Airbag Helmet: Design and Analysis of Helmet Piezoelectric Accelerometer

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Abstract. The author invented an airbag helmet to provide effective protection for two-wheeled vehicle riders. This paper illustrates the design and analysis of this Helmet Piezoelectric Accelerometer. Analysis is based on the finite element model of solid mechanics (e.g. linear elasticity and piezoelectricity) with a carefully selected software of COMSOL Multiphysics. Finite element analysis method helped the author to reduce the need for physical prototypes in design process. With a high degree of accuracy, the author modeled complex material physical deformations with detailed visualization and solved the problem. Equations were used for calculation during the process. This paper provides the design of comsol-based solid mechanics and piezoelectricity simulation and simulates the process of converting the mechanical vibration into voltage signals by using piezoceramics, so as to supply power to the airbag accelerometer and release the airbag in time. The reliability and safety of the design are verified by means of the mechanical and electrical simulation. In case of a traffic accident, the airbag will inflate instantly and form a balloon-shaped helmet wrapping the rider's head to secure the head effectively.

1. Introduction

Frequent traffic accidents cause high casualty rate. With portability and affordability, motorcycles, bicycles, electric bicycles and other two-wheeled vehicles are popular with the general public, and become necessary means of transportation for many families. However, the risk of driving two-wheeled vehicles is high due to the weaknesses of such vehicles, including poor stability, unstable speed and lack of protection facilities, and frequent traffic accidents involving such vehicles cause high casualty rate. Therefore, the effective protection for riders of such vehicles is particularly important. The present protection measures mainly include wearing helmets to protect the fragile head organs and tissues of riders. The commercially available helmets are similar, and the design mainly focuses on improving the firmness of surface materials and the overall air permeability of the helmet.

As a passive security device, airbag is widely applied to automobiles[1]. At the time of a crash, the combination of the airbag and seat belt can provide effective anti-collision protection for the passengers, making head injury rate decreased by 25% and facial injury rate decreased by about 80%. Based on the superior protection performance of the airbag, an airbag helmet is put forward in the design to provide head protection for two-wheeled riders. This paper emphasizes the design and analysis of a helmet piezoelectric accelerometer, the core component of the airbag helmet that is used to trigger the entire airbag device in time and provide timely and reliable security protection.

Piezoelectric materials are crystalline materials generating a voltage between two end faces when they are placed under a pressure, e.g. piezoceramics, crystal quartz, and piezoelectric polymers[2]. The
main application fields of the piezoelectric materials are vibrational energy-to-electric energy transducers and electric energy-to-vibrational energy transducers. We choose a vibrational energy-to-electric energy transducer as an accelerometer able to convert mechanical energy into electric energy. In emergency, the transducer can provide an instantaneous voltage higher than the threshold voltage of the airbag helmet to safely release its airbag, as shown in Figure 1. The piezoelectric power generation is an energy conversion technology. The helmet accelerometer based on such technology is simple in structure, easy to be miniaturized and integrated and free of thermal generation, electromagnetic interference and pollution, meet the power demand of low-power products, and provide timely protection for riders with quick piezoelectric response [3]. Therefore, this paper provides a mechanical simulation and design for the piezoelectric accelerometer.

2. Research Means
The finite element analysis is to simulate a real physical system by means of a mathematical approximation. With simple and interactional elements, such research is to infinitely approximate a real system based on unknown quantities with finite unknown quantities. The finite element model is an idealized mathematical abstraction of the real system. The model consists of some elements of simple shapes, and these elements are connected by means of nodes and bear certain loads[4]. The helmet piezoelectric accelerometer is analyzed based on the finite element model of solid mechanics (e.g. linear elasticity and piezoelectricity). The commonly used finite element analysis software includes Femap+ NX Nastran, COMSOL Multiphysics and pFEPG. COMSOL Multiphysics includes lots of predefined physical application modes covering fluid flow, heat conduction, structural mechanics, electromagnetic analysis, electromechanical coupling analysis and other physical fields with which users can quickly build models. In addition, COMSOL-defined models are flexible in solving many common physical problems or convenient for users to define their individual partial differential equations. Therefore, we chose COMSOL as our simulation computing tool.

