Design and Performance Analysis of a Lateral Thrust Measuring Device

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Abstract: This paper takes multi-dimensional force measurement of lateral force power unit as research objective, and a piezoelectric multi-dimensional force measuring device with piezoelectric quartz crystal as force sensitive component is designed. First, the mathematical model between sensors’ output and measured lateral force is established by theoretical derivation. The relationship between the force applied to measured object and measuring device’s output is obtained through the finite element analysis, which verifies the measurement performance of measuring device. On the other hand, through ANSYS model analysis, a conclusion that the first natural frequency of measuring device is 1467.8Hz can be obtained, and the dynamic performance of measuring device is good, which enables accurate measurement of real-time varying lateral force.

1. Introduction
To achieve accurate control of aircraft under high altitude and low pressure, direct lateral force control technology is introduced into traditional trajectory and attitude control system. The lateral thrust generated by attitude control engine generates handle torque. Lateral force control technology is less affected by flight altitude and flight speed, greatly improving the manoeuvring performance of aircraft[1]. As a key performance parameter of lateral force control technology, lateral thrust is of great significance for ensuring control precision and improving target hit rate[2]. Therefore, accurate measurement of lateral thrust is particularly significant.

For force measurement technology, there are the related research. Princeton University developed an inverted pendulum thrust test device, which measured the thrust generated by engine based on the displacement signal measured by displacement sensor[3]. R.John Stephen and K.Rajanna et al. developed a film strain gauge ion engine thrust test system to measure the thrust of engine through strain gauge sensors attached to elastic strut and a corresponding test system[4]. Ann M Wright et al. studied a six-component thrust measurement, and the load of each component was measured by six force measuring arms fixed by test stand[5]. Dwarakanath and Kang et al. developed a six-dimensional force sensor based on the Stewart parallel mechanism[6]. From the published literature, it can be obtained strain measuring devices are mostly used for force measurement. That is, the force is measured according to the deformation amount of elastic element, and the sensor of different structure is placed between measured object and fixing device. In order to satisfy the requirements of sensitivity, force-sensitive elastic links with low stiffness are generally used in strain force measuring devices. However, the low-stiffness will result in complicated structure, low natural frequency, more test links, adjustment difficulties and so on.
Aiming at the spatial six-dimensional thrust vector measurement problem of lateral force power unit, a thrust vector measuring device is designed. And the problems of traditional strain measuring device such as complex structure, low natural frequency and more test links are solved. In addition, the performance of measuring device is verified through theoretical analysis and ANSYS simulation.

2. Designing of measuring device

2.1. Researching on measurement principle

Since the lateral force control technology requires multiple power units to work together to achieve precise trajectory and attitude control, and the thrust performance of each power plant and multi-dimensional thrust performance of composite ignition are research focus, which resulting in more measurement factors and more complicated of measured object. Therefore, the tri-direction force sensor is chosen as the basic unit of measuring device here. However, the measurement of spatial six-dimensional force is not possible with only one tri-direction force sensor. Multi-point spatial arrangement method based on the tri-direction force sensor is an effective way to solve the problem of multi-dimensional force measurement. To ensure measurement results are not affected, the sensitivity of each force sensitive component is required to be the same. Meanwhile, the force acting at any point on platform should be assigned to force sensitive component in accordance with “leverage principle”. Therefore, ensuring the stiffness of each force sensitive component being the same in the same direction is necessary, which ensures the structural symmetry and the performance consistency of each fulcrum. So square arrangement is selected here. In addition to ensuring the symmetry of structure, square arrangement can avoid affecting measurement result and reducing cross interference of sensors where the position of external force action point changes greatly. The arrangement of sensors is shown in figure 1.

