear stator

Mode	Natural frequency (kHz)		
	Analytical	Finite element	Experimental
12	23.41	22.21	20.85
13	27.30	24.82	23.79
14	31.50	27.25	26.88
15	35.99	29.53	29.53
16	40.79	31.53	31.97

Figure 2.3 illustrates the finite element result of the 14th and 15th mode shapes of the stator at 27.25 and 29.53 kHz, respectively, where the operating frequency is expected in between these modes. Note that the overall structural deformation is scaled up to show the vibration mode shape of the stator, the teeth are not actually crossing each other. Since the rubber elements have larger deformation compared with the brass and piezoelectric elements, this makes some rubber elements which have deformation shape pointing to the side seem to move over the fixed boundary but, in fact, they are not. It is just only the enlargement of deformed elements. The nodes on the side boundary are still fixed according to the boundary condition shown in Figure 2.2. The wave configuration could be expected based on its natural mode shape because the structure tends to behave closely to the natural mode shape when the system is operated near its natural frequency. The traveling wave is generated by combining two transverse vibration modes which have the same mode shape but different phase locations. The operating frequency that excites the dual piezoelectric actuators is not at the natural frequency, because the vibration response of the stator at the natural frequency is only a pure standing wave. Hence, the operating frequency is occurred in between the 14th and 15th modes. Moreover, the desirable traveling wave must move in one direction along the stator with consistency in wave amplitude, and the wave direction can be controlled by alternating the phase difference of the excitation signals.

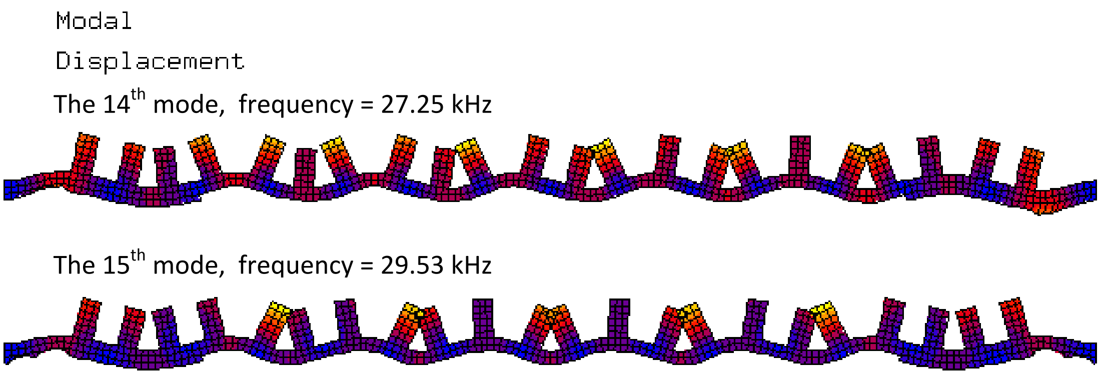

Figure 2.3. The 14th and 15th vibration mode shapes.

Following this, frequency response of the stator is investigated. The dual actuators are subjected to two sinusoidal voltages with amplitude of 54 V. These are 54sin(ωt) and 54cos(ωt) for the left and the right actuators, respectively. The excitation frequency ω is varied from 20 to 35 kHz in order to investigate the system response and to determine the operating frequency. Results show that the linear stator creates pure standing waves with high wave amplitude when the system is excited at natural frequencies. Likewise, there are ultrasonic motors that work near the natural frequency and yield superb performances because the systems respond with high wave amplitude at the natural frequency (Lu et al. 2006; Higuchi 1995; Zhu 2004; Mracek and Hemsel 2006; Zhang et al. 2006). Harmonic analysis is employed for the determination of displacement response of the wave. The wave configuration can be determined by transient analysis. In this case study, the operating frequency that yields the traveling wave is at 29.2 kHz which is in between the 14^{th} and 15^{th} modes as illustrated in Figure 2.4.

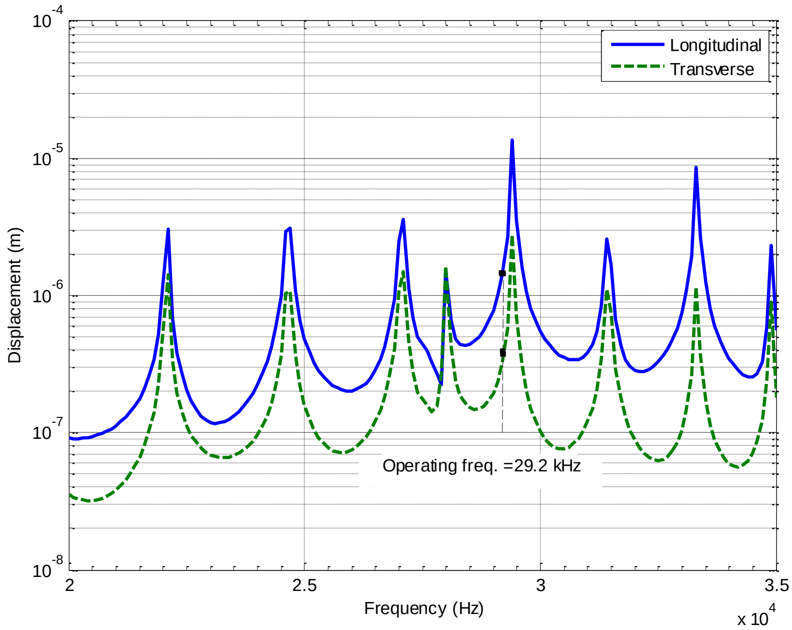

Figure 2.4. Harmonic response of the linear stator with dual piezoelectric actuators

An elliptical motion at the contact surface of a tooth tip is induced by the coupling of longitudinal and transverse displacements. Figure 2.5 shows nodal trajectories of the tooth tips at the contact surface based on the finite element result when the system is excited at the operating frequency of 29.2 kHz. The plot is in the same scale for both x- and y-axes to illustrate the aspect ratio of the elliptical path. The nodal trajectories of other tooth tips on the stator are also investigated, it is found that they all move in the same direction. Recalling that the motor moves in opposite direction to the trajectory path, the friction force generated on the contact surface is dependent on the transverse displacement, while the velocity of the motor depends on the longitudinal displacement. Hence, size of the elliptical trajectory is important to the motor performance. Figure 2.6 illustrates the stator deformation while the system is excited at the operating frequency. Note that the piezoelectric and rubber elements are hidden to enlarge the stator deformation and show the traveling wave. The size of elliptical trajectories (Figure 2.5) and the stator deformation (Figure 2.6) show that the traveling wave has large amplitude at the middle span and small amplitude near the end supports.

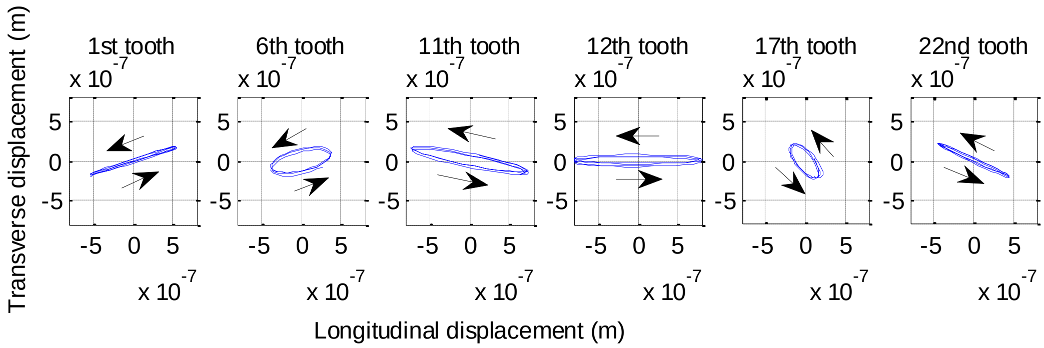

Figure 2.5. Elliptical trajectories of the tooth tips at the operating frequency.

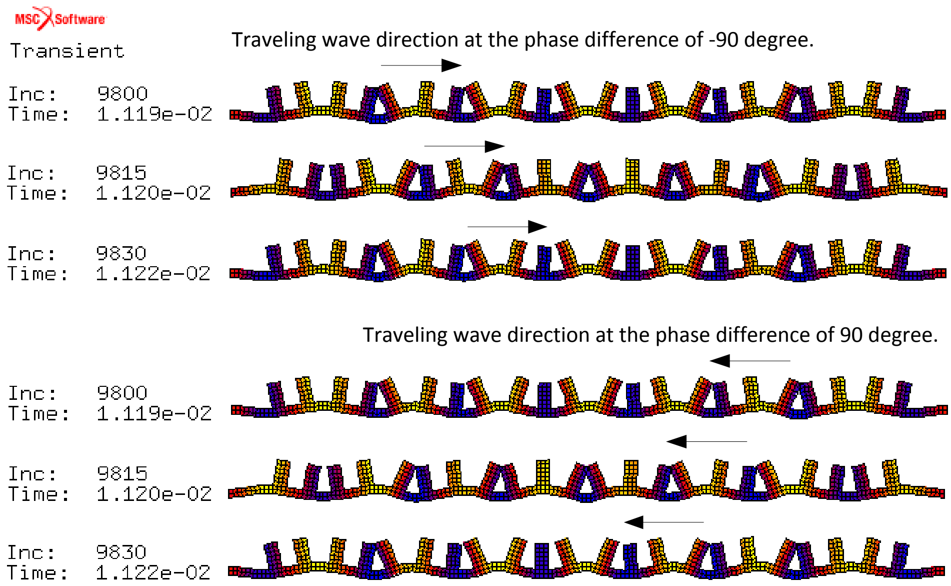

Figure 2.6. Traveling wave on the stator at the operating frequency.

The motor velocity is related to stator geometry, transverse wave amplitude, wave length and operating frequency as shown in Equation (5). The finite element results of these parameters at the operating frequency (29.2 kHz) are the harmonic transverse wave amplitude of 0.42 μm and the traveling wave length of 10.5 mm. As a result, the calculated motor velocity is 16.1 cm/s. However, the analytical motor velocity is based only on the stator vibration characteristic without the motor contact condition. The result may not be directly compared with the experimental result.

