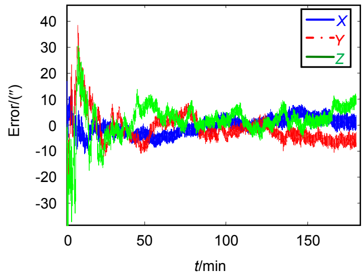
Opto-Electronic Engineering
光 电 工 程

Article
2019 年，第 46 卷，第 1 期

DOI: 10.12086/oee.2019.180556

Ship angular flexure measurement method based on ring laser gyro units



Zheng Jiaxing*, Dai Dongkai, Wu Wei, Zhou Jinpeng

College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha, Hunan 410073, China

Abstract: For ship angular flexure measurement based on the ring laser gyro units, a simplified attitude matching method has been proposed, where the Kalman filter observation provides direct measurement of the desired ship angular flexure plus the 'relative attitude' term. The 'relative attitude', insensitive to the gyro biases of each LGU, arises from the gyro bias difference and initial ship angular flexure. Additionally, considering its slow-varying characteristics, the angular rate of the quasi-static angular flexure should be modeled as random walks. Numerical simulations validate that the simplified attitude matching method can track both the slow-varying angular flexure caused by sunshine heating and the short-time large-magnitude angular flexure caused by factors such as helm's operation. According to full-scale experiments in several actual ships, the proposed method can reach an accuracy of 20″.

Keywords: angular flexure; ring laser gyro; Kalman filter; random walk; quasi-static flexure model

Citation: Zheng J X, Dai D K, Wu W, *et al*. Ship angular flexure measurement method based on ring laser gyro units[J]. *Opto-Electronic Engineering*, 2019, **46**(1): 180556

基于激光陀螺组合体的船体角形变测量方法

郑佳兴*，戴东凯，吴　伟，周金鹏

国防科技大学前沿交叉学科学院，湖南 长沙 410073

摘要：本文提出了一种新的改进的姿态匹配方法用于激光陀螺组合体测量船体角变形，该方法的 Kalman 滤波观测量直接包括待测的船体角形变和"相对姿态误差"项，"相对姿态误差"项对单个激光陀螺组合体的陀螺零偏不敏感，主要源自于两套激光陀螺组合体的陀螺漂移差值和初始船体角形变。此外，考虑到船体静态角形变的缓变特征，船体静态变形角速度可建模为随机游走过程。仿真结果表明，本文提出的简化的姿态匹配方法能跟踪日照引起的准静态缓变角变形和船体机动等因素引起的短周期大幅角变形。该方法也经过了多条舰船的实船试验验证，船体角变形的测量精度优于 20″。

关键词：角变形；环形激光陀螺；卡尔曼滤波；随机游走；准静态变形模型

中图分类号：U666.1　　　　文献标志码：A

引用格式：郑佳兴，戴东凯，吴伟，等. 基于激光陀螺组合体的船体角形变测量方法[J]. 光电工程，2019，**46**(1): 180556

收稿日期：2018-10-09；　收到修改稿日期：2018-11-21

基金项目：国家自然科学基金资助项目(61573368)

作者简介：郑佳兴(1984-)，男，博士，讲师，主要从事惯性技术应用的研究。E-mail: 362422833@qq.com

1 Introduction

Ship angular flexure can be segmented into quasi-static and dynamic categories, the difference being time characteristics. Experiments have shown that quasi-static flexure can reach about 1°~1.5° under sunshine heating[1], and the dynamic flexure may reach about several arc minutes. Consequently, the attitude of shipboard apparatus (such as radar antennas, optical systems), acquired from the central master inertial navigation system (MINS), may be corrupted significantly by the existence of ship structure angular flexure[1-9].

