基于激光诱导石墨烯的木制惯性测量单元

李晨[1,2,3],李浩[1],杨研伟[1]

（1 陕西科技大学 机电工程学院,西安 710021）
（2 西安交通大学 机械工程学院,西安 710049）
（3 西安交通大学 精密微纳制造技术全国重点实验室,西安 710054）

摘　要：针对商用低精度惯性测量单元具有高成本、制造工艺复杂、废弃后污染环境、不能生物降解等缺点,提出一种低成本、可生物降解的木制惯性测量单元。该设计包含平衡振子和非平衡振子单元,分别用于测量 3 轴加速度和 3 轴角加速度。采用激光诱导石墨烯的工艺在木梁上制备应变传感器阵列,并形成多组惠斯顿电桥测量电路。结果表明：加速度方面,X 轴灵敏度为 $0.006\ \text{mV/g}$,Y 轴灵敏度为 $8.695\times10^{-4}\ \text{mV/g}$,$Z$ 轴灵敏度为 $0.200\ \text{mV/g}$;角加速度方面,X 轴灵敏度为 $0.285\ \text{mV/(rad/s}^2)$,绕 Y 轴旋转的灵敏度为 $0.305\ \text{mV/(rad/s}^2)$,绕 Z 轴旋转的灵敏度为 $0.765\ \text{mV/(rad/s}^2)$。与有限单元法仿真结果对比,实验测量误差在 10% 以内,且具有良好的重复测量精度。该惯性测量单元在木制船舶、木制载具、木制家具等方面具有潜在的应用前景。

关键词：惯性测量单元;激光诱导石墨烯;陀螺仪;加速度计;木材

中图分类号：TH703;V261.8　　　　**文献标识码**：A　　　　**doi**：10.3788/gzxb20245302.0212005

0 引言

　　惯性测量单元(Inertial Measurement Unit, IMU)是一种电子设备,用于测量和报告物体的加速度、角速率,物体的朝向,IMU 一般包括三轴陀螺仪和三轴加速度计[1-3]。陀螺仪主要分为激光陀螺仪[4]、光纤陀螺仪[5]、微机电系统(Micro-Electro-Mechanical System, MEMS)陀螺仪[6]等。其中 MEMS 陀螺仪成本低,能批量生产,且具有稳定性和进动性。MEMS 陀螺仪主要有压阻式、压电式和电容式等,其中压阻式 MEMS 传感器结构和制作工艺简单、直流响应好、可靠性高、成本低[7-9]。KUROKAMI S 等设计了一种新型压阻式加速度传感器,在光束中带有狭缝,大大提高了灵敏度[10]。MESSINA M 等研发了一种加速度传感器,能够实时检测运动员头部状态,具有良好的抗干扰效果和灵敏度[11]。DONG Peitao 等设计了一种高性能单片式三轴压阻式冲击加速度计,测量范围为 $50\ 000\ g\sim100\ 000\ g$($g$ 表示重力加速度),X 轴、Y 轴和 Z 轴的灵敏度分别为 $2.17\ \mu\text{V/g}$、$2.25\ \mu\text{V/g}$ 和 $2.64\ \mu\text{V/g}$[12]。ZHAI Yanxin 等设计了一种基于体碳化硅处理技术的用于高温环境的微机电系统加速度计,在输入电压为 5 V 时的动态灵敏度为 $0.21\ \text{mV/g}$[13]。

　　目前,MEMS 陀螺仪主要采用硅作为基底制备的电子产品,当传感器报废被抛弃,其中含有的重金属(例如镉、镍、铬、锌、汞、铍和铅)可能污染环境,而含有的普通金属(例如铝、铁、铜和锡)不易回收,可能浪费资源[14-17]。因此采用一种绿色环保的电子产品尤为重要,石墨烯具有高导电性且是固有强度很高的材料之一[18-19]。激光诱导石墨烯(Laser-Induced Graphene, LIG)由 PENG Z 等[20]利用中心波长为 $10.6\ \mu\text{m}$ 的 CO_2 激光器在大气环境中照射柔性衬底聚酰亚胺(Polyimide, PI)制备石墨烯。LIG 具有高导电性,并且降低了石墨烯的制作成本。随着 LIG 问世,越来越多的研究团队开始关注这项技术,并对不同激光波长、不同诱导

http://www.photon.ac.cn

材料进行了研究[21-24]。YE R等[25]使用CO_2激光器在木材上制备了LIG,其方块电阻可达$10\ \Omega\cdot sq^{-1}$。本课题组[26]利用光纤激光器在松木上制备LIG,其方块电阻为$8\ \Omega\cdot sq^{-1}$,并利用该技术制备了压力和温度传感器。

本文利用1 070 nm波长的光纤激光在松木上诱导石墨烯,并将其制备成IMU,通过仿真设计和优化,探讨了基于激光诱导石墨烯的木制IMU的可行性、性能和灵敏度。

1　实验

1.1　实验材料

工程中常用的木材有桦木、桉木、松木等。其中松木具有硬度高、抗磨损力强的优点,并且性能稳定,不易变形。松木在风干情况下,水分含量约为11.5％,纤维素含量为46.8％～57.33％,木质素含量为24.12％～30.85％[27]。本课题组前期系统研究了松木的物理性质[26],例如密度、弹性模量、泊松比和屈服极限。松木的线膨胀系数为3.39×10^{-6} m/℃,而且松木中木质素含量较高,有利于LIG的制备,本工作以松木为主要框架[28]。聚乳酸PLA(SANLU, LOGO1)是一种聚酯类聚合物和一种新型的生物降解材料,PLA是一种常用3D打印材料,被选用为惯性轮的材料。不锈钢Cr13(Cr 14.0％～15.5％,Ni 3.5％～5.5％,Cu 2.5％～4.5％,Mo 0.5％,Mn 1.0％,Si 1.0％)具有密度大、耐腐蚀的优点,被选用为惯性球的材料。主要材料的物理属性如表1所示。

表 1　材料属性
Table 1　Material attribute

Material	Density $/(kg\cdot m^{-3})$	Elastic modulus/MPa	Poisson's ratio	Yield strength/MPa
Pine	550	4 211	0.42	41
PLA	1 240	3 000	0.35	60
Cr13	7 850	20 000	0.3	345