![Figure 1. Sensors’ arrangement.](image)

Taking the centre of the square where the four sensors are located as origin O, the XY plane coincides with the lower surface of sensors to establish a coordinate system. Under the reference coordinate system, the lateral force acting on model can be equivalently decomposed into three unidirectional forces components and three moments($F_x, F_y, F_z, M_x, M_y, M_z$). Assuming the distance between adjacent sensors is 2a, according to static balance principle, the equilibrium equation can be obtained.

\[
\begin{align*}
F_x &= F_{x1} + F_{x2} + F_{x3} + F_{x4} \\
F_y &= F_{y1} + F_{y2} + F_{y3} + F_{y4} \\
F_z &= F_{z1} + F_{z2} + F_{z3} + F_{z4} \\
M_x &= a(F_{z1} - F_{z2} - F_{z3} + F_{z4}) \\
M_y &= a(F_{x1} + F_{x2} - F_{x3} - F_{x4}) \\
M_z &= a(-F_{x1} + F_{x2} + F_{x3} - F_{x4} - F_{y1} - F_{y2} + F_{y3} + F_{y4})
\end{align*}
\]
2.2. Force sensitive component

Force sensitive component is mechanically sensitive components of measurement system[7]. Real-time variation of the force generated by lateral force power unit requires force sensitive component to have sufficient sensitivity and natural frequency in addition to meeting the requirements of force measurement. Meanwhile, the force sensitive component must ensure measuring device has enough installation space for measured device. The physical properties of quartz crystal is relatively stable, and its sensitivity varies little with time. Moreover, quartz crystal has advantages of high stiffness, high natural frequency, fast transient response and long-time stability[8]. Meanwhile, quartz crystal is anisotropic material, so quartz crystal can be cut in different directions to obtain different geometric cutting-type, and different geometric cutting-type can measure different types of force. Normal load can be measured by X0 cutting-type, and tangential load can be measured by Y0 cutting-type. Tri-direction force sensor is the combination of one X0 crystal group and two Y0 crystal group (figure 2)[9]. Besides, quartz crystal has high Curie points and good temperature stability, so it’s ideal for environment with large temperature changes. Therefore, piezoelectric quartz crystal is selected as force sensitive component of measuring device.

![Figure 2 Combined crystal group of tri-direction force sensor.](image)

2.3. Mechanical structure of measuring device

The structure of measuring device is shown in figure 3.

![Figure 3. Measuring device model.](image)

The base of measuring device is fixed to test bench, and connection datum is connected with measured object. Sensors are arranged inside measuring device and are integral with flange and base. Compared with traditional strain gauge force measuring device, this measuring device has the advantages of simple structure, good precision retentivity, easy to dismount, fully sealed package of sensors, high degree of protection and so on. The base of measuring device is fixed with measuring object, and the rest of space is completely open. Centre of measurement is the interface of measuring device and measured object. Datum is positioned, so the positional consistency is good during measuring. Therefore, piezoelectric force measuring device is more suitable for the measurement of spatial six-dimensional thrust vector.

3. Measuring principle

3.1. Mathematical model

Measuring simulation is shown in figure 4. Lateral force generating device is circumferentially
distributed. When lateral force generating device works, the measured object will generate two forces and three moments, which are lift($F_s$), lateral force($F_c$), rolling moment($M_g$), yawing moment($M_p$), pitching moment($M_f$).

![Force and moment diagram]

**Figure 4.** Analog measurement model.

Assuming lateral force generating device generates a lateral force $F$ and the coordinate if acting point is $(m, n, l)$, the expressions of force and moment generated by device under measurement are as follows:

$$
\begin{bmatrix}
F_c \\
F_s \\
M_p \\
M_g \\
M_f
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
0 & 1 \\
0 & -l \\
l & 0 \\
-n & m
\end{bmatrix}
\begin{bmatrix}
F_w \\
F_c
\end{bmatrix}
$$

(2)

Since lateral force generating device is circumferentially distributed, so $m^2 + n^2 = r^2$. Where $F_{xc}$ and $F_{yc}$ are component forces of lateral force($F$) on x axis and y axis, and $r$ is the distance from the point of action to z axis. When the output of measuring device is known, the magnitude, direction and point of action of lateral force can be derived by expression(2).