Due to ring laser gyros' reliable performance, the ring laser gyro units (LGUs) can be applied for ship angular flexure measurement. Based on the ring laser gyro units (LGUs), ship flexure measurement methods, have been developed quickly. To take the advantage of the smoothing effect of the integration process, an attitude matching method has been developed recently[10], where the Kalman filter observation, not defined by the angular rate difference, is derived from the two LGUs' attitude information. In addition, the model of the ship quasi-static angular flexure has been developed as well, considering the slow-varying characteristic, modeling quasi-static flexure as random constants seems too rough, where its variation may be coupled into other state variables, influencing the measurement accuracy significantly, the angular rate of the quasi-static angular flexure should be modeled as random walks[11].

However, the attitude matching method may be further simplified, reducing the real-time computational load significantly. In the remainder of this paper, the simplified attitude matching method is first derived. In the following section, the characteristics of the quasi-static flexure are analyzed, and the new quasi-static angular flexure model is introduced. The Kalman filter model is then developed. Simulation results are then presented to demonstrate the effectiveness of the proposed simplified attitude matching method, followed by conclusions.

2 Simplified attitude matching equations

LGU1 and LGU2 are rigidly fixed near the central MINS and any peripheral device, respectively. The angular misalignment (i.e., ship angular flexure) between LGU1 and LGU2 can be estimated via Kalman filtering based on the successive outputs of LGUs.

For the attitude matching method, the Kalman filter observation is derived from the two LGUs' attitude information. To avoid the initial alignment problem of attitude update, each LGU's attitude is defined with respect to its own initial body frame (denoted by i_1-frame and i_2-frame). Thereby, with the initial direction cosine matrices (DCMs) being identity matrices, each LGU's attitude can be updated by processing successive LGU outputs of incremental rotation.

If b_1-frame and b_2-frame are LGU1 and LGU2 body frame, respectively; $\boldsymbol{\varphi}$ and $\boldsymbol{\varphi}_0$ are the Euler rotation angles representing ship angular flexures at time t_k and initial time t_0; $\boldsymbol{\theta}_\mathrm{r}$ and $\boldsymbol{\theta}'_\mathrm{r}$ are the two LGUs' attitude errors caused by gyro errors and other noises, then the attitude matching equation for ship angular flexure measurement may be given by[10]:

$$\boldsymbol{Z}=\boldsymbol{\varphi}-\boldsymbol{A}\boldsymbol{\varphi}_0+(\hat{\boldsymbol{C}}_{b_1}^{i_1\,\mathrm{T}}\boldsymbol{\theta}_\mathrm{r}-\hat{\boldsymbol{C}}_{b_2}^{i_2\,\mathrm{T}}\boldsymbol{\theta}'_\mathrm{r}) \quad , \tag{1}$$

where $\boldsymbol{Z}$ is a 3×1 vector, and $\boldsymbol{A}$ is a 3×3 matrix, both of which are derived from the two LGUs' estimated DCMs, denoted by $\hat{\boldsymbol{C}}_{b_1}^{i_1}$ and $\hat{\boldsymbol{C}}_{b_2}^{i_2}$.

Actually, the attitude matching equation may be further simplified, where the Kalman filter observation provides direct measurement of the desired ship angular flexure plus the 'relative attitude' term.

Due to the gyro biases, the estimated LGU DCM (i.e., $\hat{\boldsymbol{C}}_{b_1}^{i_1}$ and $\hat{\boldsymbol{C}}_{b_2}^{i_2}$) may gradually depart from the true LGU DCMs (i.e., $\boldsymbol{C}_{b_1}^{i_1}$ and $\boldsymbol{C}_{b_2}^{i_2}$), given by:

$$\begin{cases}\boldsymbol{C}_{b_1}^{i_1}=\boldsymbol{C}_{\hat{i}_1}^{i_1}\hat{\boldsymbol{C}}_{b_1}^{i_1}\\ \boldsymbol{C}_{b_2}^{i_2}=\boldsymbol{C}_{\hat{i}_2}^{i_2}\hat{\boldsymbol{C}}_{b_2}^{i_2}\end{cases} . \tag{2}$$