1.2　LIG电阻制备

将干燥的松木框架放入真腔内,通过机械泵使真空腔内的真空度保持在0～700 Pa之间。打开激光器(华工科技产业股份有限公司,LG20),并使用软件控制激光振镜在木制梁和框架上加工多个4×1的LIG电阻。调节焦点到样品表面以下4 mm。采用激光诱导石墨烯电阻的最优工艺参数是:激光功率为2 W,打标速度为$100\ mm\cdot s^{-1}$,打标次数为10次,激光脉冲频率为20 kHz[26]。LIG制备完成后,使用环氧树脂导电胶(Ausbond,Q/ASB 027-2017)将铜导线与LIG电阻相连构成惠斯顿电桥。

2　设计与仿真

2.1　IMU结构设计

压阻式传感器有许多典型的结构[29]。考虑到本工作的IMU的应用和木材的性质,结构设计如图1(a)所示。传感器框架尺寸为100 mm×100 mm×5 mm,4根木质梁与惯性体平台连接,在4个梁和上部框架上制备共12个LIG电阻,并用电线连接成3个惠斯通电桥,如图1(b)所示。在木制框架双侧对称布置铁质半球,构成平衡振子单元;在木制框架单侧布置PLA材质的惯性轮,构成非平衡振子单元,如图1(c)所示。结构尺寸如表2所示。

梁与框交界处的位置和质量块边缘所受到的应力为

$$\sigma_1=\frac{3ml_1}{2bh_1^2}\cdot a \tag{1}$$

$$\sigma_2=-\frac{3ml_1}{2bh_1^2}\cdot a \tag{2}$$

式中,m为质量块的质量,l_1为质量块与框的距离,b为梁的宽度,h_1为梁的厚度,a为加速度。

梁与框交界处的应变为

$$\varepsilon=\frac{3ml_1a}{2Ebh_1^2} \tag{3}$$

(a) Design position of sensor varistor

(b) Houston bridge

(c) The structure of balanced and unbalanced oscillator units
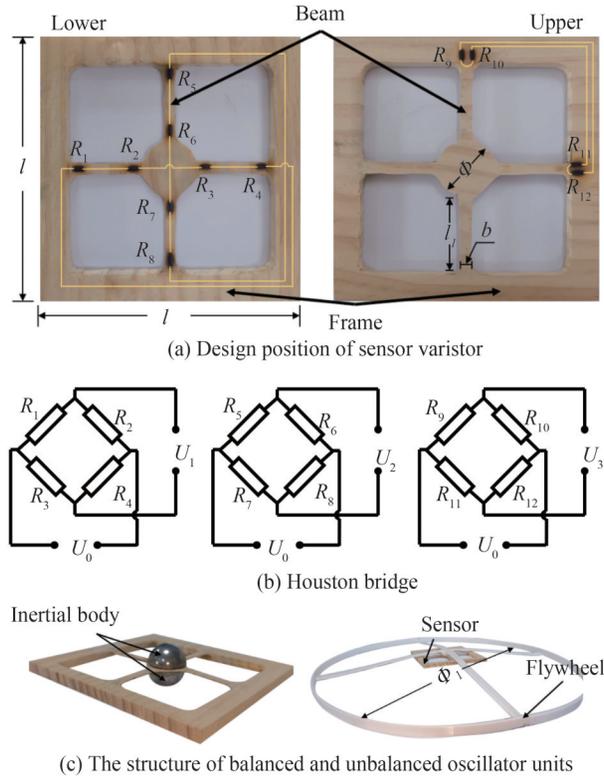
图 1　IMU 结构设计

Fig.1　The structure design of IMU

表 2　IMU 的结构尺寸

Table 2　The structural dimensions of IMU

Parameter	Value/mm	Illustrate
l	100	
h	5	The thickness of the frame
l_1	30	
b	3	
h_1	1	The thickness of the beam
Φ	20	
h_2	1	Thickness of Inertial Body Connection Platform
Φ_1	400	

式中,E 为松木的杨氏模量。

由式(1)~(3)分析可知,IMU 沿 X 轴和 Z 轴的加速度范围为 $\pm 10\,g$,沿 Y 轴的加速度范围为 $-g\sim+3\,g$,绕 X 轴和 Z 轴的角加速度范围为 $\pm 8\,\text{rad/s}^2$,绕 Y 轴的角加速度范围为 $\pm 23\,\text{rad/s}^2$。

激光诱导出的石墨烯电阻的阻值大约为 $100\,\Omega$,将 R_1、R_2、R_3、R_4 连接成第一个惠斯通电桥,将 R_5、R_6、R_7、R_8 连接成第二个惠斯通电桥,将 R_9、R_{10}、R_{11}、R_{12} 连接成第三个惠斯通电桥,这样传感器就有三个霍斯顿电桥,如图 1(b)所示,其中电源电压为 $U_0=2\,\text{V}$,$U_i(i=1,2,3)$ 为电桥的输出电压。第一个惠斯通电桥的输出电压 U_1 与四个 LIG 电阻的应变关系式为

$$U_1=\frac{U_0}{4}K\left(\varepsilon_{R_1}-\varepsilon_{R_2}+\varepsilon_{R_3}-\varepsilon_{R_4}\right) \tag{4}$$

第二个惠斯通电桥的输出电压 U_2 与四个 LIG 电阻的应变关系式为

$$U_2=\frac{U_0}{4}K\left(\varepsilon_{R_5}-\varepsilon_{R_6}+\varepsilon_{R_7}-\varepsilon_{R_8}\right) \tag{5}$$

第三个惠斯通电桥的输出电压 U_3 与四个 LIG 电阻的应变关系式为

$$U_3 = \frac{U_0}{4} K \left(\varepsilon_{R_9} - \varepsilon_{R_{10}} + \varepsilon_{R_{11}} - \varepsilon_{R_{12}} \right) \qquad (6)$$

式中，K 为灵敏系数，$K = 86.53 \ \text{mV/Pa}$，$\varepsilon_{R_i} (i=1,2,3,\cdots,12)$ 为 R_i 压敏电阻的平均应变。