2.5 TESTING AND PERFORMANCE OF THE ULTRASONIC LINEAR MOTOR WITH DUAL ACTUATORS

One objective of the ultrasonic motor design is to reduce the energy consumption, the number of actuators, the applied voltage and to simplify the motor structure for fabrication. However, the amplitude of the generated wave must continuously remain. Figure 2.7 illustrates the linear stator with the dual piezoelectric actuators. Three electrical wires are attached each onto the open surfaces of the two actuators and the stator. Conductive epoxy is used for bonding the piezoelectric ceramic actuators with the stator, and the bonding is assumed to be perfect. The two piezoelectric actuators are connected to the brass stator which functions as a common ground. Figure 2.8 shows full assembly of the ultrasonic linear motor with the dual actuators. The fixed support and pre-load are integrated into the motor structure. In action, the stator faces down to contact the floor which acts as a stationary rotor. In this case, the pre-load is the compressive force which is included the weight of a load mass on the top of the stator and the weight of the stator itself. The motor moves itself relative to the floor in the direction opposite to the elliptical trajectory.

Figure 2.7. The linear stator with dual piezoelectric actuators.

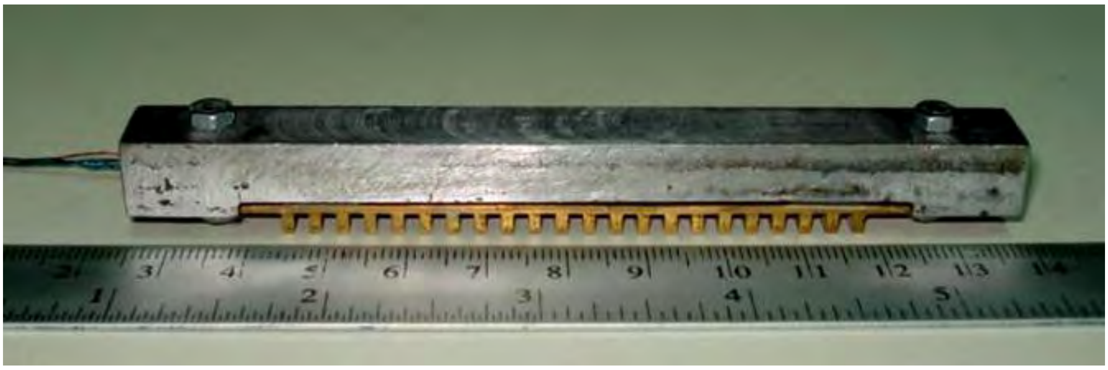

Figure 2.8. The full assembly of the linear motor with the fixed support and pre-load.

The main objective of the impedance measurement is to determine of the stator natural frequency and to study the interaction between the piezoelectric actuator and stator. Thus, only one actuator is excited. Natural frequencies of the motor are measured by using an impedance analyzer machine (Hewlett Packard, model 4194A). The impedance of the stator is measured on one piezoelectric actuator while another actuator is open-circuit. The stator is fixed with the preload at the supports. The voltage for measuring the stator impedance is set at 1 Vrms. Impedance and phase responses of the linear stator are plotted over the frequency range of 20 to 34 kHz as shown in Figure 2.9. Noise occurs when the system is measured below 25 kHz. The noise below 25 kHz may occur due to the conductive glue layer between the piezoelectric actuator and the brass structure. However, the natural frequency of the linear stator can be indicated at the frequency that yields low impedance output. Result shows that natural frequencies of the motor occur at 20.85, 23.79, 26.88, 29.53 and 31.97 kHz. These correspond respectively to the 12^{th} to the 16^{th} modes, as previously presented in Table II. The experimental results are in agreement with the analytical and the finite element results.

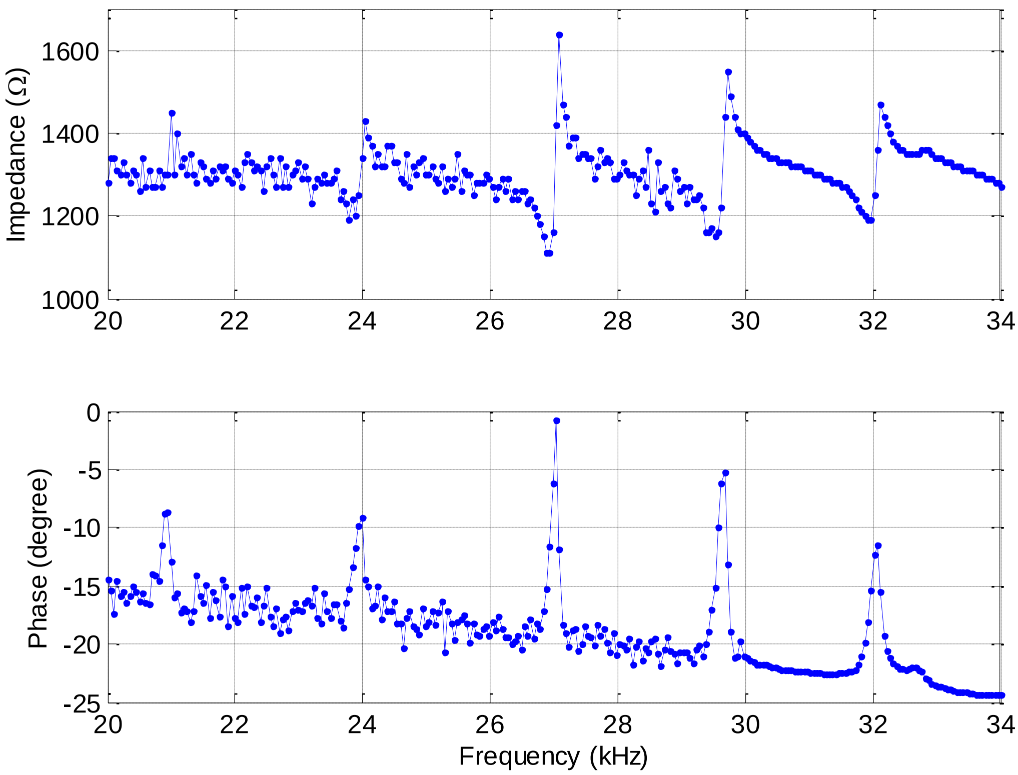

Figure 2.9. Impedance and phase responses of the linear motor with dual piezoelectric actuators.

Besides the above experiment, the performance of the linear motor with the dual actuators is studied. The test setup is illustrated in Figure 2.10. The pre-load is a weight inclusive of the motor bodyweight which generates a compression force between the stator teeth and contact floor. The motor is turn on long time before releasing to run in a 35-cm track for all loads to assure the same testing condition. The speed of the motor is measured by time-of-travel in a finite distance and calculated to be an average speed. The applied voltage is presented in terms of amplitude of the harmonic excitation signal. The driving force of the motor is measured by the capability of load pulling, also known as the thrust force.

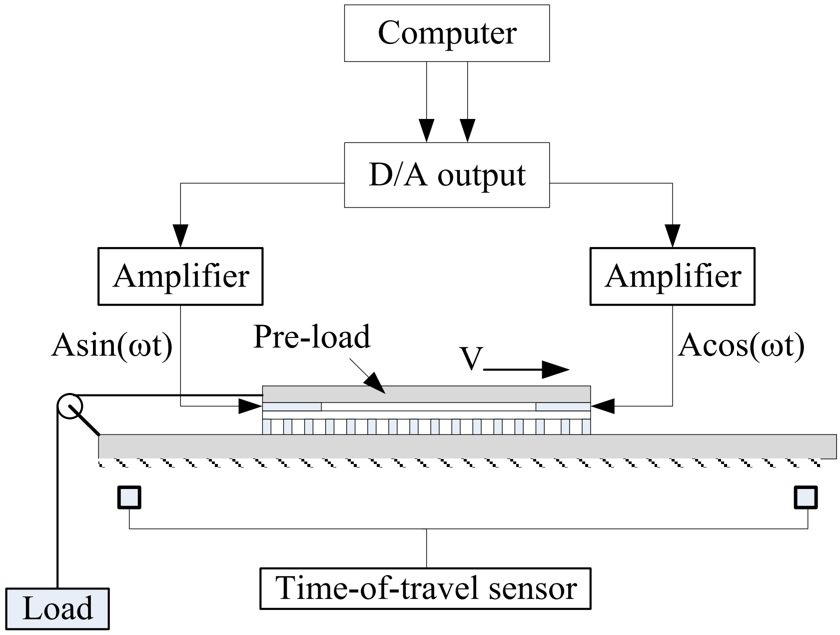

Figure 2.10. Test setup of the linear motor with dual piezoelectric actuators.

The linear motor performance is tested and reported. The voltage is set as a constant. Then, the operating frequency is adjusted at the optimal frequency that yields the maximum no-load velocity. The relationship between velocity and pre-load of the motor is shown in Figure 2.11. When amplitude of the applied voltage is constant, the motor velocity depends on the pre-load. The result reveals that velocity increases when pre-load increases for an amount of the pre-load and after that the velocity decreases. Accordingly, the optimal pre-load of 101.5 g yields the maximum motor velocity of 11.43 cm/s at an applied voltage amplitude of 31 V. This optimal pre-load is subsequently used in the investigation of other performance parameters of the motor.