3. Research Process
As shown in Figure 2, the accelerometer model is modularized into three modules of different materials: iron a, copper b and lead zirconate-titanate piezoceramic c. The iron and copper modules belong to linear elastic materials, and the lead zirconate-titanate piezoceramic belongs to a piezoelectric material. Their dimensions are shown as follows: a: 2mm×3mm×0.8mm, b: 10mm×5mm×0.2mm and c: 4mm×3mm×0.2mm.
The linear elastic mechanics is an important branch of solid mechanics. It studies the deformation and internal force of the elastic objects under the external force and other external factors. As the foundation of material mechanics, structural mechanics, plastic mechanics and inter-disciplines, the linear elastic mechanics is widely applied to construction, machinery, chemical and aerospace engineering fields. The linear elastic materials used in this model should satisfy the following equations:

**Equilibrium equation:**

\[
\begin{align*}
\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} + f_x &= 0 \\
\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} + f_y &= 0 \\
\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} + f_z &= 0
\end{align*}
\]

**Geometric equation:**

\[
\begin{align*}
\varepsilon_{xx} &= \frac{\partial u}{\partial x} \\
\varepsilon_{yy} &= \frac{\partial v}{\partial y} \\
\varepsilon_{zz} &= \frac{\partial w}{\partial z} \\
\varepsilon_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\
\varepsilon_{yz} &= \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \\
\varepsilon_{xz} &= \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}
\end{align*}
\]

** Constitutive equation:**

\[
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\varepsilon_{xy} \\
\varepsilon_{yz} \\
\varepsilon_{xz}
\end{bmatrix} = \begin{bmatrix}
1 - \nu & \nu & \nu & 0 & 0 & 0 \\
\nu & 1 - \nu & \nu & 0 & 0 & 0 \\
\nu & \nu & 1 - \nu & 0 & 0 & 0 \\
0 & 0 & 0 & (1 - 2\nu)/2 & 0 & 0 \\
0 & 0 & 0 & 0 & (1 - 2\nu)/2 & 0 \\
0 & 0 & 0 & 0 & 0 & (1 - 2\nu)/2
\end{bmatrix} \begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{xy} \\
\sigma_{yz} \\
\sigma_{xz}
\end{bmatrix}
\]

Where, $\sigma_{xx}, \sigma_{yy}, \sigma_{zz}$ represent normal stresses in three directions in a rectangular coordinate system, and $\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}$ represent corresponding normal strains; $\sigma_{xy}, \sigma_{xz}, \sigma_{yz}$ represent three shear stresses in a rectangular coordinate system, and $\varepsilon_{yz}, \varepsilon_{xz}, \varepsilon_{xy}$ represent corresponding shear strains; $u, v, w$ represent displacements in three directions in a rectangular coordinate system; $E$ represents Young modulus, and $\nu$ represents Poisson ratio.

In addition to these equations, the piezoelectric materials should also satisfy the piezoelectric equation. The piezoelectricity of the piezoelectric materials relates to the interaction between mechanics and electricity. The piezoelectric equation is an expression describing the relationship between the mechanical quantity and electrical quantity of crystals[5]. The piezoelectric chips (vibrators) would be in different electrical and mechanical boundary conditions according to application states and test conditions. That is, independent variables for the piezoelectric equation are optional. Therefore, there are 4 types of equations describing the piezoelectric effects of piezoelectric materials, namely typed, type e, type g and type h, according to the mechanical boundary conditions.
(mechanical freedom and mechanical gripping) and the electrical boundary conditions (electrical short circuit and electrical open circuit). The helmet accelerometer belongs to the boundary conditions for the third type of piezoelectric equation, i.e., the mechanical gripping and electrical short circuit. Boundary conditions for the third type of piezoelectric equation are shown as follows:

\[
S = s^D T + g D
\]
\[
E = -g T + \beta T D
\]

Where, \(\beta T\) is the dielectric constant in case of a constant stress (in free state), \(s^D\) is the elastic stiffness coefficient in case of a constant electric displacement (in open circuit state), \(T\) is the stress, \(D\) is the electric displacement, \(S\) is the strain, and \(E\) is the electric field intensity.