当 IMU 模块发生运动时，惯性体具有惯性，导致梁发生弹性变形，传感器上 LIG 电阻发生变化，通过霍斯顿电桥输出电压分析，通过平衡振子单元与非平衡振子单元进行对比，最后可以得出 IMU 的运动状态。

2.2 有限元分析

为了分析 IMU 的性能，对 IMU 进行建模，并使用有限元方法进行应变分析。IMU 的建模与网格划分如图 2 所示。

(a) Unbalanced oscillator unit   (b) Balance oscillator unit
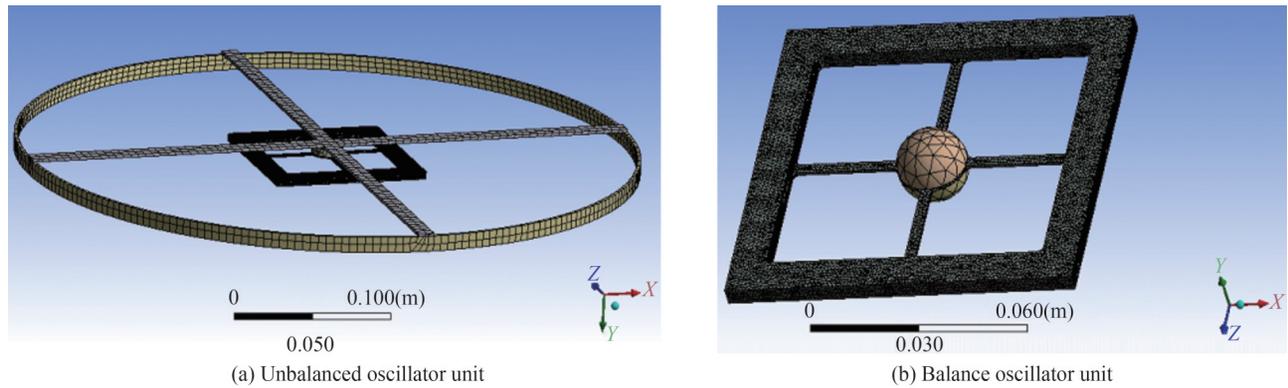
图 2 IMU 建模与网格划分
Fig. 2 IMU modeling and meshing

对两个传感器进行应变分析，四周框架采用固定约束，对传感器 Y 轴方向施加一个重力加速度，再对传感器分别沿 X、Y 或 Z 轴做加速度或角加速度。

如图 3(a) 所示，当非平衡振子单元绕 Y 轴以 23 rad/s² 角加速度运动时，R_2，R_3、R_6 和 R_7 发生的应变最大，

(a) Strain diagram of the unbalanced oscillator unit rotates around the Y-axis (α=23 rad/s²)

(b) Strain diagram of the balanced oscillator unit moving in a straight line along the Y-axis (α=28 m/s²)
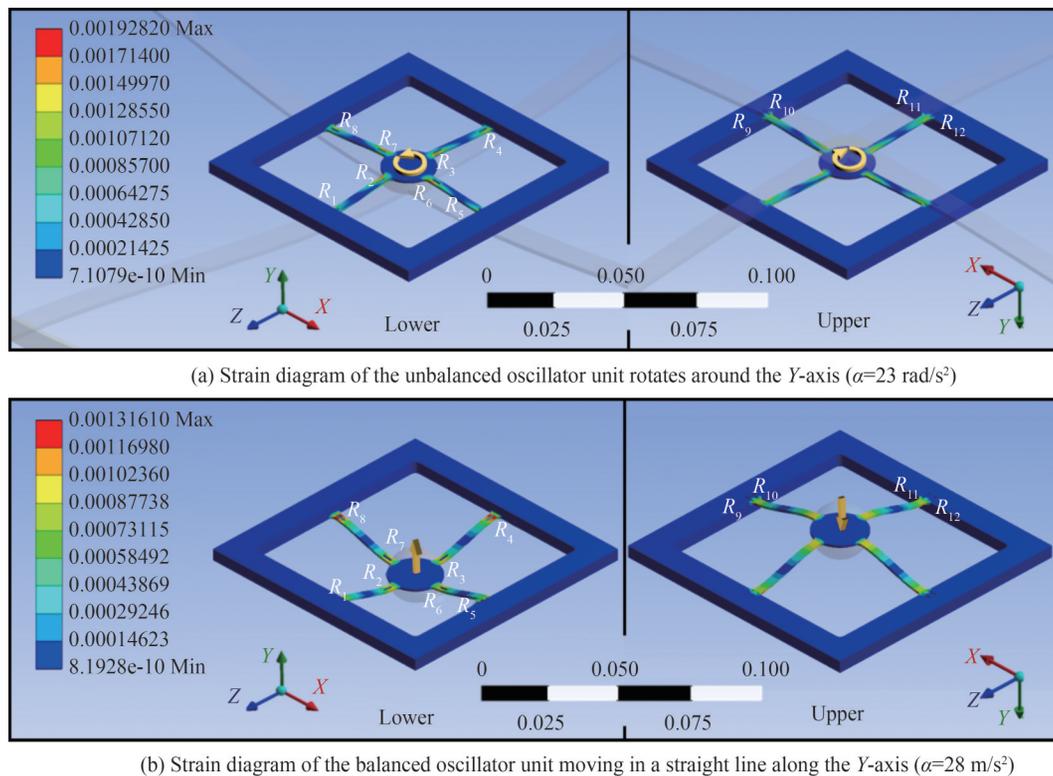
图 3 IMU 应变仿真图
Fig. 3 Strain simulation diagram of IMU

平均应变为 2.682×10^{-4},而只受重力的应变变化为 1.060×10^{-5};R_1、R_4、R_5 和 R_8 受到的应变较小,平均应变为 1.798×10^{-4},而只受重力的应变变化为 9.480×10^{-5};R_9 和 R_{12} 受到的应变很小,平均应变为 1.751×10^{-4},而只受重力的应变变化为 6.160×10^{-5};R_{10} 和 R_{11} 受到的应变基本没有,应变为 1.377×10^{-4}。由式(4)~(6)可以得出 $U_1 = 38.4$ mV,$U_2 = 38.9$ mV,$U_3 = 26.0$ mV。

