

A Calibration Device for Force-Torque Sensors

Nicolay Zarutskiy, Roman Bulkin

Abstract—The paper deals with the existing methods of force-torque sensor calibration with a number of components from one to six, analyzed their advantages and disadvantages, the necessity of introduction of a calibration method. Calibration method and its constructive realization are also described here. A calibration method allows performing automated force-torque sensor calibration both with selected components of the main vector of forces and moments and with complex loading. Thus, two main advantages of the proposed calibration method are achieved: the automation of the calibration process and universality.

Keywords—Automation, calibration, calibration device, calibration method, force-torque sensors.

I. INTRODUCTION

THE final stage of force-torque system development is its basic tests to determine the technical and operational characteristics. Particular attention is paid to the calibration of force-torque sensor (FTS), which is the main source of system errors. Calibration is a particularly important stage in the production of FTS technology in series production. The task of creating equipment to carry out the calibration with high accuracy is equal in importance to the problem of the design of the FTS.

II. CALIBRATION METHODS

A. Typical FTS

Fig. 1 shows the appearance of a typical FTS. Most FTS consists of mounting flange 1 and sensitive flange 2.

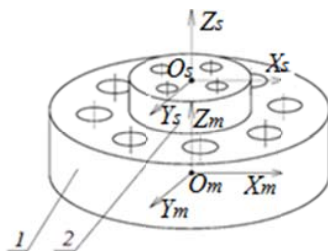


Fig. 1 Appearance of a typical FTS

At FTS generally operates the main vector of forces and moments (main vector), consisting of the resultant vector of the forces \mathbf{F} (the resultant vector), and the resultant vector of the moments \mathbf{M} (the resultant moment).

The FTS coordinate system OXYZ coincides with the coordinate system $O_m X_m Y_m Z_m$ of the FTS mounting flange.

N. Zarutskiy and R. Bulkin are with the Central Research Institute of Robotics and Technical Cybernetics, Saint-Petersburg, Russia (phone: +7-812-552-61-77; e-mail: zarutskiy@rtc.ru, r.bulkin@rtc.ru).

FTS measuring center is a center of FTS coordinate system OXYZ. Components F_x , F_y , F_z of the resultant vector and components M_x , M_y , M_z of the resultant moment act on the FTS sensitive flange in the calibration process.

B. FTS Calibration Methods

One way to calibrate the FTS is a loading on FTS with six components of load on a calibration device. FTS is mounted on the calibration device, then the sensor is mounted to adapter flange, which with the help of pulleys and weights along each axis of the sensor is applied the known values of a component of the main vector. For easy processing measurements, the sensor should be set so that the measurement center (stiffness center) coincides with the point of application of the vector \mathbf{F} [1]. Examples of such calibration devices can be found in [2] - see Fig. 2, [3], [4].

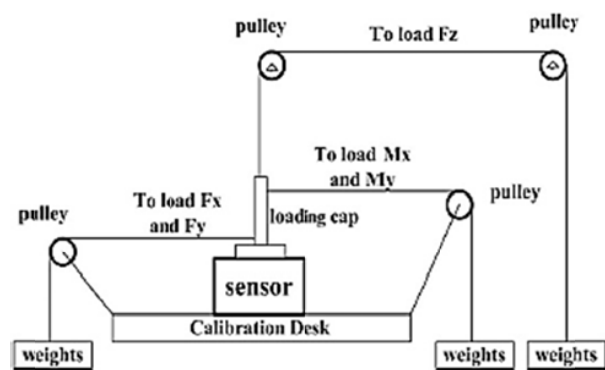


Fig. 2 FTS loading with all six components of the main vector

In order to reduce the cost developing systems for the study of experimental, FTS are often designed on the basis of standard test equipment. Fig. 3 describes an installation on the basis of a universal materials testing machine CMT5000, ensuring the accuracy of 1% strength [5].



Fig. 3 The test equipment used for the calibration of FTS

Another calibration method is "Shape from motion" where the FTS with the load weights rotates by manipulator around a horizontal axis of the manipulator on 360° with a certain pitch (see Fig. 4). Also FTS with fixed load is rotated by manipulator relative to the longitudinal axis of the manipulator flange. At each step, the FTS is affected by the gravity load of weight and moments of this force and on each step signals are removed from the FTS that allows to perform an automated calibration.



Fig. 4 Realization of the calibration method "Shape from motion": FTS is attached to the load of known weight that rotates by the manipulator along a predetermined trajectory

The advantage of this calibration method is the ability to automate the FTS calibration process through the use of an industrial manipulator as a part of the calibration device (in [6], an industrial robot KUKA KR-3 is used for this purpose). However, a disadvantage of this approach compared to the first described calibration method is the inability to specify the limiting values of the individual components of the force vector without changing the test load.