The real-time ship flexure, denoted by $\boldsymbol{C}_{b_2}^{b_1}$, may be expressed in terms of the attitudes information of the two LGUs, as follows:

$$\boldsymbol{C}_{b_2}^{b_1}=\hat{\boldsymbol{C}}_{b_1}^{i_1\,\mathrm{T}}\boldsymbol{C}_{\hat{i}_1}^{i_1\,\mathrm{T}}\boldsymbol{C}_{i_2}^{i_1}\boldsymbol{C}_{\hat{i}_2}^{i_2}\hat{\boldsymbol{C}}_{b_2}^{i_2}=\hat{\boldsymbol{C}}_{b_1}^{i_1\,\mathrm{T}}\boldsymbol{C}_{\hat{i}_2}^{\hat{i}_1}\hat{\boldsymbol{C}}_{b_2}^{i_2} \quad . \tag{3}$$

Substituting for

$$\boldsymbol{C}_{\hat{i}_2}^{\hat{i}_1}\approx I+[\boldsymbol{\theta}_\mathrm{d}\times],$$

$$\boldsymbol{C}_{b_2}^{b_1}=I+[\boldsymbol{\varphi}\times],$$

gives:

$$I+[\boldsymbol{\varphi}\times]=\hat{\boldsymbol{C}}_{b_1}^{i_1\,\mathrm{T}}\{I+[\boldsymbol{\theta}_\mathrm{d}\times]\}\hat{\boldsymbol{C}}_{b_2}^{i_2} \quad , \tag{4}$$

where $[\boldsymbol{\varphi}\times]$ is the skew symmetric form of vector $\boldsymbol{\varphi}$, and the same definition applies to $[\boldsymbol{\theta}_\mathrm{d}\times]$. From an element by element comparison, the vector form may be given by:

$$\boldsymbol{Z}=\boldsymbol{\varphi}-\boldsymbol{A}\boldsymbol{\theta}_\mathrm{d} \quad , \tag{5}$$

where $\boldsymbol{\theta}_\mathrm{d}$ is the 'relative attitude' of the estimated initial LGU1 reference frame ($\hat{i}_1$-frame) with respect to the estimated initial LGU2 reference frame ($\hat{i}_2$-frame), arising from the gyro bias difference (i.e., $\boldsymbol{\varepsilon}_1-\boldsymbol{\varepsilon}_2$) between the two LGUs and the initial ship flexure, given by:

$$\dot{\boldsymbol{\theta}}_\mathrm{d}\approx\hat{\boldsymbol{C}}_{b_1}^{i_1}(\boldsymbol{\varepsilon}_1^{b_1}-\boldsymbol{\varepsilon}_2^{b_2}) \quad , \tag{6}$$

where the initial 'relative attitude' just be the initial ship angular flexure.

Obviously, the attitude matching equation (5) has no analytical decisions, and ship angular flexure may be estimated via Kalman filtering. To constitute the state-space dynamic model for Kalman filtering, ship angular flexure should be modeled properly.

Since the dynamic flexure may be modeled as second-order Markov processes[2,10,12], giving acceptable results in most applications, the emphasis here will be placed on the quasi-static flexure model analyzing.

3 Ship quasi-static flexure model

The main contributor to the quasi-static flexure is temperature, with secondary effects caused by changing store configuration and steady winds[13], and experiments have shown that quasi-static flexure can reach about 1°~1.5° under sunshine heating[1-2] .

Additionally, owing to the ship helm's operation, the short-time large-magnitude angular flexure may take place. As in Ref.[7], there was a 7′ angular flexure witnessed when ship turned its direction, with an experimental data shown in Fig. 1, the periods of which seems much longer than that of that of dynamic flexure caused by sea waves. Therefore, this kind of angular flexure may belong to the quasi-static flexure, rather than the dynamic flexure.