如图 3(b)所示,当平衡振子单元沿 Y 轴以 28 m/s² 加速度运动时,R_1、R_4、R_5 和 R_8 发生的应变最大,平均应变为 2.151×10^{-4},与只受重力的应变变化为 1.530×10^{-4};R_2、R_3、R_6 和 R_7 受到的应变较小,平均应变为 7.144×10^{-5},与只受重力的应变变化为 -2.000×10^{-5};R_9、R_{10}、R_{11} 和 R_{12} 受到的应变很小,平均应变为 1.016×10^{-4},与只受重力的应变变化为 3.010×10^{-5}。由式(4)~(6)可以得出 $U_1 = 24.9$ mV,$U_2 = 25.0$ mV,$U_3 = 17.5$ mV。

非平衡振子单元相对于平衡振子单元,对于角加速度更加敏感,当传感器沿 Y 轴做角加速度时,4 个梁的应变相同,应力主要集中在靠近惯性轮的 4 个压力电阻位置,当传感器沿 X 轴(Z 轴)做角加速度时,对应 Z 轴(X 轴)上两个梁的应力分布基本相同,应力主要集中在靠近惯性轮且向上翻的压敏电阻上。通过平衡振子传感器与非平衡振子传感器进行对比,可以检测角加速度。

3 测试与分析

3.1 IMU 的测试

如图 4,试验平台采用单片机(广州市星翼电子科技有限公司,F103vgt6)控制步进电机(深圳市东么川伺服控制技术有限公司,普菲德 42BYGH34-401AS),由于步进电机在不同转速的情况下,角加速度不同,进而传感器可以测量此时的角加速度或加速度,将平衡与非平衡振子单元的木质框架固定在运动平台,通过动态信号采集仪(江苏东华测试技术股份有限公司,型号 DH5922N)与霍斯顿电桥连接,检测出传感器的运动状态。所有测试实验在恒温(25 ℃)恒湿(45%RH~55%RH)的大气环境下进行。
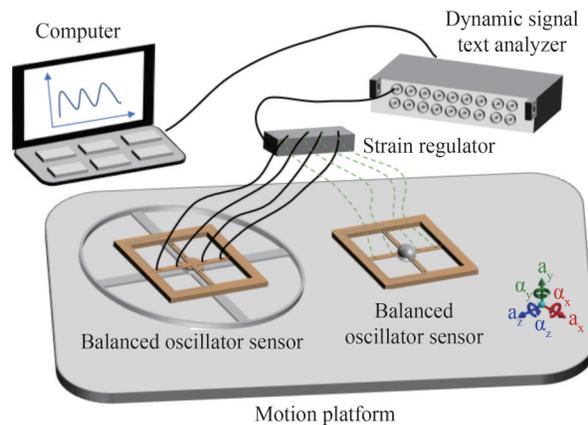
图 4 实验平台
Fig. 4 Experimental platform

对两个传感器进行加速度与角加速度测试,采用步进电机给传感器提供速度与角速度,通过改变步进电机的输入频率进而改变步进电机的转速,利用动态信号采集系统对平台的传感器信号进行采集与分析。

将商业加速度传感器(朗斯测试技术有限公司,KISTLER 8766A100AB)与非平衡振子单元一同放置于实验运动平台(大恒光电,GCD-011100M)上,如图 5 所示,商业传感器与非平衡振子单元在同一个运动平台,绕 Z 轴旋转,线加速度为 5 m/s²,通过两个传感器的对比,可以看出非平衡振子单元与商业传感器测量变化、测量时间与趋势基本相同,测量误差为 11%,可以证明本工作的 IMU 在测量加速度或角加速度方面可行。
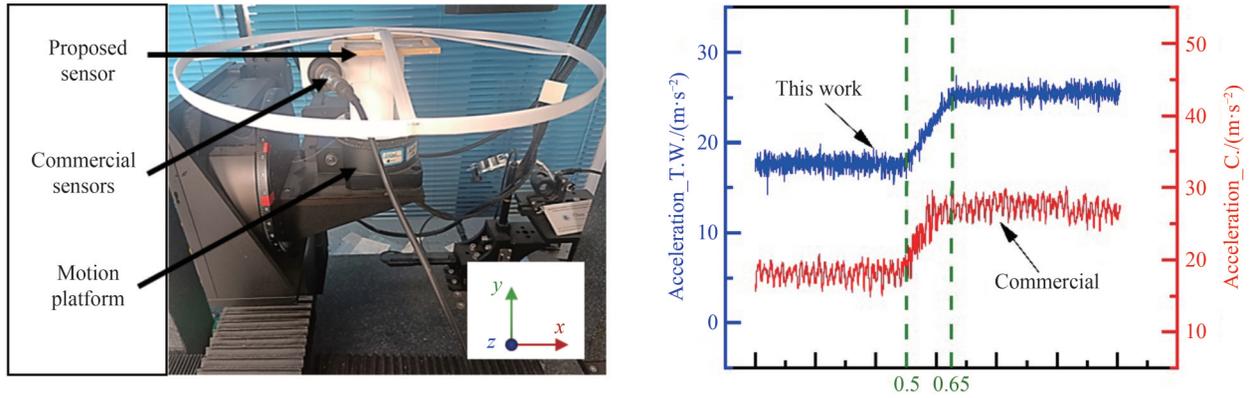
图 5　非平衡振子与商业传感器绕 Z 轴旋转采集信号

Fig. 5　Unbalanced oscillator and commercial units rotate around Z-axis to collect acceleration signals