### 3.2. Simulation analysis

Simulating measuring device with ANSYS Workbench. The 3D model built by Pro/E is imported into ANSYS Workbench static analysis. A lateral force($F$) where $F_x = F_y = 1000N$ is applied to measured object. The lateral force is perpendicular to z-axis and the coordinate of action point is $(50, 256, 375.5)$. The sensors’ output is obtained by ANSYS simulation analysis. The simulation analysis diagram is shown in Figure 5.

![ANSYS simulation analysis]

**Figure 5.** ANSYS simulation analysis.
It is known that $2a = 242 \text{mm}$. Bring the outputs of tri-direction force sensors into formula (1), the three-axis forces and three-axis moments can be calculated. The output of measuring device and calculation results are shown in Table 1.

| Sensors’ output | Resultant force(N) | Moment(Nm) |
|----------------|---------------------|------------|
| X1 654.75 X2 -583.28 X3 1112.3 X4 -183.74 | $F_x=1000.03$ | $M_x=-374.315$ |
| Y1 1099.6 Y2 -581.05 Y3 663.85 Y4 -182.44 | $F_y=999.96$ | $M_y=373.877$ |
| Z1 1544.7 Z2 2.0122 Z3 -1547 Z4 0.20174 | $F_z=0.08606$ | $M_z=-204.665$ |

Bringing the three-axis forces and three-axis moments measured by measuring device into equation (2), the magnitude, direction and action point of lateral force can be reserved. Calculation results are shown in Table 2.

| Measured value of lateral force | |
|---------------------------------||
| $F_x(N)$ | $F_y(N)$ | $m$ | $n$ | $l$ |
|-------------------|-------------------|------|------|------|
| 1000.03 | 999.96 | 51.12 | 255.78 | 374.0 |

It can be concluded from Table 2 that the maximum difference between force values simulated by ANSYS and applied to measuring device is 0.04N. Simultaneously, the maximum difference between measured force point coordinate value and practical coordinate value is in millimeter level. Therefore, the measuring device can be used for lateral force measurement.

4. Model analysis
Since lateral force generating device has the characteristics of starting, shutting down frequently, short working time, and the force generated by lateral force generating device changes in real time, so measuring device should have good dynamic performance in addition to satisfying measuring accuracy[10]. As a modern method to study the dynamic characteristics of structure, model analysis can be applied to evaluate dynamic characteristics of existing structural system[11]. Modal analysis is actually the solution to the natural frequency of system. At present, natural frequency is mostly used to evaluate the dynamic performance of measuring device. Generally considered that the higher natural frequency of measuring device, the better dynamic performance of measuring device. Therefore, the natural frequency is required to be as large as possible. The first six-order modal analysis of measuring device is performed by ANSYS Workbench. The first six natural frequencies of measuring device are shown in Table 3. Figures 6~11 show the first six-stage arrays and deformations of measuring device.

| First six natural frequencies | |
|-------------------------------||
| Mode | Frequency[Hz] |
|------|---------------|
| 1 | 1467.8 |
| 2 | 1507 |
| 3 | 1617.7 |
| 4 | 1620.4 |
| 5 | 1779.7 |
| 6 | 2551.7 |
It can be concluded from model analysis that the first natural frequency of measuring device is 1467.8Hz, which can satisfy measurement requirement and avoid resonance during measure.

5. Conclusion
This paper takes multi-dimensional force measurement of lateral force power unit as research objective. Taking piezoelectric quartz crystal as force sensitive material, and the principle and method of lateral force measurement were described. A lateral force measuring device was designed and theoretical, finite element analysis of measuring device was carried out.

(1) The magnitude, direction and application point of the force calculated by theoretical derivation and ANSYS simulation are basically equivalent to the magnitude, direction and action point of the force applied to the measured object. Therefore, the measuring device can satisfy the precision requirement of lateral force measurement.

(2) Through modal analysis, it can be concluded that the natural frequency of measuring device is large and the dynamic performance is good. So the measuring device can accurately measure the lateral force that changes in real time.
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