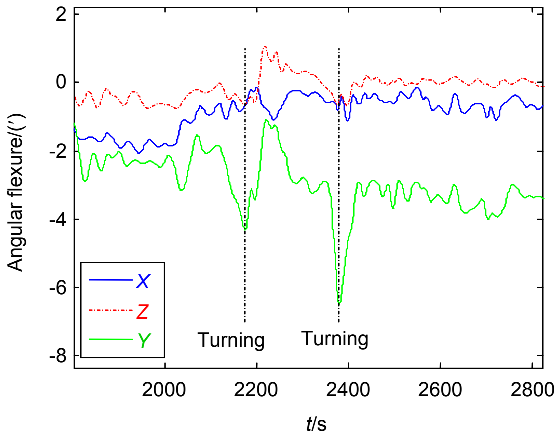


Fig. 1 Experimental qasi-static flexure

Writing $\boldsymbol{\varphi} = \boldsymbol{\Phi}_0 + \delta\boldsymbol{\Phi}_k + \boldsymbol{\theta}_k$, the attitude matching Equation (5) can be rewritten as:

$$\boldsymbol{Z}_k = \boldsymbol{\Phi}_0 + \delta\boldsymbol{\Phi}_k + \boldsymbol{\theta}_k - \boldsymbol{A}\boldsymbol{\theta}_{\rm d} \quad , \tag{7}$$

where $\boldsymbol{\Phi}_0$ is the quasi-static flexure at initial time t_0; $\delta\boldsymbol{\Phi}_k = \boldsymbol{\Phi}_k - \boldsymbol{\Phi}_0$ represents the quasi-static flexure variation; and $\boldsymbol{\theta}_k$ is the dynamic flexure at time t_k .

If the quasi-static flexure is modeled as random constants in short time like [10,12-14], the variation term $\delta\boldsymbol{\Phi}_k$ may be ignored in Kalman filtering. Furthermore, the truly existent variation term will be coupled to other terms, such as $\boldsymbol{\Phi}_0$, $\boldsymbol{\theta}_k$, or $\boldsymbol{A}\boldsymbol{\theta}_{\rm d}$, degrading the measurement accuracy significantly (see Section 5).

To effectively track the variation of the quasi-static angular flexure, the quasi-static flexure model has to be modified urgently. Considering the main quasi-static flexure contributor is temperature, thereby the quasi-static flexure may vary with time smoothly and slowly. Thus, in short time (e.g., 20 minutes), the quasi-static flexure may vary linearly with time, given by:

$$\dot{\boldsymbol{\Phi}}_k^i = \dot{\boldsymbol{\Phi}}_{k-1}^i \qquad i = x, y, z \quad , \tag{8}$$

However, strictly speaking, the quasi-static flexure may not vary linearly in long time (e.g., several hours), the angular rate of quasi-static flexure may vary slowly with time, showing non-stationary, unpredictable behavior, thereby the angular rate of quasi-static flexure may be modeled as random walks, so that the non-stationary change of which can be tracked, given by:

$$\dot{\boldsymbol{\Phi}}_k^i = \dot{\boldsymbol{\Phi}}_{k-1}^i + \boldsymbol{w}_{k-1}^i, \quad i = x, y, z \quad , \tag{9}$$

The corresponding discrete-time model can be written as[11]:

$$\boldsymbol{\Phi}_k^i = 2\boldsymbol{\Phi}_{k-1}^i - \boldsymbol{\Phi}_{k-2}^i + c_{\Phi}^i \boldsymbol{e}_{k-1}, \quad i = x, y, z \quad , \tag{10}$$

If the parameter c_{Φ}^i is adjusted properly, the new model can track the variation in quasi-static flexure effectively (see Section 5).

4 Kalman filter model

The dynamic-state model for Kalman filtering may be set up based on the 'relative attitude' model [Equation (6)], quasi-static flexure model [Equation (10)], the dynamic flexure model, and the gyro bias difference model.