3.2　IMU 性能分析

对平衡振子和非平衡振子单元进行角加速度和加速度信号采集，从输入 0.98~9.8 rad/s² 范围内进行测试，因为设计的传感器成对称结构，因此只需测量 X 轴或 Z 轴即可，本文测量的为 Z 轴。图 6 是非平衡振子单元绕 X 轴以 2.94 rad/s² 旋转采集的信号，其中 A 部分为运动前的噪声，B 部分是传感器在做加减速度时产生的波峰，C 部分是加速度运动停止后结构震荡产生的信号。
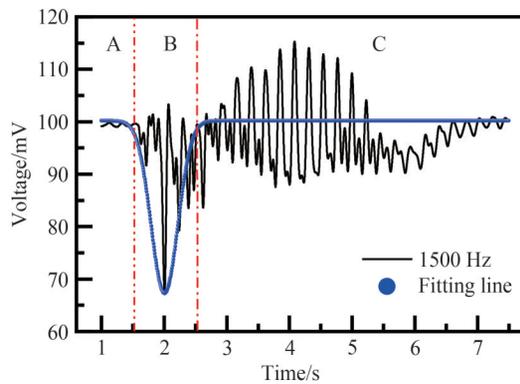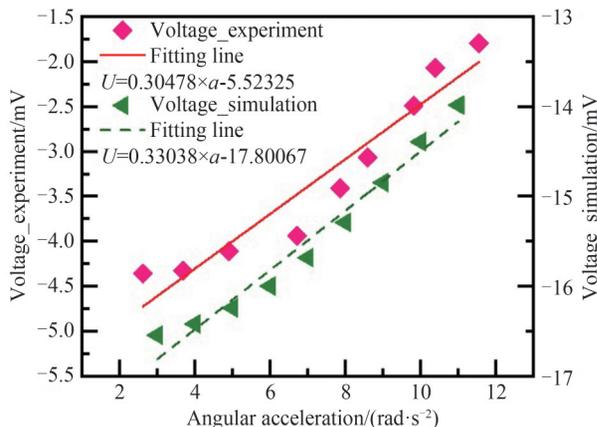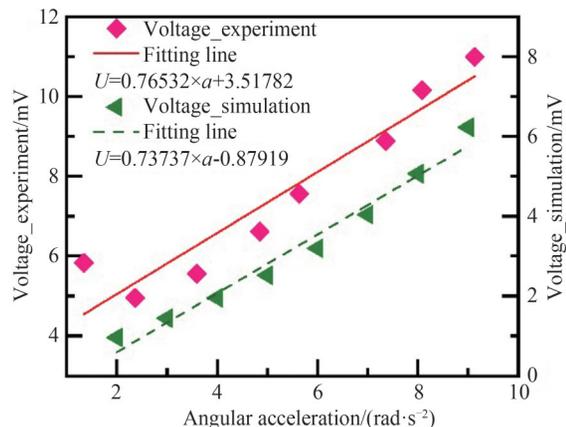
图 6　非平衡振子单元绕 X 轴旋转（$\alpha=2.94$ rad/s²）的输出电压信号

Fig. 6　The unbalance oscillator unit rotates around the X-axis（$\alpha=2.94$ rad/s²） output voltage signal

采集非平衡振子单元运动信号，如图 7（a）所示，其绕 Y 轴旋转的灵敏度为 0.305 mV/(rad/s²)；如图 7（b）所示，绕 Z 轴旋转的灵敏度为 0.765 mV/(rad/s²)；在其它相同实验条件下，绕 X 轴旋转的灵敏度为 0.285 mV/(rad/s²)，而进行沿 X 与 Z 轴加速度时，灵敏度过低，无法用于测量，其中沿 Y 轴直线运动的灵敏度为 1.110 mV/g，如图 7（c）所示。平衡振子单元在做旋转运动时，无信号变化，做直线运动时，如图 7（d）所示，沿

(a) The unbalanced oscillator unit rotates around the Y-axis

(b) The unbalanced oscillator unit rotates around the Z-axis

(c) The unbalanced oscillator unit accelerates along the Y-axis

(d) The balance oscillator unit accelerates along the Z-axis
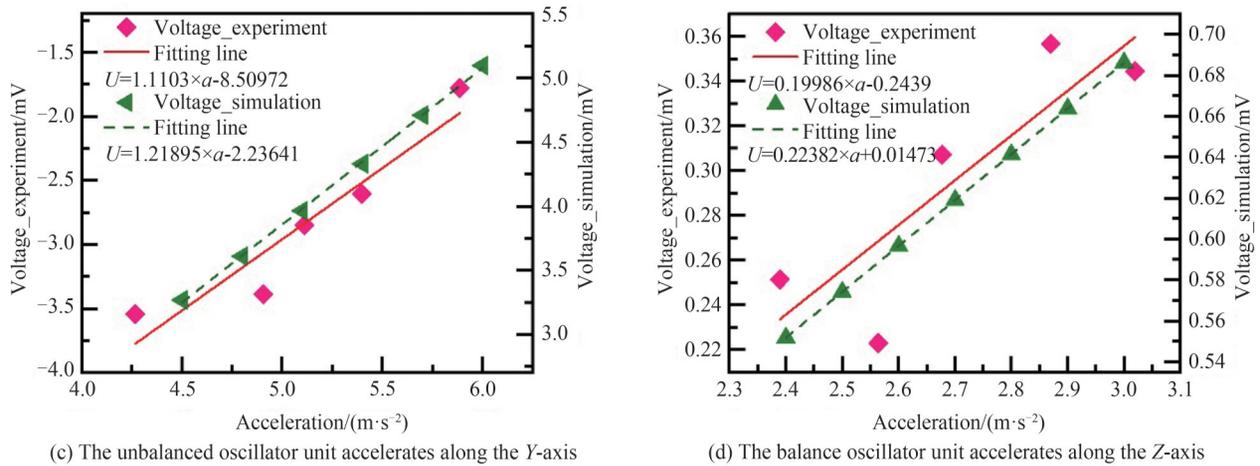
图7　测试与仿真结果对比

Fig.7　Comparison of test and simulation results

Z 轴运动的灵敏度为 0.200 mV/g;在其它相同实验条件下,沿 Y 轴直线运动的灵敏度为 $8.695×10^{-4}$ mV/g;沿 X 轴运动的灵敏度很小,无法用于测量。实验数据与仿真相比,误差在 10% 以内。

对平衡和非平衡振子单元的敏感运动方向进行重复性试验,在角加速度方面,只有非平衡振子单元较为敏感,对其绕 Z 轴和 X 轴按角加速度为 7.2 rad/s² 旋转,连续测量 40 次,如图 8(a)、(b)所示;在加速度方面,Y 轴较