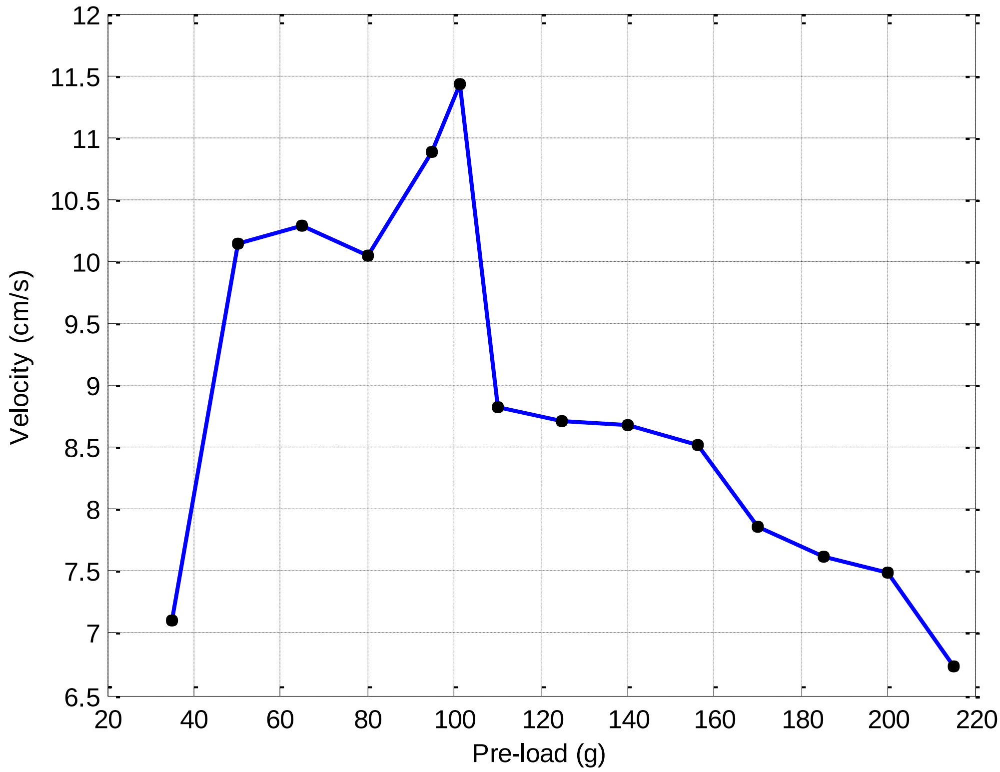

Figure 2.11. Relationship between motor velocity and pre-load.

Thereafter, relationships among performance parameters, such as velocity, driving force and applied voltage of the linear motor with the dual actuators are studied. Figure 2.12 illustrates relationship between velocity and applied voltage. The applied voltage on the piezoelectric actuators is varied from 25 V to 59 V, resulting in a linear increase of motor velocity. However, a too high electrical voltage could possibly cause depolarization of the piezoelectric actuators due to the rise of temperature during operation (Roh and Kwon 2004). In the experiment, the operating frequency of the motor is 28.21 kHz which is computer generated. The pre-load was set at 101.5 g. The result shows that a maximum velocity of 17.6 cm/s can be reached by applying an excitation voltage of 59 V. From determination of piezoelectric power consumption (Liang, Sun, and Rogers 1994; Brennan and McGowan 1997), the power consumption of the linear motor is 0.2 W.

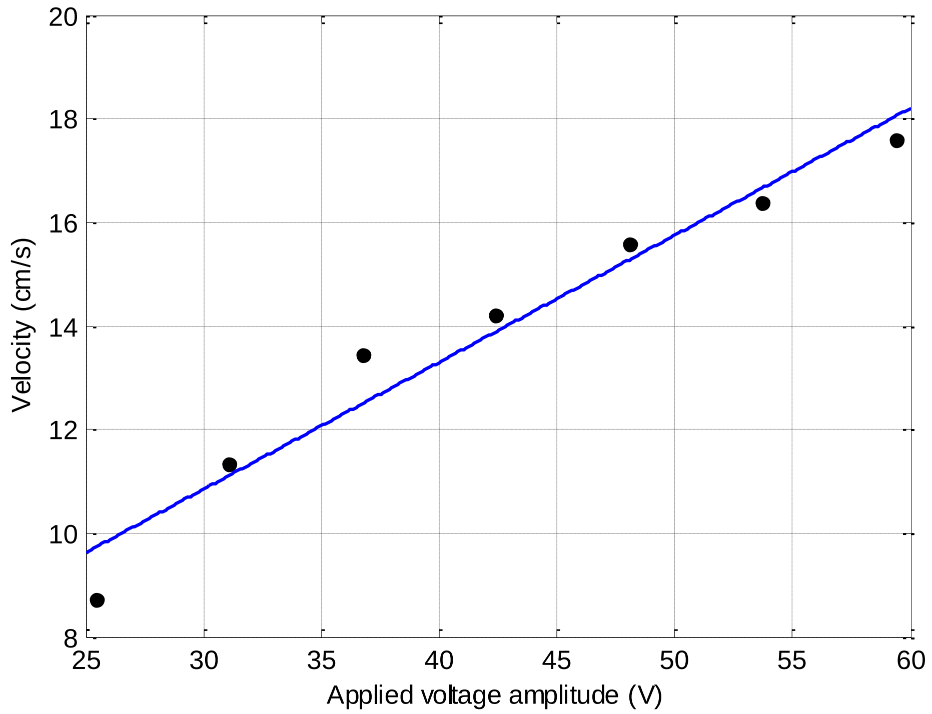

Figure 2.12. Relationship between motor velocity and applied voltage amplitude.

The relationship between driving force and applied voltage is illustrated in Figure 2.13. Experimental result indicates that the driving force depends on the applied voltage on the piezoelectric actuators. The driving force linearly increases as applied voltage amplitude increases. In the test, the linear motor yields a maximum driving force of 0.343 N at an applied voltage amplitude of 60.8 V. Thus, the power consumption at maximum driving force is 0.22 W.

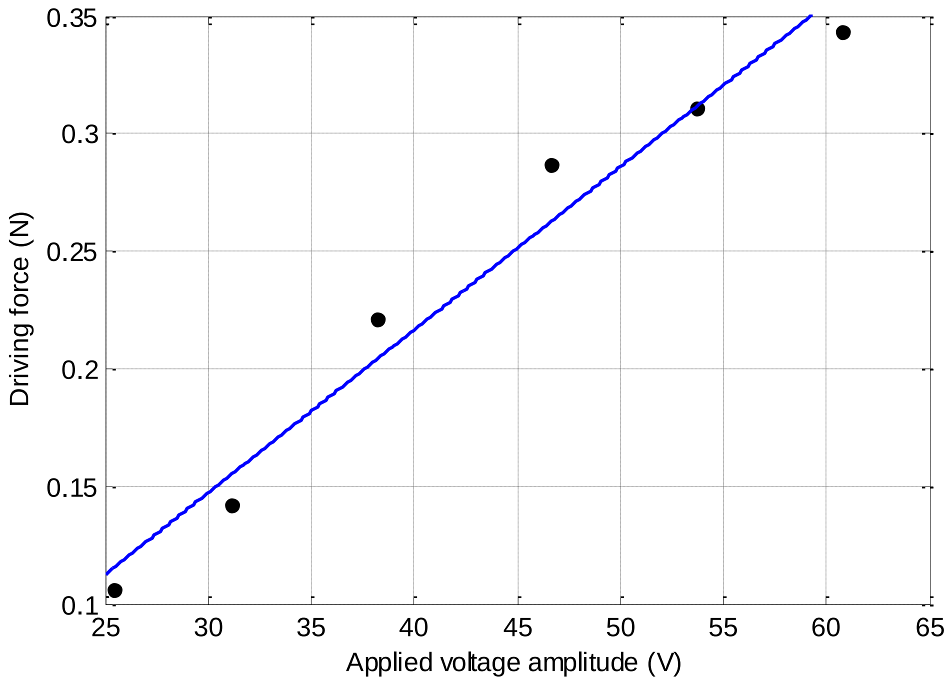

Figure 2.13. Relationship between driving force and applied voltage amplitude.

The relationship between the motor velocity and driving force is also known as a motor characteristic curve, as illustrated in Figure 2.14. In this study, the motor characteristic curve is determined by measuring the motor velocity when the driving load is changed at the specific applied voltage, operating frequency and pre-load conditions. The voltage and operating frequency are set as constants during the test. Hence, the power consumption is constant for all loads. The experimental results reveal that maximum motor velocity occurred at zero driving force, as known as the no-load speed. On the other hand, maximum driving force is generated when the motor operates at zero speed. For test setup at the applied voltage of 54 V, result shows that the maximum velocity is 16.41 cm/s and the maximum driving force is 0.31 N and the power consumption of the motor is 0.17 W. Mechanical power is a product of the driving force and velocity. Hence, for a given constant power into a motor, the velocity is inversely proportional to the driving force as shown in Figure 2.14. In some other cases, the nonlinear behavior of ultrasonic motors may be caused by the friction between the stator and floor (Zhang et al., 2006) and the nonlinear behavior of the piezoelectric material when excited at high voltage (Rho et al.. 2005).