Usually, gyro bias difference may be modeled as random walks, given by[15]:

$$\boldsymbol{\varepsilon}_{1/k}^i - \boldsymbol{\varepsilon}_{2/k}^i = (\boldsymbol{\varepsilon}_{1/k-1}^i - \boldsymbol{\varepsilon}_{2/k-1}^i) + c_{\varepsilon}^i \boldsymbol{e}_{k-1}'' \quad , \tag{11}$$

where $i = x, y, z$. Dynamic flexure can be modeled as second-order Markov processes[2,7], its corresponding discrete time model can be written as:

$$\boldsymbol{\theta}_k^i = -a_{2\theta i}\boldsymbol{\theta}_{k-1}^i - a_{3\theta i}\boldsymbol{\theta}_{k-2}^i + c_{\theta}^i \boldsymbol{e}_{k-1}''' \quad , \tag{12}$$

where $i = x, y, z$. For the simplified attitude matching equation, the 18-component state vector may be given by:

$$\boldsymbol{X}_k = \left[\boldsymbol{\Phi}_k, \boldsymbol{\Phi}_{k-1}, \boldsymbol{\theta}_k, \boldsymbol{\theta}_{k-1}, \boldsymbol{\theta}_d, \ \boldsymbol{\varepsilon}_1 - \boldsymbol{\varepsilon}_2\right]^{\rm T} \quad . \tag{13}$$

The state-space dynamic model for Kalman filtering may be formed as follows:

$$\boldsymbol{X}_k = \boldsymbol{\Phi}_{k/k-1}\boldsymbol{X}_{k-1} + \boldsymbol{w}_k \quad , \tag{14}$$

$$\boldsymbol{\Phi}_{k/k-1} = {\rm diag}\left\{\left[\boldsymbol{F}_{6\times6}', \ \boldsymbol{F}_{6\times6}'', \ \boldsymbol{F}_{6\times6}'''\right]\right\} \quad , \tag{15}$$

$$\boldsymbol{F}_{6\times6}' = \begin{bmatrix} 2\boldsymbol{I}_{3\times3}, & -\boldsymbol{I}_{3\times3} \\ 0_{3\times3}, & \boldsymbol{I}_{3\times3} \end{bmatrix},$$

$$\boldsymbol{F}_{6\times6}'' = \begin{bmatrix} \boldsymbol{A}_{3\times3}', & \boldsymbol{A}_{3\times3}'' \\ \boldsymbol{I}_{3\times3}, & 0_{3\times3} \end{bmatrix},$$

$$\boldsymbol{F}_{6\times6}''' = \begin{bmatrix} \boldsymbol{I}_{3\times3}, & h\widehat{\boldsymbol{C}}_{b_1}^{i_1} \\ 0_{3\times3}, & \boldsymbol{I}_{3\times3} \end{bmatrix},$$

$$\boldsymbol{A}_{3\times3}' = {\rm diag}\left\{\left[-a_{2\theta x}, -a_{2\theta y}, -a_{2\theta z}\right]\right\},$$

$$\boldsymbol{A}_{3\times3}'' = {\rm diag}\left\{\left[-a_{3\theta x}, -a_{3\theta y}, -a_{3\theta z}\right]\right\} \quad . \tag{16}$$

Based on the simplified attitude matching Equation (5), the measurement model can be expressed as:

$$\begin{cases} \boldsymbol{Z}_k = \boldsymbol{H}_k\boldsymbol{X}_k + \boldsymbol{v}_k \\ \boldsymbol{H}_k = \left[\boldsymbol{I}_{3\times3}, \ \boldsymbol{0}_{3\times3}, \ \boldsymbol{I}_{3\times3}, \ \boldsymbol{0}_{3\times3}, -\boldsymbol{A}, \ \boldsymbol{0}_{3\times3}\right]_{3\times18} \end{cases} . \tag{17}$$

Comparing the relative attitude model [Equation (6)], the quasi-static flexure model [Equation (10)], and the dynamic flexure model [Equation (12)], the propagation of the relative attitude is different from that of the flexure model. Additionally, from Equation (5), the contribution manners of the flexure and the relative attitude to the Kalman filter measurement $\boldsymbol{Z}$ are different as well. Therefore, the relative attitude and the flexure can be separated via Kalman filtering (see Section 5).