(a) The unbalanced oscillator unit rotates around the Z-axis

(b) The unbalanced oscillator unit rotates around the X-axis

(c) The unbalanced oscillator unit moves in a straight line along the Y-axis

(d) The balance oscillator unit moves in a straight line along the Y-axis
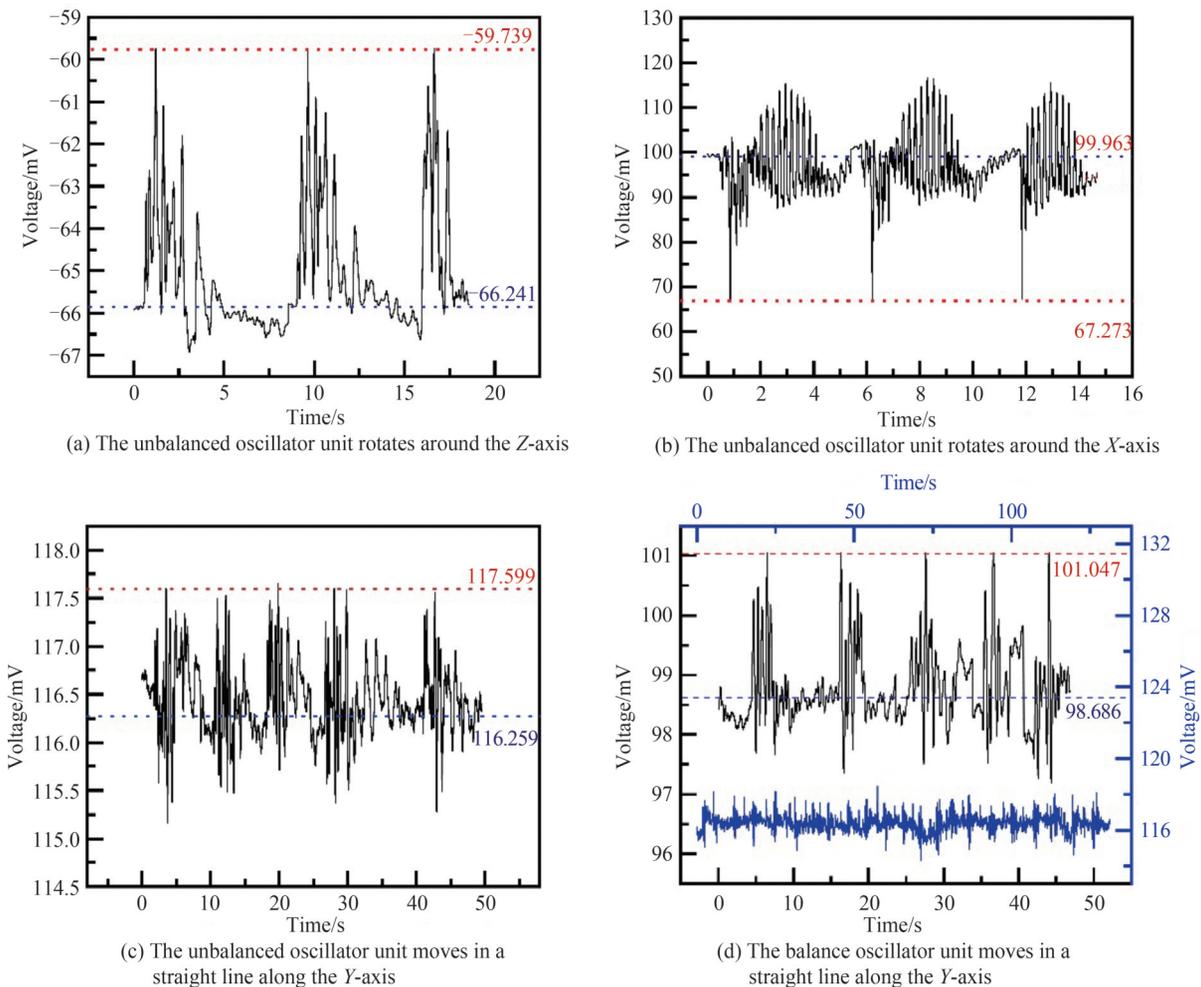
图8　IMU在周期性负载下的测试结果

Fig.8　Test results of IMU under periodic load

为敏感,对其沿Y轴重复5.9 m/s²加速变化,连续测量40次,采集信号的振动幅度基本相同,如图8(c)、(d)。从实验结果可以看出制作的传感器具有一定的重复性和稳定性。

根据课题组之前的研究[26],LIG压敏电阻会受到温度与湿度的影响,设计了LIG制备温度和湿度传感器,将其制备在非平衡和平衡振子单元框上,进行联合使用,进而补偿温度与湿度对IMU模块的测量误差。

本工作的IMU与市场上低精度的IMU相比,角加速度测量范围更广,且在Z轴的灵敏度更高。由于整体设计采用可降解的木材和PLA,所以该设计更环保,对环境更友好,并且这些材料是常见、低成本的,因此具有成本优势。详细性能对比如表3所示。

表3 商用低精度的IMU与所提出的IMU的性能对比
Table 3 Performance comparison between commercial low precision IMUs and proposed IMU

Model	Angular acceleration range/(rad·s⁻²)	Sensitivity/ (mV·s²·rad⁻¹)	Acceleration range(g)	Sensitivity/ (mV·g⁻¹)	Price	Degradable	Ref.
Piezoresistive triaxial accelerometer	± 8		± 3	X:0.113 Y:0.108 Z:1.010	—	No	[8]
MEMS–Based Piezoresistive Accelerometer for Head Injuries Monitoring	— —		± 500	0.22	—	No	[11]
Monolithic triaxial piezoresistive shock accelerometer	— —		50 000~100 000	X:2.17 Y:2.25 Z:2.64 $(\times 10^{-3})$	—	No	[12]
Bulk SiC MEMS accelerometer	— —		± 1	0.21	—	No	[13]
QMI8658	0.028	0.312	± 16		$2.57	No	[30]
QMA6100P	— —		± 2	62.4	$1.71	No	[31]
LSM6DSOTR	± 4.36	0.76	± 2	0.061	$7.47	No	[32]
Our IMU	X, Z:± 8 Y:± 23	X:0.285 Y:0.305 Z:0.765	X, Z:± 10 Y:$-1\sim 3$	X:0.006 Y:8.695 $\times 10^{-4}$ Z:0.200	$<$4.5	Yes	This work