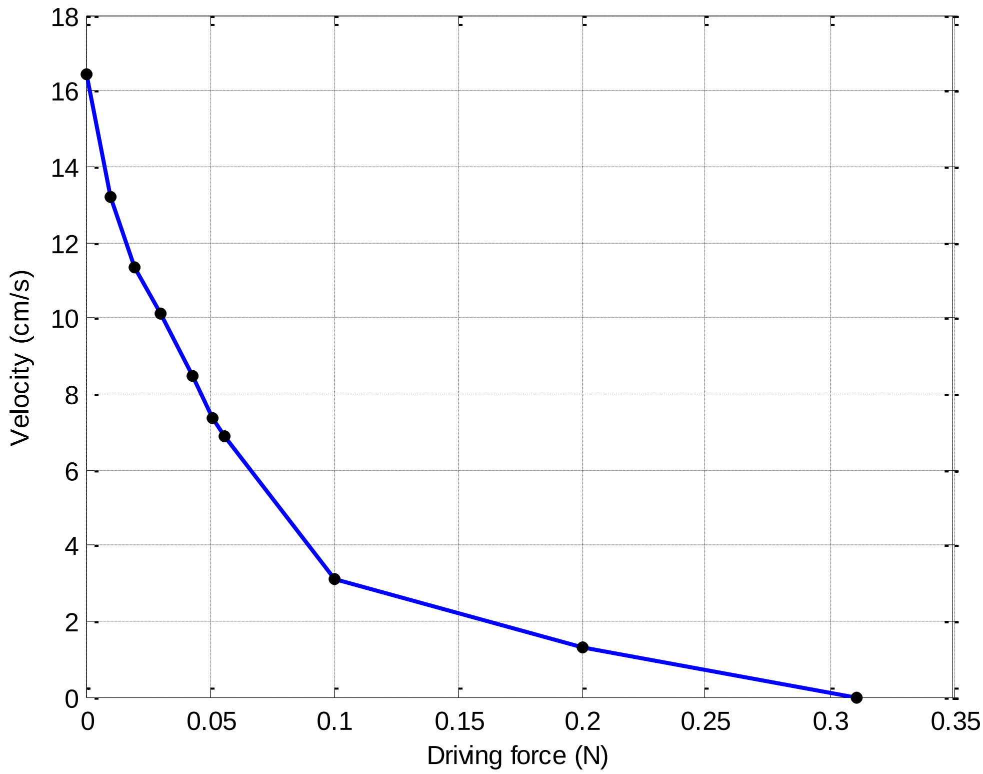

Figure 2.14. Relationship between motor velocity and driving force at applied voltage of 54 V.

Other published works on ultrasonic linear motors are reviewed and summarized in Table III. Please note that their designs, dimensions and testing conditions are different. Hence, they could not be compared with each other. However, Table III can be a useful guide for ultrasonic linear motor design and performance. It is shown that volume of piezoelectric material used for the linear motors is in the range of 60-435.2 mm^3, the no-load velocity is in the range of 8-62 cm/s, the maximum driving force is in the range of 0.29-3.99 N, and other parameters are shown in Table III. It can be notice that the presented motor has the least amount of piezoelectric material volume, yet it still performs the traveling wave motor task. In general, the traveling wave motor has low efficient because it operates based on the d_{31} effect which yields the lower displacement conversion for a given excitation voltage compared with the standing wave motor. However, it still has the advantage that it preserves the stator-actuator integration with compact size as mentioned before.

TABLE III Design factor and performance of ultrasonic linear motor

	Volume of actuator (mm^3)	Size of stator without teeth (mm)	Pre-load (g)	Applied voltage (V_{amp})	Total power input (W)	Maximum driving force (N)	No-load velocity (cm/s)	Driving frequency (kHz)
1. Presented motor	<u>60</u>	85x6x1	101.5	60	0.22	0.343	17.62	28.2
2. Lu et al. 2006 (Lu et al. 2006)	<u>435.2</u>	40.5x11x2	N/A	92	N/A	N/A	9.45	38.6
3. Rho et al. 2005 (Rho et al. 2005)	280	53x10x3	N/A	99	2.45	3.99	36	35.4
4. Roh and Kwon 2004 (Roh and Kwon 2004)	384	54x8x1	100	100	N/A	0.29	<u>62</u>	28.6
5. Roh et al. 2001 (Roh, Lee, and Han 2001)	432	75x8x1	200	100	N/A	N/A	40	23.5
6. He et al. 1998 (He et al. 1998)	400	40x10x1	100	36	N/A	N/A	<u>8</u>	23.4

Note: <u>maximum</u>, <u>minimum</u>

2.6 CHAPTER SUMMARY

An ultrasonic linear motor with dual piezoelectric actuators has been studied and tested in this work. The design deploys two piezoelectric actuators that are bonded with a linear stator, one actuator near each end of the support. Movement direction of the motor is controlled by alternating phase difference between two harmonic control signals. Analytical, finite element and experimental results of the natural frequency of the linear stator reveal positive agreement. The operating frequency resulted from the finite element analysis (29.2 kHz) is in good comparison to that from the experimental result (28.2 kHz). Based on the experimental testing, the suitable pre-load pressed on the motor is 101.5 g. The maximum velocity of the motor is 17.59 cm/s at an applied voltage of 59 V. The power consumption of the motor is 0.2 W.

The design of the ultrasonic linear motor with dual piezoelectric actuators exhibits a simpler structure with less number of actuators, thus yielding a low system structural stiffness in comparison to conventional ultrasonic linear motors with fully laminated actuators. Even though, the fewer piezoelectric actuators weaken the driving force. But, the dual piezoelectric motor is designed to operate near the resonance frequency. Thus, it has high vibration amplitude and low structural stiffness to partially compensate the fewer number of actuators. The new design of the ultrasonic linear motor with dual actuators presented in this work has the least amount of piezoelectric material volume, yet it still performs the traveling wave motor task. Moreover, the design of the linear motor can be scaled down. This opens up an opportunity for many applications that require a tiny translation actuator.

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CHAPTER 3

CONCLUSIONS

This research has investigated the characteristics of the ultrasonic motor with the partially laminated piezoelectric actuators. Design and performance testing of an ultrasonic linear motor with dual piezoelectric actuator patches are studied. The motor system consists of a linear stator, a pre-load weight, and two piezoelectric actuator patches. The piezoelectric actuators are bonded with the linear elastic stator at specific locations. The stator generates propagating waves when the piezoelectric actuators are subjected to harmonic excitations. Vibration characteristics of the linear stator are analyzed and compared with finite element and experimental results. The analytical, finite element and experimental results show agreement. In the experiments, performance of the ultrasonic linear motor is tested. Relationships between velocity and pre-load weight, velocity and applied voltage, driving force and applied voltage, and velocity and driving force are reported.

The design of the ultrasonic linear motor with dual piezoelectric actuators exhibits a simpler structure with less number of actuators, thus yielding a low system structural stiffness in comparison to conventional ultrasonic linear motors with fully laminated actuators. Even though, the fewer piezoelectric actuators weaken the driving force. But, the dual piezoelectric motor is designed to operate near the resonance frequency. Thus, it has high vibration amplitude and low structural stiffness to partially compensate the fewer number of actuators. The new design of the ultrasonic linear motor with dual actuators presented in this work has the least amount of piezoelectric material volume, yet it still performs the traveling wave motor task. Moreover, the design of the linear motor can be scaled down. This opens up an opportunity for many applications that require a tiny translation actuator.

ภาคผนวก

(APPENDIX)

Design and Performance Testing of an Ultrasonic Linear Motor with Dual Piezoelectric Actuators

Pruittikorn Smithmaitrie, Panumas Suybangdum, Pitak Laoratanakul, and Nantakan Muensit

***Abstract*—In this work, design and performance testing of an ultrasonic linear motor with dual piezoelectric actuator patches are studied. The motor system consists of a linear stator, a pre-load weight, and two piezoelectric actuator patches. The piezoelectric actuators are bonded with the linear elastic stator at specific locations. The stator generates propagating waves when the piezoelectric actuators are subjected to harmonic excitations. Vibration characteristics of the linear stator are analyzed and compared with finite element and experimental results. The analytical, finite element, and experimental results show agreement. In the experiments, performance of the ultrasonic linear motor is tested. Relationships between velocity and pre-load weight, velocity and applied voltage, driving force and applied voltage, and velocity and driving force are reported. The design of the dual piezoelectric actuators yields a simpler structure with a smaller number of actuators and lower stator stiffness compared with a conventional design of an ultrasonic linear motor with fully laminated piezoelectric actuators.**

I. Introduction

Ultrasonic motors can be classified into two major categories based on vibration characteristics: traveling wave motors and standing wave motors [1], [2]. An ultrasonic motor usually consists of a stator and a rotor. The stator drives the rotor by means of mechanical waves at the contact area. The waves are generated by piezoelectric actuators that are bonded with the stator. The electrical excitation applied to the piezoelectric actuator induces deformation on the piezoelectric actuator and stator [3], [4]. There are many advantages of ultrasonic motors over conventional electromagnetic motors. For instance, ultrasonic motors have high driving force per body weight, high precision in order of nanometer [5], high torque at low speed without a gear mechanism [2], no magnetic field working without restriction of induction [6], [7], high static friction holding-force without power supply [2], [5], [8], ability to work in a vacuum environment [9], [10], short response time, compact size, light weight, and quiet operation. However, the ultrasonic motor still has noise in ultrasonic range, which should be considered in some cases.

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Types of ultrasonic linear motors are direct flexural waves, hybrid transducers, sandwich vibrators, multimode vibrators, surface acoustic waves, impact motors, π-shaped transducers, and the Paderborn rowing type. The direct flexural waves [11], [12] have simpler structure and more flexibility. The hybrid transducers [13] have many advantages such as a large mechanical output and good performance, and also give bidirectional motion. The sandwich vibrators [14] can achieve very high speed and large thrust. The multi-mode vibrators [5], [15], [16] have a simple structure, but they require simultaneously excitation of two vibration modes at a specific synchronization of the two modes, which causes restrictions on design and fabrication. The surface acoustic wave motors [9], [17]–[20] have high energy density and tiny size. The impact motors [21]–[24] have a compact working unit. The advantages of π-shaped transducers and Paderborn rowing type [1] are that they have low energy loss and high efficiency and vibration amplitude because they use the d_{33} effect instead of the d_{31} effect. There are many techniques to improve performance of motors such as using actuators that are made of multi-layer piezoelectric ceramics instead of single-layer piezoelectric ceramics [15] because they generate larger mechanical output for a given voltage, thus yielding the higher motor speed and driving load; replacing a single driving foot with double driving feet to increase torque of the motor [5] and using high-efficiency friction materials [18], [23] can generate maximum driving force at the contact area between the stator and the rotor.

Various designs of traveling wave ultrasonic motors have been reported. The traveling wave linear motor using a ring-type stator, designed by [25], was excited by a pair of orthogonal mode shapes at the same resonance frequency. This motor has high velocity and short time constant, but it has a large size stator. The surface acoustic wave motor, proposed by [17], [19], used the interdigital transducer with a high-frequency electrical power source to generate the high-frequency traveling wave on the media surface. This design yielded very high output force density with tiny size of stator. However, the system required the high voltage and high power supply to drive the transducer. The vibrator-absorber linear motor making use of the d_{33} effect, proposed by [9], generated high vibration amplitude resulting in high velocity and thrust force. The main drawback is its large size.