The ratio of FTS parameters in the FTS operating range of the various components of the load vector is that the use of the test load, develops a maximum torque value, does not allow to develop the maximum values of the forces, and the test load, which provides a task force corresponding to the maximum value of the FTS operating range causes FTS overloading with moments.

As a result of the analysis of existing approaches to FTS calibration, a novel calibration device construction is offered, which combines the advantages of the first described and second described approaches, namely the possibility of setting the individual components of the main vector including the maximum values of the FTS operating range, and calibration process automation by using a six-DOF drive system (SDS), for example an industrial manipulator.

An additional advantage of the proposed calibration method is the ability to specify not only the individual components of the main vector, but also complex loading, allowing for the experimental works.

III. AN ALTERNATIVE CALIBRATION METHOD

A. The Scheme of the Calibration Device

The scheme of the calibration device is shown in Fig. 5. The calibration device consists of a frame 1 on which there are pulleys 2.

With ropes load of the weights 3, is transmitted to the flange 4 rigidly connected to the FTS mounting flange. FTS sensitive flange is connected to the output unit of SDS (not shown in Fig. 5), allowing to provide six degrees of freedom of FTS motion.

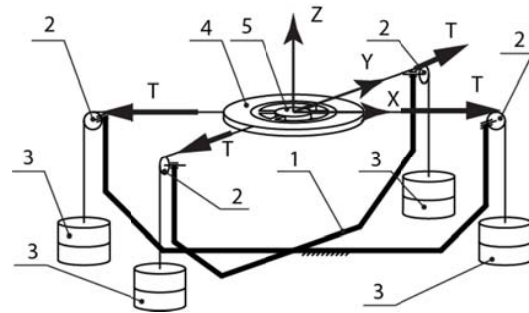


Fig. 5 The proposed calibration scheme

The proposed calibration method is as follows.

1. FTS sensitive flange is fixed to the SDS output flange, while the FTS mounting flange is fixed to flange. At the flange on each side, two-DOF joint is fixed (total four two-DOF joints).
2. SDS is moved by SDS in initial position, so that each of the ropes connected one ends to the output of two-DOF joints (four ropes), and others free ends rounded pulleys mounted on the fixed frame, parallel to the plane of the FTS mounting flange. Two ropes parallel to the X_m axis of the FTS mounting flange and two ropes parallel to the Y_m axis of the FTS mounting flange. Equal weight loads are fixed on the free ends of the ropes (see Figs. 6 and 7).
3. SDS in accordance with the specified program automatically performs incremental FTS displacement and orientation. To specify the selected components of the main vector, SDS moves FTS, along one of the $O_m X_m Y_m Z_m$ coordinate system axes of the FTS mounting flange, or rotates FTS about one of the coordinate system $O_m X_m Y_m Z_m$ axes of FTS mounting flange. The OXYZ FTS coordinate system coincides with the $O_m X_m Y_m Z_m$ coordinate system of the FTS mounting flange. FTS measuring center is the center of OXYZ FTS coordinate system.

B. Setting Selected Components of the Main Vector

Load F_z is described in Fig. 3 (a). To create a force $+F_z$, SDS moves FTS attached to the flange in the negative direction of the axis Z. To create a force $-F_z$, SDS moves FTS in the positive direction of the axis Z. The strength F_z is calculated by:

$$F_z = (\sin\gamma_1 + \sin\gamma_2 + \sin\gamma_3 + \sin\gamma_4) \cdot T,$$

where $\gamma_1, \gamma_2, \gamma_3, \gamma_4$ – rope deflection angles from the FTS mounting flange plane, T – the tension force of ropes created by the load of weights. The values $\gamma_1, \gamma_2, \gamma_3, \gamma_4$ are removed from the angle sensors.

Load M_X (M_Y) is described in Figs. 3 (b) and (c). To create a moment $+M_X$ ($+M_Y$) SDS turns FTS attached to the flange so that the vector points are in the same direction as the positive direction of X (Y) axis.

To create a moment $-M_X$ ($-M_Y$), SDS turns FTS so that the vector points are in the same direction as the negative direction of the X-axis (Y).