In addition, the charge conservation of the piezoelectric materials in the electrostatic field should be considered too. The piezoelectric materials have no free charge but bound charges. The piezoelectric material has an internal domain structure. When the material is polarized, the internal electric dipoles are deflected to the polarization direction and induce the bound charges at both ends of the material. These induced electric dipoles are paired positive and negative charges in direction consistent with that of the electric field to some extent. As a result, the electric field in the dielectric materials is different from that in free space. When a piezoelectric material is deformed in tension or compression, both ends of the material adsorb or release charges with changing distances among electric dipoles, which is called positive piezoelectric effect. The polarized vector field \(P\) and polarized charge density \(\rho_p\) are involved in the following relational expression:

\[
\rho_p = -P \cdot \mathbf{p}
\]

The polarization effect can locally change the electric field in the materials:

\[
\mathbf{P} \cdot \mathbf{E} = \frac{\rho + \rho_p}{\varepsilon_0}
\]

Electric displacement \(D\) is defined as:

\[
D = \varepsilon_0 E + P
\]

The electric displacement equation can be expressed as:

\[
\mathbf{P} \cdot \mathbf{D} = \rho
\]

If a rider accidentally gets hit on the head during riding, the piezoelectric accelerometer is impacted and induces a voltage due to the acceleration. We can assume the acceleration in direction \(Z\) at this time, and use comsol to solve the natural vibration frequency as well as changes in transient displacement and potential.

4. Analysis Results

4.1. Variations in potential and voltage of accelerometer at different accelerations

We simulated the variations in potential of the lead zirconate-titanate piezoceramic with time at four accelerations, and observed the variation at a chosen point in the piezoceramic, as shown in Figure 3. Figure 3 reveals that the potential value increases with time. In addition, high acceleration results in high potential value and increases potential rate. That is, when a rider at high acceleration is in danger, the accelerometer can quickly supply power to the airbag to release the airbag and protect the head.

Further, we calculated the relationship between the system acceleration and voltage to visually express the feasibility of the design, as shown in Figure 4. The Figure 4 shows that the accelerometer voltage has a linear relationship with the acceleration, and the voltage increases with the acceleration, which conforms to the piezoelectric equation. Meanwhile, high voltage will be generated at a low acceleration to ensure the smooth release of the airbag and prove the reliability of the design. The emergency braking speed of motorcycle is about 8m/s², so the threshold voltage can be set to a voltage value \(U_{cri}\) corresponding to the acceleration of 8m/s² (see Figure 4). Therefore, the airbag can be opened when the voltage generated by the accelerometer exceeds the threshold voltage \(U_{cri}\).
4.2. Variation in accelerometer displacement at different accelerations

The deformation displacements of the accelerometer at different accelerations are shown in Figure 5. When the acceleration increases, the deformation displacement of the accelerometer will increase, and more mechanical energy will be converted into electric energy.
4.3. Variation in displacement at different characteristic frequencies

Resonance is a phenomenon that the amplitude of a mechanical system increases significantly when the system is excited at a frequency close to its certain order natural frequency. The resonance displacement means that when resonance occurs, the mechanical system has an obvious vibration mode with the maximum energy input to the system for excitation. Depending on simulation in comsol, six characteristic frequencies of the system are calculated: 16863Hz, 18322Hz, 22736Hz, 46743Hz, 55226Hz and 65764Hz, as shown in Figure 6.

5. Prospect

This paper provides the design of comsol-based solid mechanics and piezoelectricity simulation and simulates the process of converting the mechanical vibration into voltage signals by using piezoceramics, so as to supply power to the airbag accelerometer and release the airbag in time. The reliability and safety of the design are verified by means of the mechanical and electrical simulation. In case of a traffic accident, the airbag will inflate instantly and form a balloon-shaped helmet wrapping the rider's head to secure the head effectively.

Helmet products are extensively applicable to people, including special populations (children, aged people, the deaf and the blind) and mass groups who travel by two-wheeled vehicles for
low-carbon and environmental protection. These products are also suitable for multiple circumstances, such as roads, construction sites, underground survey spaces and cross-country race fields. Taking piezoceramics with piezoelectric effect as the core component, the design converts the impact vibration into electric energy to release the helmet airbag in time and protect the rider in danger. Therefore, the helmet airbag plays an important role in improving road safety and decreasing injury rate, even death rate. The product needs no external batteries, has a light and simple structure, and provides good safety experience for riders. It is one of the necessary devices for travel and widely applicable to daily use of the people.

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