Ultrasonic motors are attractive devices for applications on automatic focusing devices of digital cameras and optical lens zooming operation in personal digital assistants (PDA) and mobile phones [10], [24], [26], image processing [23], robot, aerospace, automatic control, military industry, medical instrument [22], chemical mixing process, pharmaceutical, and food industries that demand an exact control of powder feeding [27].

The design of the dual piezoelectric actuator is a kind of traveling wave ultrasonic motor. Although efficiency of general traveling wave ultrasonic motors is low, there are a few advantages as well. One is that the driving structure can be integrated into a system. By design of the actuator bonded location, it can turn a continuous structure into wave media. This is a different design concept rather than the use of a separated driving system such as a contact driving motor. In addition, this work presents the use of only two piezoelectric patches for creating the traveling wave and capable of controlling the wave direction on a flat beam. The design is capable of scaling down the size. This could provide a linear translation on flat media as well, similar to the printed circuit board (PCB) motor giving the rotational motion [28]. Other possible applications of this linear traveling wave driver are powder transport and linear translation on micro electromechanical system devices.

All these ultrasonic motors have been using certain numbers of active piezoelectric actuators to create mechanical vibration on the stator. A large number of piezoelectric actuators will cause both high energy consumption and undesired system stiffness, resulting in requirement of high applied voltage for the generation of effective vibration on the stator. In structural mechanics, the lower stiffness structure gives the larger vibration amplitude for the same amount of applied energy. Moreover, the ultrasonic motor should not be operated at too high a frequency due to the limitation of the electrical power supply. At high frequency, the piezoelectric actuator consumes high electrical power. This is because the piezoelectric actuator acts as a capacitance load and its power consumption depends on frequency [29], [30]. Moreover, if the high applied voltage is acquired to achieve the high vibration amplitude, this may lead to heat accumulation due to the mechanical vibration, which would raise the temperature of the system during operation. This could cause depolarization of the piezoelectric actuator because it operates at high temperature due to the heat from the mechanical strain under the active electrical field [6]. Furthermore, many ultrasonic linear motors are complicated in fabrication [15]. For this reason, one of the main objectives of this research is to reduce the number of piezoelectric actuators, so that it will be simpler for fabrication, require lower applied voltage, and consume less energy. Even though, the fewer piezoelectric actuators weaken the driving force. However, the dual piezoelectric motor is designed to operate near the resonance frequency. Thus, it has high vibration amplitude and low structural stiffness to partially compensate for the reduced number of actuators. Hence, a new design of an ultrasonic linear motor with dual piezoelectric actuators is introduced in this work. The principle of operation of the ultrasonic linear motor is discussed. Vibration characteristics of the linear stator are investigated by using the finite element method. In addition, the performance of the ultrasonic linear motor with dual piezoelectric actuators is assessed. Key relationships among performance parameters such as velocity, pre-load weight, applied voltage, and driving force are reported. Topics of discussion are presented in detail in the following sections.

II. The Design and the Principle of Operation

An ultrasonic linear motor with dual piezoelectric actuators consists of a beam stator with rectangular teeth, damping material patches, and two piezoelectric actuators bonded with the beam structure near both ends of the beam, as shown in Fig. 1. The actuator design is that the length of the actuator is equal to the wavelength (λ); the location phase shift between the two actuators is one-half of the wavelength ($\lambda/2$). Both actuators are bonded with the stator on the same surface, and their piezoelectric domains point in the same direction, toward the teeth. The phase difference of the two harmonic excitations on the piezoelectric actuators is 90°, so that the rotor can be driven efficiently [9]. The transverse vibration mode number of a beam, with fixed boundary conditions on both ends, is counted by the number of antinodes [31]. That is, one wavelength has two antinodes. Hence, in this work, the operating frequency occurs in between the 14th and 15th modes, which correspond respectively to the 7 and 7-and-a-half wavelengths. Note that the actuator design proposed in this work is different from Roh *et al.* [6], which has the $\lambda/2$ actuator length. In addition, on the same surface, Roh's actuators have no location phase shift and the piezoelectric domains point in opposite directions.

The stator generates traveling waves when the piezoelectric actuators are excited by harmonic excitations. The wave should propagate on the stator in one direction with consistency in wave amplitude. However, traveling waves reflect when they hit a physical boundary at the end of the stator. This distorts the pattern of the traveling waves. Accordingly, damping material patches are at-

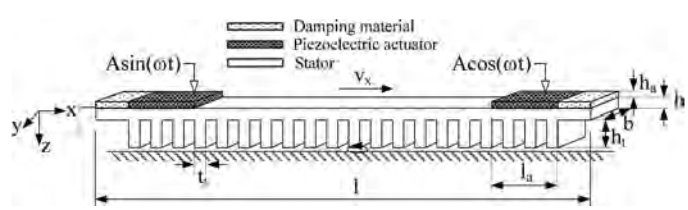

Fig. 1. Design of the ultrasonic linear motor with dual piezoelectric actuators.

tached to the stator at both ends of the stator adjacent to the fixed supports to prevent wave reflections. The piezoelectric ceramic actuators are polarized in the thickness direction. The two harmonic excitations are $A\sin(\omega t)$ and $A\cos(\omega t)$ signals, where A is the signal amplitude, ω is the driving frequency, and t is the time. The body of the stator is grounded. Direction of the traveling waves can be controlled by alternating the phase difference between the two control signals. Teeth on the stator are designed to expand the wave amplitude and to create elliptical motions at the tips of the teeth. The elliptical motions at the tips generate driving forces against the contact surface [9], [18]. The velocity of the motor can be controlled by adjusting the amplitude of excitation voltages on the piezoelectric actuators.

The stator is assumed to be a thin beam. Hence, vibration theory of the elastic thin beam is applicable to analyze the characteristics of the stator. The governing equation of a homogeneous isotropic solid beam [32] is expressed as follows:

$$YI\frac{\partial^4 u_3}{\partial x^4} + \rho bh\frac{\partial^2 u_3}{\partial t^2} = 0, \tag{1}$$

where Y is Young's modulus, $I = bh^3/12$ is the area moment of inertia of the beam cross-section, b is the beam width, h is the beam thickness, u_3 is the transverse displacement, ρ is the mass density, and bh represents the cross-section area. The solution of the governing equation is

$$u_3(x,t) = A_z\sin(\omega t - kx), \tag{2}$$

where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, and A_z is the transverse wave amplitude. In addition to the transverse displacement, the longitudinal displacement of a tooth tip (u_{1_tip}) is given by

$$u_{1\_\mathrm{tip}}(x,z,t) = -a\frac{\partial u_3}{\partial x} = aA_zk\cos(\omega t - kx), \tag{3}$$

where a is the distance from the beam neutral surface to the teeth contact surface. Based on (2) and (3), the trajectory of a point at the tooth tip can be achieved:

$$\left(\frac{u_{1\_\mathrm{tip}}}{aA_zk}\right)^2 + \left(\frac{u_3}{A_z}\right)^2 = 1. \tag{4}$$

Eq. (4) shows that the trajectory of the point is elliptical. When the stator is pressed against the surface, the stator moves itself by the friction force exerting at the contact surface. The velocity in the x-direction is obtained by the derivate of (3):

$$v_x = -aA_zk\omega\sin(\omega t - kx). \tag{5}$$

Eq. (5) represents the maximum speed reachable by the motor. The motor moves in opposite direction to the wave direction. Thus, the motor can move in another direction by reversing the wave direction. The natural frequency of the beam with fixed-fixed boundary condition [31] can be written as

$$f_i = \frac{1}{2\pi L^2}\left(\frac{(2i+1)\pi}{2}\right)^2\sqrt{\frac{YI}{m}}, \quad \text{for } i > 5, \tag{6}$$

where L is the length of the beam and m is the mass per unit length of the beam. In the case study, the mass of the teeth on the linear stator is also included into the mass per unit length of the beam by approximation [4]. To verify the theoretical analysis, the ultrasonic linear motor with dual piezoelectric actuators is studied using a finite element software package. The finite element model of the ultrasonic motor is discussed next.

III. Finite Element Model of the Ultrasonic Linear Motor with Dual Piezoelectric Actuators

According to the design described above, the stator of the ultrasonic linear motor is modeled to study the vibration characteristics, the frequency response, and the local motion of the tooth tip. The linear stator is made of brass. The dimensions of the stator are: width b of 6 mm, length l of 85 mm, and beam thickness h of 1 mm. The teeth dimensions are: height h_t of 3 mm, width b of 6 mm, and thickness t_t of 1.5 mm. The teeth are used for amplifying the elliptical trajectory at the surface contact. The piezoelectric actuator is made of lead zirconate titanate (PZT-4). The actuator dimensions are: length l_a of 10 mm, width b of 6 mm, and thickness h_a of 0.5 mm, as shown in Fig. 1. In this study, the length of the actuator is equal to the wavelength of the 15th mode. The two piezoelectric actuators are located one at each end of the stator. The actuators are excited by a pair of electrical signals, $A\sin(\omega t)$ and $A\cos(\omega t)$. Capacitance of the piezoelectric actuator is measured by using a LCR meter (GW Instek LCR-821, Good Will Instrument Co. Ltd., Taipei, Taiwan). It is assumed that the piezoelectric actuator (PZT-4) is an orthotropic material. The related shear modulus can be calculated based on the given modulus of elasticity and Poisson's ratio. Properties of the piezoelectric material and its damping coefficient are provided by the manufacturer. Note that the common damping properties [33] of the materials and real excitation amplitude are used in the finite element model to estimate the system response. The stator is made of brass because it is practical in manufacturing and processing. Other properties of the stator, the actuators, and the damping materials are described in Table I.