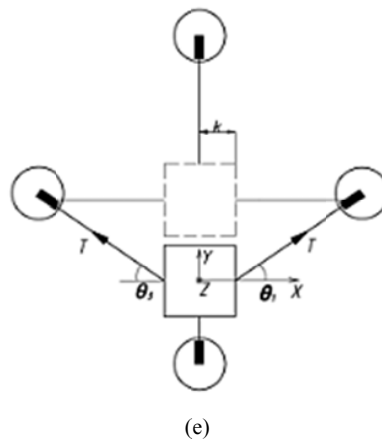
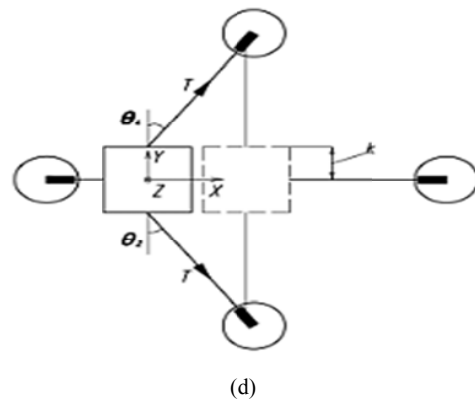
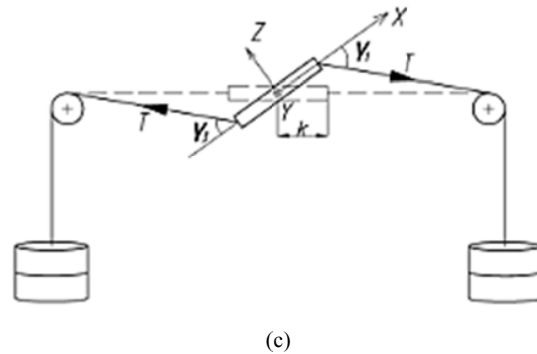
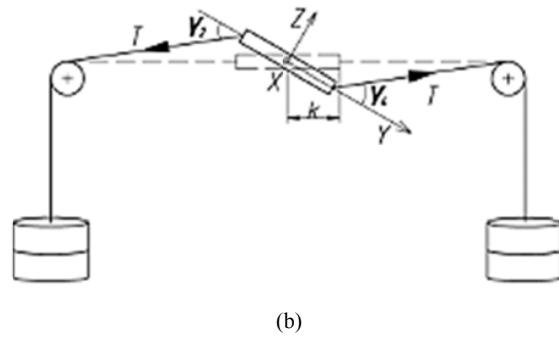
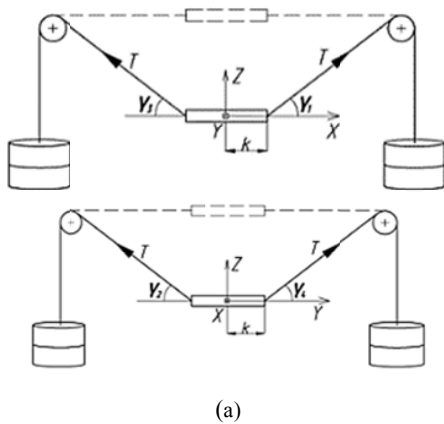
The moment M_X is calculated according to the formula: $M_X = (\sin\gamma_2 + \sin\gamma_4) \cdot k \cdot T$, where k – the projection of the distance between the FTS measurement center and the center axis of rotation of 2-DOF joint on a plane FTS mounting flange, measured in the direction of the X(Y)-axis of FTS coordinate system. The values γ_2, γ_4 are removed from the angle sensors. Moment M_Y is calculated by the formula: $M_Y = (\sin\gamma_1 + \sin\gamma_3) \cdot k \cdot T$. The values γ_1, γ_3 are removed from the angle sensors.

Load F_X (F_Y) is described in Figs. 3 (d) and (e). To create a force $+F_X$ ($+F_Y$), SDS moves FTS attached to the flange in the negative direction X (Y) axis. To create a force $-F_X$ ($-F_Y$), SDS moves FTS in the positive direction X (Y) axis. The force F_X is calculated as follows: $F_X = (\sin\theta_2 + \sin\theta_4) \cdot T$, where θ_2, θ_4 – rope deviation angles of the Y-axis of FTS coordinate system. The values θ_2, θ_4 are removed from the angle sensors. A strength F_Y is calculated as follows: $F_Y = (\sin\theta_1 + \sin\theta_3) \cdot T$, where θ_1, θ_3 – angle rope deviation from the X-axis of FTS coordinate system. The values θ_1, θ_3 are removed from the angle sensors.

Load M_Z is described in see in Fig. 3 (f). To create a moment $+M_Z$ SDS turns FTS attached to the flange so that the vector points are in the same direction as the positive direction of Z axis. To create a moment $-M_Z$, SDS turns FTS so that the vector points are in the same direction as the negative direction of Z axis. Moment M_Z is calculated according to the formula:

$$M_Z = (\sin\theta_1 + \sin\theta_2 + \sin\theta_3 + \sin\theta_4) \cdot k \cdot T.$$

Values $\theta_1, \theta_2, \theta_3, \theta_4$ are removed from the angle sensors.