4 结论

本文设计的基于激光诱导石墨烯的木制IMU,采用压阻式传感器结构,利用平衡振子和非平衡振子单元同时测量,采用LIG技术在木材上制备压敏电阻,并连成霍斯顿电桥,通过输出的电信号变化,实现运动状态的测量。平衡振子单元X轴的灵敏度为0.006 mV/g,Y轴的灵敏度为8.695×10⁻⁴ mV/g,Z轴方向的灵敏度为0.200 mV/g。非平衡振子单元绕X轴旋转的灵敏度为0.285 mV/(rad/s²),绕Y轴旋转的灵敏度为0.305 mV/(rad/s²),绕Z轴旋转的灵敏度为0.765 mV/(rad/s²),Y轴加速度的灵敏度为1.110 mV/g。重复性实验证明了该设计具有重复响应性。该IMU具有一定的传感性能,其相对市面上的IMU更加绿色环保,并且更加便宜和制作便捷,有环保优势和市场前景,可用于木制船舶、车辆工程或需测量振动的木制建筑等领域。

参考文献

[1] BOGUE R. MEMS sensors:past,present and future[J]. Sensor Review,2007,27(1):7-13.
[2] BENOUSSAAD M,SIJOBERT B,MOMBAUR K,et al. Robust foot clearance estimation based on the integration of foot-mounted imu acceleration data[J]. Sensors,2015,16(1):12.
[3] LIM M K,DU H,SU C,et al. A micromachined piezoresistive accelerometer with high sensitivity:design and modelling[J]. Microelectronic Engineering,1999,49(3-4):263-272.
[4] BADAOUI NEL,MORBIEU B,MARTIN P,et al. Towards a solid-state ring laser gyroscope[J]. Comptes Rendus Physique,2014,15(10):841-850.
[5] QI Y,FENG W B,LI F K,et al. An ultra-short coil fiber optic gyroscope[J]. Optics & Laser Technology,2023,157:

　　108751.

［6］ QIN Z, DING X, GE X, et al. A mode order optimized disk resonator gyroscope considering thermoelastic damping［J］. International Journal of Mechanical Sciences, 2022, 236: 107737.

［7］ KHLIFI A, AHMED A, MEZGHANI B, et al. Theoretical and numerical investigation of a new 3-axis su-8 mems piezoresistive accelerometer［J］. Microelectronics Journal, 2022, 128: 105552.

［8］ ZHANG J, HE C, ZHANG H, et al. The dual cycle bridge detection of piezoresistive triaxial accelerometer based on mems technology［J］. Journal of Semiconductors, 2014, 35(6): 064012.

［9］ MUKHIYA R, SANTOSH M, SHARMA A, et al. Fabrication and characterization of a bulk micromachined polysilicon piezoresistive accelerometer［J］. Materials Today: Proceedings, 2022, 48: 619-621.

［10］ KUROKAMI S, MOHAMAD ZBIN, YIN Y, et al. Piezoresistive acceleration sensor with high sensitivity and high responsiveness［J］. Key Engineering Materials, 2013, 534: 169-172.

［11］ MESSINA M, NJUGUNA J, PALAS C. Mechanical structural design of a mems-based piezoresistive accelerometer for head injuries monitoring: a computational analysis by increments of the sensor mass moment of inertia: 1［J］. Sensors, 2018, 18(1): 289.

［12］ DONG P, LI X, YANG H, et al. High-performance monolithic triaxial piezoresistive shock accelerometers［J］. Sensors and Actuators A: Physical, 2008, 141(2): 339-346.

［13］ ZHAI Y, LI H, TAO Z, et al. Design, fabrication and test of a bulk sic mems accelerometer［J］. Microelectronic Engineering, 2022, 260: 111793.

［14］ RAUTELA R, ARYA S, VISHWAKARMA S, et al. E-waste management and its effects on the environment and human health［J］. Science of The Total Environment, 2021, 773: 145623.

［15］ BAWA-ALLAH K A. Assessment of heavy metal pollution in nigerian surface freshwaters and sediment: a meta-analysis using ecological and human health risk indices［J］. Journal of Contaminant Hydrology, 2023, 256: 104199.

［16］ WANG Z, LUO P, ZHA X, et al. Overview assessment of risk evaluation and treatment technologies for heavy metal pollution of water and soil［J］. Journal of Cleaner Production, 2022, 379: 134043.

［17］ JADHAO P R, AHMAD E, PANT K K, et al. Advancements in the field of electronic waste recycling: critical assessment of chemical route for generation of energy and valuable products coupled with metal recovery［J］. Separation and Purification Technology, 2022, 289: 120773.

［18］ LEE C, WEI X, KYSAR J W, et al. Measurement of the elastic properties and intrinsic strength of monolayer graphene［J］. Science, 2008, 321(5887): 385-388.

［19］ MÜLLER U, JOST T, KURZBÖCK C, et al. Crash simulation of wood and composite wood for future automotive engineering［J］. Wood Material Science & Engineering, 2020, 15(5): 312-324.

［20］ PENG Z, YE R, MANN J A, et al. Flexible boron-doped laser-induced graphene microsupercapacitors［J］. ACS Nano, 2015, 9(6): 5868-5875.

［21］ BAI C, ZHANG J, GAO C, et al. Planar micro-supercapacitor based on laser processing［J］. Chinese Journal of Lasers, 2021, 48(2): 0202013.

［22］ YU Y, JOSHI P C, WU J, et al. Laser-induced carbon-based smart flexible sensor array for multiflavors detection［J］. ACS Applied Materials & Interfaces, 2018, 10(40): 34005-34012.

［23］ DIXIT N, SINGH S P. Laser-induced graphene (LIG) as a smart and sustainable material to restrain pandemics and endemics: a perspective［J］. ACS Omega, 2022, 7(6): 5112-5130.