To predict the experimental result, the stator is modeled and simulated by using a finite element software package: MSC.Marc (MSC Software, Santa Ana, CA). The finite element model of the linear stator with dual piezoelectric actuators is illustrated in Fig. 2. The stator

TABLE I. Material Properties of the Ultrasonic Linear Motor With Dual Piezoelectric Actuators.

	PZT-4 actuator	Brass stator	Silicon rubber damping material	Unit
Modulus of elasticity	(Orthotropic)	(Isotropic)	(Isotropic)	
Y_{11}	79	96	4.2×10^{-3}	GPa
Y_{33}	66	96	4.2×10^{-3}	GPa
Density	7700	8400	1510	kg/m^3
Poisson's ratio	0.33	0.35	0.45	
Damping coefficient	0.0013	0.0005 [33]	0.05 [33]	
Piezoelectric constant				
e_{33}	17.56	—	—	C/m^2
e_{31}	−4.38	—	—	C/m^2
Permittivity	1.018×10^{-8}	—	—	F/m
Capacitance	2096	—	—	pF

is bonded with damping material patches at supported boundaries to prevent wave reflections. The model is assumed to be a 2-dimensional plane strain problem. The plane strain assumption assumes that there is no change of strain in the depth direction (the y-direction in Fig. 1). Thus, the strain in a cross-section of the x-z plane can be represented the deformation of the structure. The boundary conditions of the stator are stipulated to be fixed at both ends. The excitation voltages are 54sin(ωt) on one actuator and 54cos(ωt) on the other one. The excitation frequency is varied to determine the operating frequency that generates a traveling wave. All material properties and dimensions of the finite element model are assigned according to the previous descriptions.

IV. Vibration Characteristics of the Stator

Analytical and finite element models of the stator with dual piezoelectric actuators are carried out and simulated to determine the system response based on the boundary conditions and excitations as operated. Details of the experimental testing are discussed in the next section. The modal analysis is conducted to study the free vibration characteristics of the system. Natural frequencies of the stator for the analytical, finite element, and experimental results are presented in Table II. The results of natural frequencies are observed at the higher modes because the operating frequency is expected near the 15th mode according to the actuator design. In Table II, the analytical results are quite different from the finite element and experimental results. The reason is that the analytical method has its own limitation due to the approximation of the geometry derivation. That is, the linear stator is assumed to be a simple beam. However, mass of the teeth on motor also induced the mass per unit length to the structure. In addition, the effective thickness of the beam has to be approximated to cover the effect of structural stiffness due to the teeth [3], [4]. Natural frequencies are obtained in the early range of ultrasonic frequency (just above 20 kHz). The reasons for this are to avoid causing audible noises at the lower frequency operation and that a power amplifier circuit has a limited capability for generating signals at higher frequency operation.

Fig. 3 illustrates the finite element result of the 14th and 15th mode shapes of the stator at 27.25 and 29.53 kHz, respectively, where the operating frequency is expected in between these modes. Note that the overall structural deformation is scaled up to show the vibration mode shape of the stator; the teeth are not actually crossing each other. Because the rubber elements have larger deformation compared with the brass and piezoelectric elements, this makes some rubber elements which have deformation shape pointing to the side seem to move over the fixed boundary, but in fact, they are not. It is only the enlargement of deformed elements. The nodes on the side boundary are still fixed according to the boundary condition shown in Fig. 2. The wave configuration could be expected based on its natural mode shape because the structure tends to behave closely to the natural mode shape when

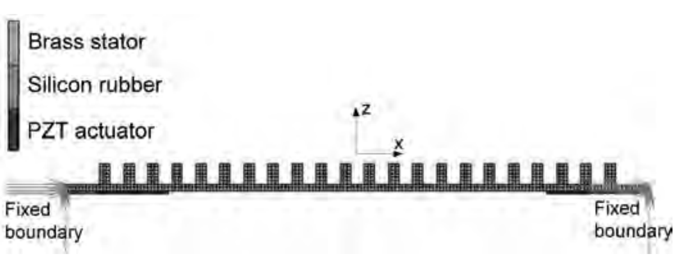

Fig. 2. Finite element model of the stator with dual piezoelectric actuators.

TABLE II. Natural Frequencies of the Ultrasonic Linear Stator.

Mode	Natural frequency (kHz) Analytical	Finite element	Experimental
12	23.41	22.21	20.85
13	27.30	24.82	23.79
14	31.50	27.25	26.88
15	35.99	29.53	29.53
16	40.79	31.53	31.97

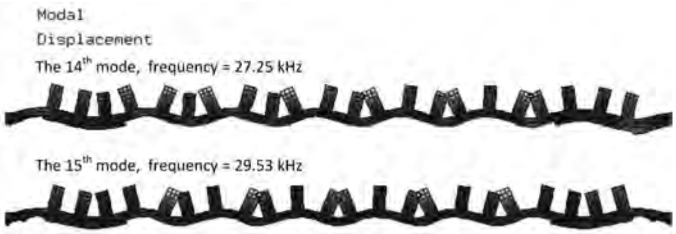

Fig. 3. The 14th and 15th vibration mode shapes.

the system is operated near its natural frequency. The traveling wave is generated by combining two transverse vibration modes that have the same mode shape but different phase locations. The operating frequency that excites the dual piezoelectric actuators is not at the natural frequency because the vibration response of the stator at the natural frequency is only a pure standing wave. Hence, the operating frequency is in between the 14th and 15th modes. Moreover, the desirable traveling wave must move in one direction along the stator with consistency in wave amplitude, and the wave direction can be controlled by alternating the phase difference of the excitation signals.

Following this, frequency response of the stator is investigated. The dual actuators are subjected to two sinusoidal voltages with amplitude of 54 V. These are $54\sin(\omega t)$ and $54\cos(\omega t)$ for the left and the right actuators, respectively. The excitation frequency ω is varied from 20 to 35 kHz to investigate the system response and to determine the operating frequency. Results show that the linear stator creates pure standing waves with high wave amplitude when the system is excited at natural frequencies. Likewise, there are ultrasonic motors that work near the natural frequency and yield superb performances because the systems respond with high wave amplitude at the natural frequency [5], [34]–[37]. Harmonic analysis is employed for the determination of displacement response of the wave. The wave configuration can be determined by transient analysis. In this case study, the operating frequency that yields the traveling wave is at 29.2 kHz, which is in between the 14th and 15th modes as illustrated in Fig. 4.

An elliptical motion at the contact surface of a tooth tip is induced by the coupling of longitudinal and transverse displacements. Fig. 5 shows nodal trajectories of the tooth tips at the contact surface based on the finite element result when the system is excited at the operating frequency of 29.2 kHz. The plot is in the same scale for both x- and y-axes to illustrate the aspect ratio of the elliptical path. The nodal trajectories of other tooth tips on the stator were also investigated, and it was found that they all move in the same direction. Recalling that the motor moves in the opposite direction to the trajectory path, the friction force generated on the contact surface is dependent on the transverse displacement, whereas the velocity of the motor depends on the longitudinal displacement. Hence, the size of the elliptical trajectory is important to the motor performance. Fig. 6 illustrates the stator deformation while the system is excited at the operating frequency. Note that the piezoelectric and rubber elements are hidden to enlarge the stator deformation and show the traveling wave. The size of elliptical trajectories (Fig. 5) and the stator deformation (Fig. 6) show that the traveling wave has large amplitude at the middle span and small amplitude near the end supports.

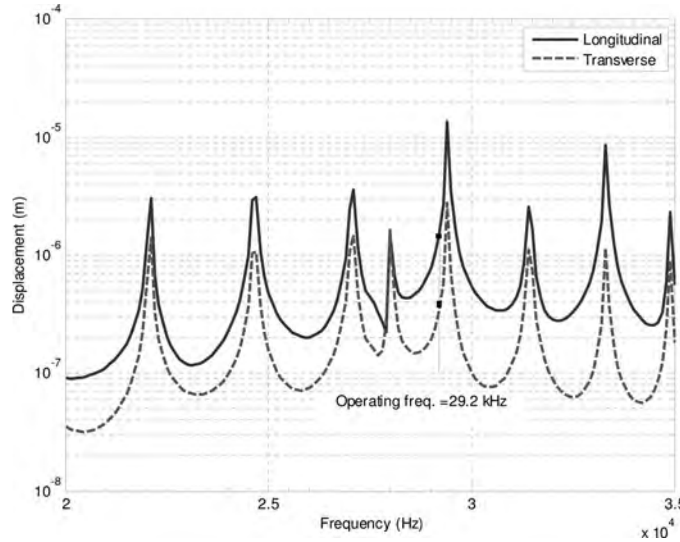

Fig. 4. Harmonic response of the linear stator with dual piezoelectric actuators.

The motor velocity is related to stator geometry, transverse wave amplitude, wavelength, and operating frequency as shown in (5). The finite element results of these

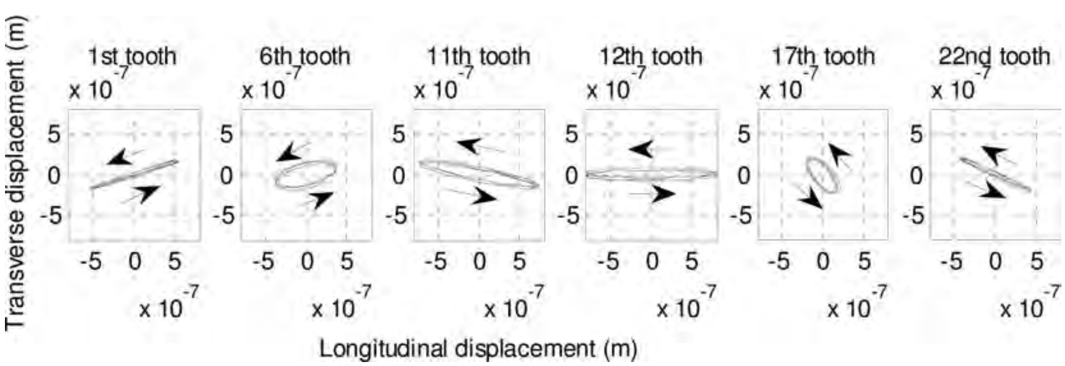

Fig. 5. Elliptical trajectories of the tooth tips at the operating frequency.