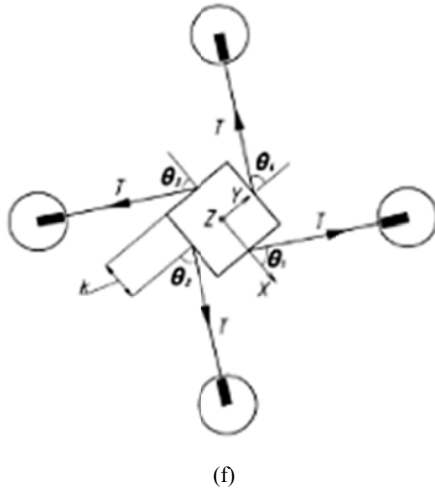


Fig. 6 Schemes of forces and moments application

C. Complex Loading

Complex FTS loading given as a superposition of the positions is created by the forces F_x , F_y , F_z and moments M_x , M_y , M_z .

At each step of the calibration a comparison of FTS indications with known values of the applied load is carried out. Load matrix M (with components F_x , F_y , F_z , M_x , M_y , M_z) $6 \times n$ dimension, where n - number of measurements and signal matrix Z , $6 \times n$ dimension are written in expression:

$$M^T = C^T Z^T, \quad (1)$$

where C - calibration matrix $n \times n$ dimension. Next, using a pseudo inversion of FTS matrix signals, calibration matrix C is calculated:

$$\begin{aligned} C^T &= (Z^T Z)^{-1} Z^T M \\ C &= (Z^+ M)^T. \end{aligned} \quad (2)$$

IV. CALIBRATION DEVICE

Calibration device consists of a frame 1 on which four pulleys 2 are mounted with freedom of angular movement about their vertical axes. There are four ropes 3, rounding the pulleys 2. The design provides precise adjustment of the pulleys 2 position relative to the frame 1. Free ends of the ropes 3 are attached to the weights 4. Fixed ends of the ropes 3 are attached to the 2-DOF joints 5. In the 2-DOF joints 5 are integrated angle sensors 6. The 2-DOF joints 5 are connected to the flange 7. FTS 8 mounting flange is connected to the flange 7, while FTS 8 sensitive flange is connected to the output unit 9 SDS 10 (See Figs. 7 and 8).

V. CONCLUSION

The proposed calibration method allows to perform automated FTS calibration both with selected components of the main vector of forces and moments and with complex loading. The proposed construction of the calibration device allows implementing this calibration method.

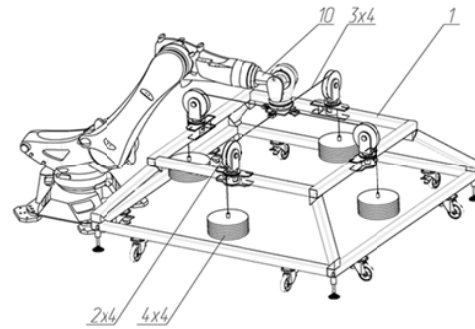


Fig. 7 Calibration device

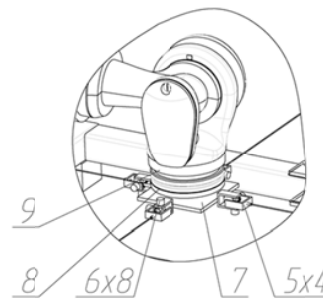


Fig. 8 Calibration device

ACKNOWLEDGMENT

The applied scientific investigations are carried out with the financial support of the Russian Federation represented by the Russian Ministry of Education and Science. The unique identifier of the applied scientific investigations is RFMEFI57814X0046.

REFERENCES

- [1] G. V. Pismenny. Systems force-torque sensitizing robots. Moscow, mechanical engineering, 1990.
- [2] Qiao-Kang Liang et al., Design of a Novel Six-Dimensional Force/Torque Sensor and Its Calibration Based on NN, ICIC 2010, LNCS 6215, Springer-Verlag Berlin Heidelberg 2010.
- [3] Ke-Jun Xu Study on Dynamic Characteristics of Six-axis Wrist Force/torque Sensor, Sensors, Focus on Tactile, Force and Stress Sensors, Book edited by: Jose Gerardo Rocha and Senentxu Lanceros-Mendez, ISBN 978-953-7619-31-2, pp. 444, December 2008, I-Tech, Vienna, Austria.
- [4] Bo Wu et al.; Decoupling Analysis of a Sliding Structure Six-axis Force/Torque Sensor; Measurement Science Review, Volume 13, No. 4, 2013.
- [5] Ma Yingkun et al.; Hybrid calibration method for six-component force/torque transducers of wind tunnel balance based on support vector machines, Chinese Journal of Aeronautics, 2013,26(3): 554-562
- [6] D. Braun, H. Wörn.; Techniques for Robotic Force Sensor Calibration. Proceedings of the 13th international workshop on computer science and information technologies CSIT'2011, Garmisch-Partenkirchen Germany, 2011.