［24］ WAN Z, N-TNGUYEN, GAO Y, et al. Laser induced graphene for biosensors［J］. Sustainable Materials and Technologies, 2020, 25: e00205.

［25］ YE R, CHYAN Y, ZHANG J, et al. Laser‐Induced graphene formation on wood［J］. Advanced Materials, 2017, 29(37): 1702211.

［26］ LI Chen, YANG Yanwei, XIA Tian, et al. Integrated sensor based on laser-induced graphene on wood［J］. Chinese Journal of Lasers, 2022, 49(2): 0202005.
　　李晨,杨研伟,夏田,等. 基于木材上激光诱导石墨烯集成传感器的研究［J］. 中国激光, 2022, 49(2): 0202005.

［27］ 沈隽. 木材加工技术［M］. 北京:化学工业出版社, 2005.

［28］ CHYAN Y, YE R, LI Y, et al. Laser-induced graphene by multiple lasing: toward electronics on cloth, paper, and food［J］. ACS Nano, 2018, 12(3): 2176-2183.

［29］ HAN J, ZHAO Z, NIU W, et al. A low cross-axis sensitivity piezoresistive accelerometer fabricated by masked-maskless wet etching［J］. Sensors and Actuators A: Physical, 2018, 283: 17-25.

［30］ Corporation LimitedQST. QMI8658(IMU). ［EB/OL］. ［2022-6-20］. https://www.qstcorp.com/imu_prod/QMI8658.

［31］ Corporation LimitedQST. QMA6100P. ［EB/OL］. ［2015］. https://www.qstcorp.com/acce_prod/QMA6100P.

［32］ STMicroelectronics. Lsm6dso, Full range acceleration range ±2 g. ［EB/OL］. ［2019-2-2］. https://www.st.com/zh/mems-and-sensors/lsm6dso.html.

Wood Inertial Measurement Unit Based on Laser-induced Graphene

LI Chen[1,2,3], LI Hao[1], YANG Yanwei[1]

（1 *College of Mechanical and Electrical Engineering，Shaanxi University of Science & Technology，Xi'an* 710021，*China*）
（2 *College of Mechanical Engineering，Xi'an Jiaotong University，Xi'an* 710049，*China*）
（3 *State Key Laboratory for Manufacturing System Engineering，Xi'an Jiaotong University，Xi'an* 710054，*China*）

Abstract：Inertial Measurement Unit（IMU）mainly measures and reports the specific force and angular velocity of an object. It usually consists of a three-axis accelerometer and a three-axis gyroscope. Traditional IMU have complex manufacturing processes and high costs. It is not easy to recycle，pollute the environment and cannot be biodegradable after being discarded. In this study，a kind of wood inertial measurement unit based on Laser-induced Graphene（LIG）is proposed.Camphor pine wood was selected as the sensor frame. The pine is placed in the vacuum chamber and adjust the vacuum degree in the vacuum chamber. Fiber laser and laser vibrators software was used to process LIG resistors at the pine frame resistor locations by adjusting laser frequency，laser power，scan speed，off-focus distance and other parameters，with a resistance value of about $100\ \Omega$，and to connect these resistors into multiple Wheatstone bridges. Due to the sensor's design being symmetrical along the X- and Z-axes，only the Wheatstone bridge on the beam in the X- or Z-axis direction needs to be measured. Different inertial bodies are divided into balanced oscillator unit and unbalanced oscillator unit. The inertial body of the balanced oscillator unit is a spherical inertial body（Cr13），mainly measuring acceleration；The inertial body of the unbalanced dipole element is the inertial wheel（PLA），which mainly measures the angular acceleration. The theoretical formula shows that the acceleration range of IMU along X axis and Z axis is$\pm10\ g$，the acceleration range along Y axis is $-g\sim+3\ g$，the angular acceleration range around X axis and Z axis is$\pm8\ \mathrm{rad/s^2}$，and the angular acceleration range around Y axis is$\pm23\ \mathrm{rad/s^2}$.

The product of this study is placed on a sports platform and uses a dynamic signal acquisition system to collect the output voltage of a Wheatstone bridge in the IMU. Through the joint test and comparison of the commercial acceleration sensor and unbalanced oscillator unit，it can be concluded that the designed sensor has the same change as the commercial sensor and has the ability to measure the angular rate. The results of this measurement of the Wheatstone bridge on the Z-axis beam are as follows：The sensitivity of the X-axis acceleration of the balanced oscillator unit is 0，and the sensitivity of the Y-axis acceleration is $8.695\times10^{-4}\ \mathrm{mV}/g$，the Z-axis acceleration sensitivity is $0.200\ \mathrm{mV}/g$，and the sensitivity to angular acceleration is 0. The sensitivity of Y-axis acceleration of the unbalanced oscillator unit is $1.110\ \mathrm{mV}/g$，the sensitivity of the X-axis and Z-axis acceleration is 0，the sensitivity of the angular acceleration around the X-axis is $0.285\ \mathrm{mV/(rad/s^2)}$，the sensitivity of the angular acceleration around the Y-axis is $0.305\ \mathrm{mV/(rad/s^2)}$，and the sensitivity of the angular acceleration around the Z-axis is $0.765\ \mathrm{mV/(rad/s^2)}$. By comparing the voltage output of Wheatstone in all directions of IMU under cyclic load，it is concluded that IMU of this design still has the ability to measure the angular rate and other parameters under multiple cyclic loads，so this design has a certain stability.

We propose a wooden inertial measurement unit based on laser-induced graphene，which is made of biodegradable materials and has good sensitivity and certain stability. Compared to the IMU on the market，it is more environmentally friendly，cheaper，and more convenient to manufacture，with environmental advantages and market prospects. It can be used in the fields of wooden ships，vehicle engineering，or wooden buildings that require vibration measurement. In future research，the size of this wooden IMU can be further optimized，and element doping can be applied to LIG varistors to improve their conductivity and sensitivity.

Key words：Inertial measurement unit；Laser induced graphene；Gyroscope；Accelerometer；Wood
OCIS Codes：120.7250；120.4570；160.4760