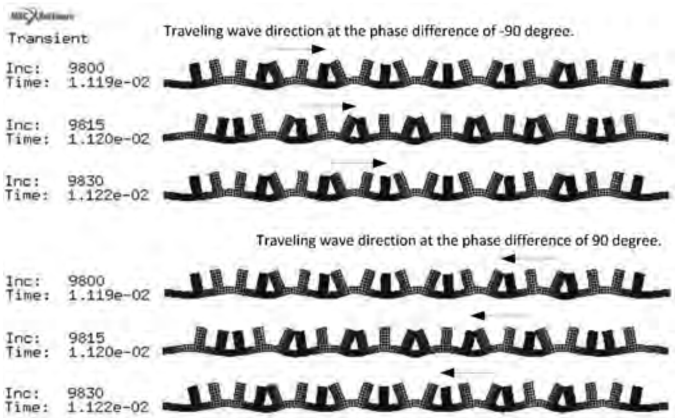

Fig. 6. Traveling wave on the stator at the operating frequency.

parameters at the operating frequency (29.2 kHz) are the harmonic transverse wave amplitude of 0.42 μm and the traveling wavelength of 10.5 mm. As a result, the calculated motor velocity is 16.1 cm/s. However, the analytical motor velocity is based only on the stator vibration characteristic without the motor contact condition. The result may not be directly compared with the experimental result.

V. Testing and Performance of the Ultrasonic Linear Motor with Dual Actuators

One objective of the ultrasonic motor design is to reduce the energy consumption, the number of actuators, and the applied voltage, and to simplify the motor structure for fabrication. However, the amplitude of the generated wave must continuously remain. Fig. 7 illustrates the linear stator with the dual piezoelectric actuators. Three electrical wires are each attached onto the open surfaces of the two actuators and the stator. Conductive epoxy is used for bonding the piezoelectric ceramic actuators with the stator, and the bonding is assumed to be perfect. The two piezoelectric actuators are connected to the brass stator, which functions as a common ground. Fig. 8 shows full assembly of the ultrasonic linear motor with the dual actuators. The fixed support and pre-load are integrated into the motor structure. In action, the stator faces down to contact the floor which acts as a stationary rotor. In this case, the pre-load is the compressive force that includes the weight of a load mass on the top of the stator and the weight of the stator itself. The motor moves itself relative to the floor in the direction opposite to the elliptical trajectory.

The main objective of the impedance measurement is to determine of the stator natural frequency and to study the interaction between the piezoelectric actuator and stator. Thus, only one actuator is excited. Natural frequencies of the motor are measured by using an impedance analyzer machine (model 4194A, Hewlett-Packard, Palo Alto). The impedance of the stator is measured on one piezoelectric actuator, whereas another actuator is open-circuit. The

Fig. 7. The linear stator with dual piezoelectric actuators.

stator is fixed with the preload at the supports. The voltage for measuring the stator impedance is set at 1 V_{rms}. Impedance and phase responses of the linear stator are plotted over the frequency range of 20 to 34 kHz as shown in Fig. 9. Noise occurs when the system is measured below 25 kHz. The noise below 25 kHz may occur due to the conductive glue layer between the piezoelectric actuator and the brass structure. However, the natural frequency of the linear stator can be indicated at the frequency that yields low impedance output. Result shows that natural frequencies of the motor occur at 20.85, 23.79, 26.88, 29.53, and 31.97 kHz. These correspond respectively to the 12th to the 16th modes, as previously presented in Table II. The experimental results are in agreement with the analytical and finite element results.

Besides the previously described experiment, the performance of the linear motor with the dual actuators was studied. The test setup is illustrated in Fig. 10. The preload is a weight inclusive of the motor body weight, which generates a compression force between the stator teeth and contact floor. The motor is turned on a long time before releasing to run in a 35-cm track for all loads to assure the same testing conditions. The speed of the motor is measured by time of travel in a finite distance and calculated to be an average speed. The applied voltage is presented in terms of amplitude of the harmonic excitation signal. The driving force of the motor is measured by the capability of load pulling, also known as the thrust force.

The linear motor performance is tested and reported. The voltage is set as a constant. Then, the operating frequency is adjusted at the optimal frequency that yields the maximum no-load velocity. The relationship between velocity and pre-load of the motor is shown in Fig. 11. When amplitude of the applied voltage is constant, the motor velocity depends on the pre-load. The result reveals that velocity increases when pre-load increases for an amount of the pre-load, and after that the velocity decreases. Accordingly, the optimal pre-load of 101.5 g yields the maximum motor velocity of 11.43 cm/s at an

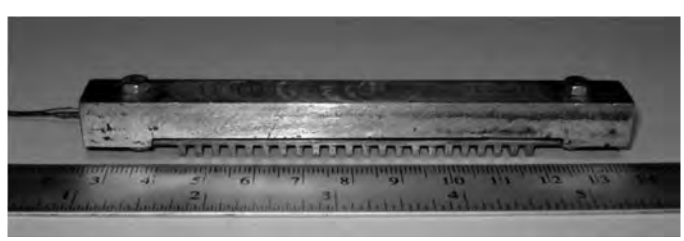

Fig. 8. The full assembly of the linear motor with the fixed support and pre-load.

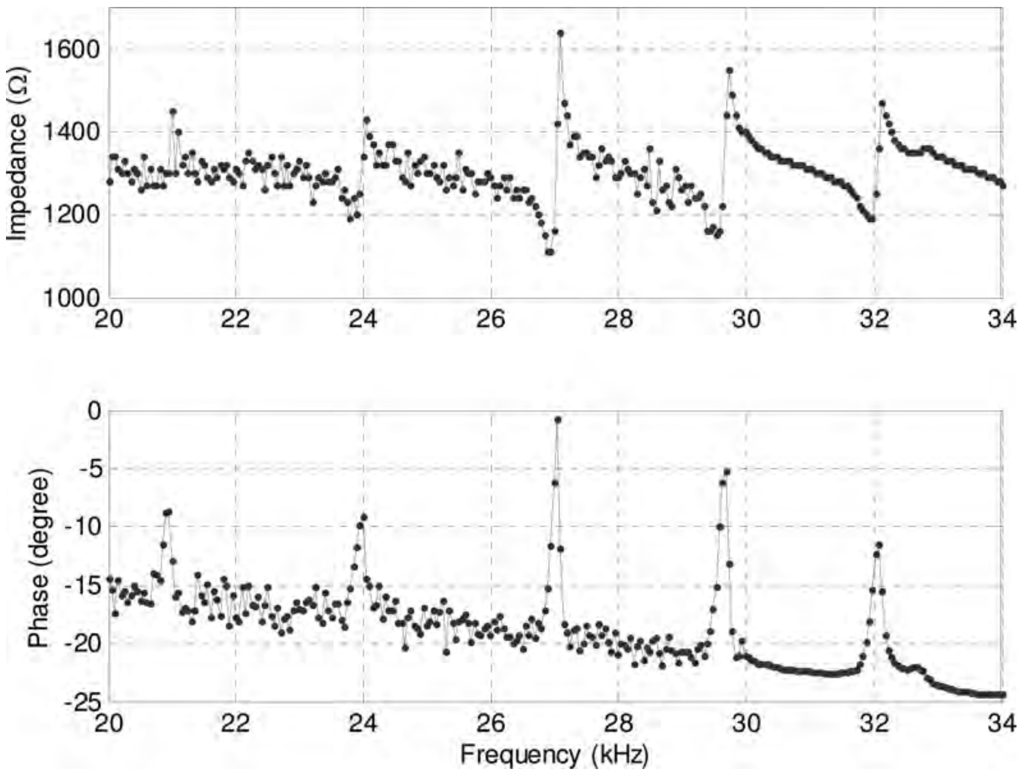

Fig. 9. Impedance and phase responses of the linear motor with dual piezoelectric actuators.

applied voltage amplitude of 31 V. This optimal pre-load is subsequently used in the investigation of other performance parameters of the motor.

Thereafter, relationships among performance parameters, such as velocity, driving force, and applied voltage of the linear motor with the dual actuators are studied. Fig. 12 illustrates relationship between velocity and applied voltage. The applied voltage on the piezoelectric actuators is varied from 25 to 59 V, resulting in a linear increase of motor velocity. However, a too-high electrical voltage could cause depolarization of the piezoelectric actuators due to the rise of temperature during operation [11]. In the experiment, the operating frequency of the motor is 28.21 kHz, which is computer generated. The pre-load was set at 101.5 g. The result shows that a maximum velocity of 17.6 cm/s can be reached by applying an excitation voltage of 59 V. From determination of piezoelectric power consumption [29], [30], the power consumption of the linear motor is 0.2 W.

The relationship between driving force and applied voltage is illustrated in Fig. 13. The experimental result indicates that the driving force depends on the applied voltage on the piezoelectric actuators. The driving force linearly increases as applied voltage amplitude increases.

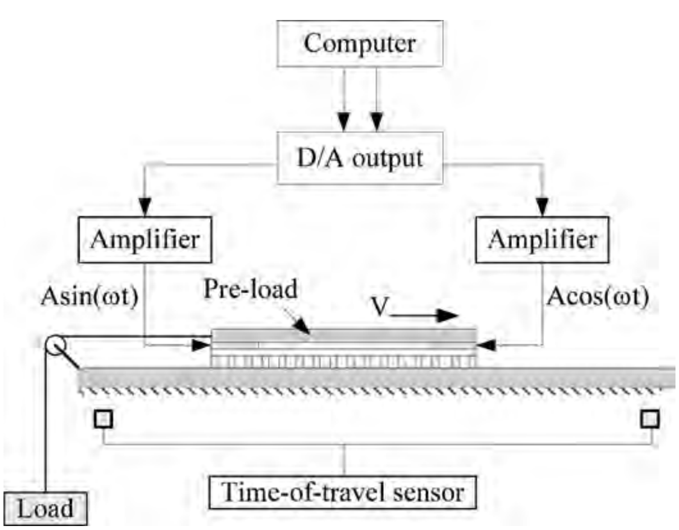

Fig. 10. Test setup of the linear motor with dual piezoelectric actuators.

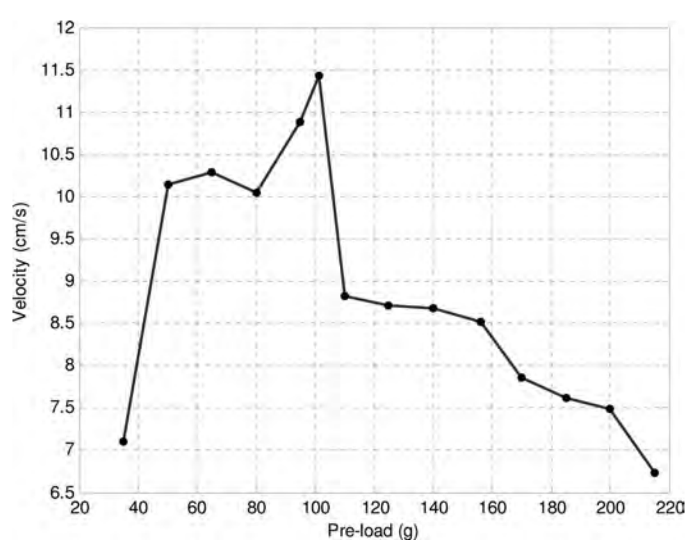

Fig. 11. Relationship between motor velocity and pre-load.

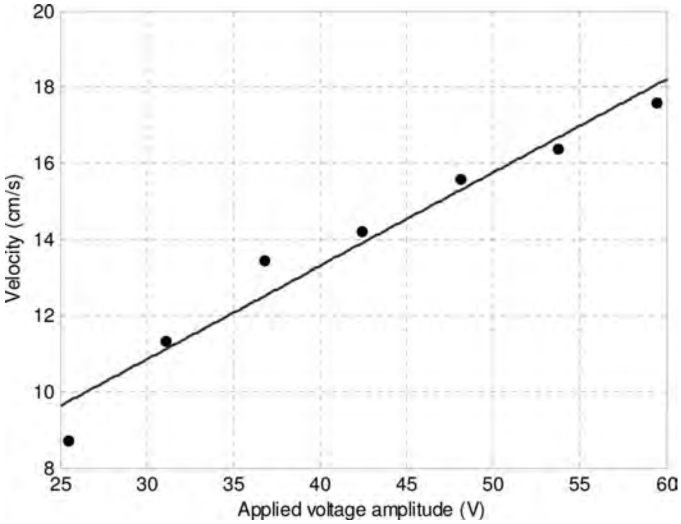

Fig. 12. Relationship between motor velocity and applied voltage amplitude.

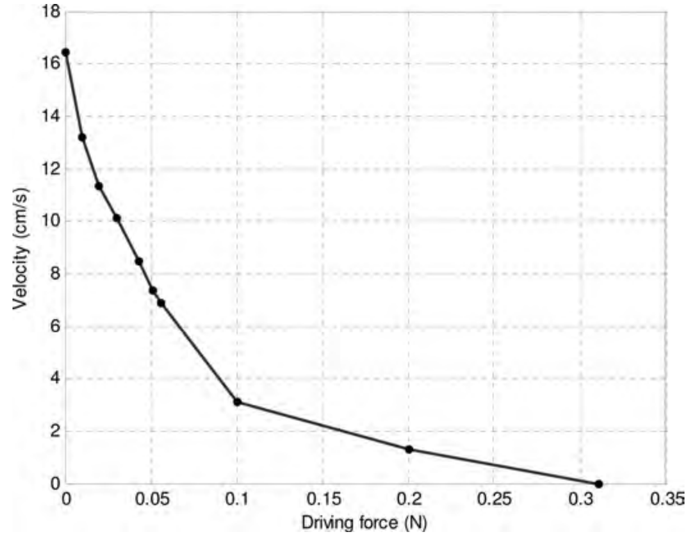

Fig. 14. Relationship between motor velocity and driving force at applied voltage of 54 V.

In the test, the linear motor yields a maximum driving force of 0.343 N at an applied voltage amplitude of 60.8 V. Thus, the power consumption at maximum driving force is 0.22 W.

The relationship between the motor velocity and driving force is also known as a motor characteristic curve, as illustrated in Fig. 14. In this study, the motor characteristic curve is determined by measuring the motor velocity when the driving load is changed at the specific applied voltage, operating frequency, and pre-load conditions. The voltage and operating frequency are set as constants during the test. Hence, the power consumption is constant for all loads. The experimental results reveal that maximum motor velocity occurred at zero driving force, as known as the no-load speed. On the other hand, maximum driving force is generated when the motor operates at zero speed. For test setup at the applied voltage of 54 V, the result shows that the maximum velocity is 16.41 cm/s and the maximum driving force is 0.31 N, and the power consumption of the motor is 0.17 W. Mechanical power is a product of the driving force and velocity. Hence, for a given constant power into a motor, the velocity is inversely proportional to the driving force as shown in Fig. 14. In some other cases, the nonlinear behavior of ultrasonic motors may be caused by the friction between the stator and floor [37] and the nonlinear behavior of the piezoelectric material when excited at high voltage [38].

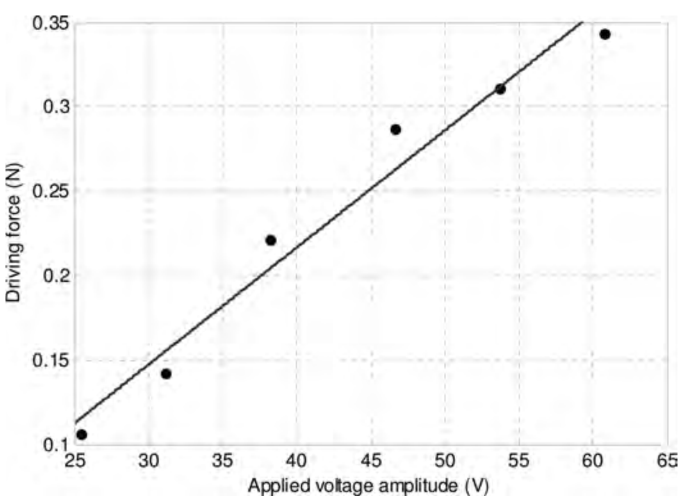

Fig. 13. Relationship between driving force and applied voltage amplitude.

Other published works on ultrasonic linear motors are reviewed and summarized in Table III. Please note that their designs, dimensions, and testing conditions are different. Hence, they could not be compared with each other. However, Table III can be a useful guide for ultrasonic linear motor design and performance. It is shown that volume of piezoelectric material used for the linear motors is in the range of 60 to 435.2 mm^3, the no-load velocity is in the range of 8 to 62 cm/s, the maximum driving force is in the range of 0.29 to 3.99 N, and other parameters are shown in Table III. It can be noticed that the presented motor has the least amount of piezoelectric material volume, yet it still performs the traveling wave motor task. In general, the traveling wave motor has low efficiency because it operates based on the d_{31} effect, which yields the lower displacement conversion for a given excitation voltage compared with the standing wave motor. However, it still has the advantage that it preserves the stator-actuator integration with compact size as mentioned before.

VI. Conclusion

An ultrasonic linear motor with dual piezoelectric actuators has been studied and tested in this work. The design deploys two piezoelectric actuators that are bonded with a linear stator, one actuator near each end of the support. Movement direction of the motor is controlled by alternating phase difference between two harmonic control signals. Analytical, finite element, and experimental results of the

TABLE III. Design Factor and Performance of Ultrasonic Linear Motor.

	Volume of actuator (mm^3)	Size of stator without teeth (mm)	Pre-load (g)	Applied voltage (V_{amp})	Total power input (W)	Maximum driving force (N)	No-load velocity (cm/s)	Driving Frequency (kHz)
1. Presented motor	*60*	85 × 6 × 1	101.5	60	0.22	0.343	17.62	28.2
2. Lu *et al.*, 2006 [5]	**435.2**	40.5 × 11 × 2	N/A	92	N/A	N/A	9.45	38.6
3. Rho *et al.*, 2005 [38]	280	53 × 10 × 3	N/A	99	2.45	3.99	36	35.4
4. Roh and Kwon, 2004 [11]	384	54 × 8 × 1	100	100	N/A	0.29	**62**	28.6
5. Roh *et al.*, 2001 [6]	432	75 × 8 × 1	200	100	N/A	N/A	40	23.5
6. He *et al.*, 1998 [8]	400	40 × 10 × 1	100	36	N/A	N/A	*8*	23.4

Note: bold text indicates maximum value; italic text indicates minimum value.

natural frequency of the linear stator reveal positive agreement. The operating frequency resulted from the finite element analysis (29.2 kHz) is in good comparison with that from the experimental result (28.2 kHz). Based on the experimental testing, the suitable pre-load pressed on the motor is 101.5 g. The maximum velocity of the motor is 17.59 cm/s at an applied voltage of 59 V. The power consumption of the motor is 0.2 W.

The design of the ultrasonic linear motor with dual piezoelectric actuators exhibits a simpler structure with fewer actuators, thus yielding a low system structural stiffness in comparison with conventional ultrasonic linear motors with fully laminated actuators, even though the fewer piezoelectric actuators weaken the driving force. But, the dual piezoelectric motor is designed to operate near the resonance frequency. Thus, it has high vibration amplitude and low structural stiffness to partially compensate for the fewer number of actuators. The new design of the ultrasonic linear motor with dual actuators presented in this work has the least amount of piezoelectric material volume, yet it still performs the traveling wave motor task. Moreover, the design of the linear motor can be scaled down. This opens up an opportunity for many applications that require a tiny translation actuator.

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