5 Simulation results

Numerical simulations have been carried out to assess the performance of the new proposed simplified attitude matching method for ship angular flexure measurement.

5.1 Simulation conditions

Ship motions are generated by a combination of sinusoidal waves, the magnitude of heading, pitch, and roll angles are limited to 3°, 3°, and 5°, respectively.

The dynamic flexure is generated by second-order Markov processes. The root mean square (RMS) of which along the roll, pitch, and yaw axes are set to 20″, 60″, and 40″, respectively.

The fixed gyro biases of LGU1 are set to 0.05 °/h, and the LGU2 are set to -0.05 °/h.

Each component of the quasi-static flexure is set to 0.1° at initial time t_0, assuming that the coarse alignment and calibration have been implemented.

Each component of the quasi-static flexure variation is simulated as a random linear plus sinusoidal process, as shown in Fig. 2. The linear process is set to 0.2 °/h. The amplitude of the sinusoidal process is set to 90″, and the periods of which is set to 1 h. Additionally, a second sinusoidal process is added to simulate the short-time large-magnitude angular flexure caused by the factors, such as ship helm's operation. The amplitude of the sinusoidal process is set to 0.1°, and the periods of which is set to 200 seconds.

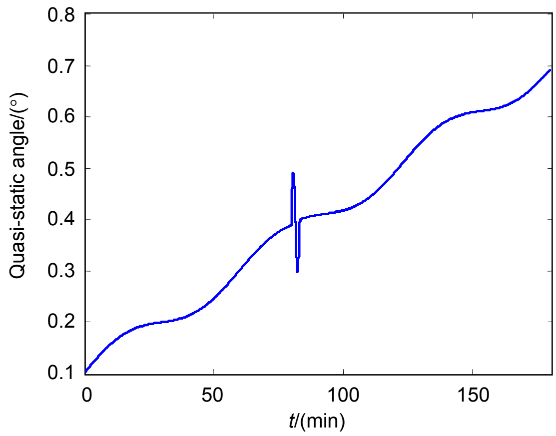


Fig. 2　Simulated quasi-static flexure

5.2 Simulations for the conventional quasi-static model

The simulation results for the conventional quasi-static model (i.e., modeling the quasi-static flexure as random constants) are shown in Fig. 3, Fig. 4, and Fig. 5, representing the estimation errors for quasi-static flexure, dynamic flexure, and the two LGUs' bias difference, respectively.

Comparing Fig. 2 and Fig. 3, we can see that the estimation error of the quasi-static flexure can approximately reach half of its variation. Thus, the model can't track the slow-varying quasi-static flexure. Fig. 4 and Fig. 5 show that the truly existent quasi-static flexure may be coupled to the estimations of dynamic flexure and the gyro bias difference.

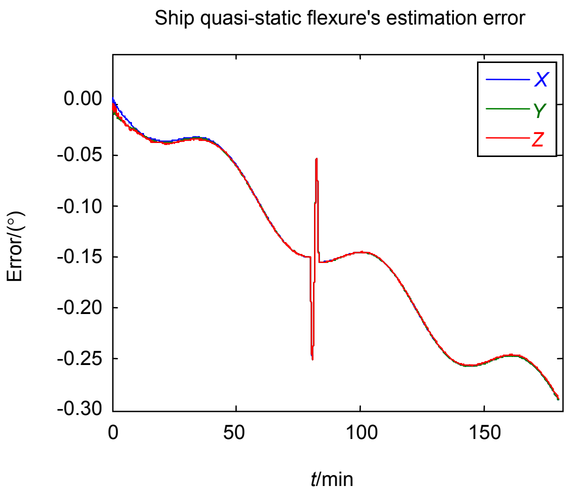


Fig. 3　Estimation error of the quasi-static flexure

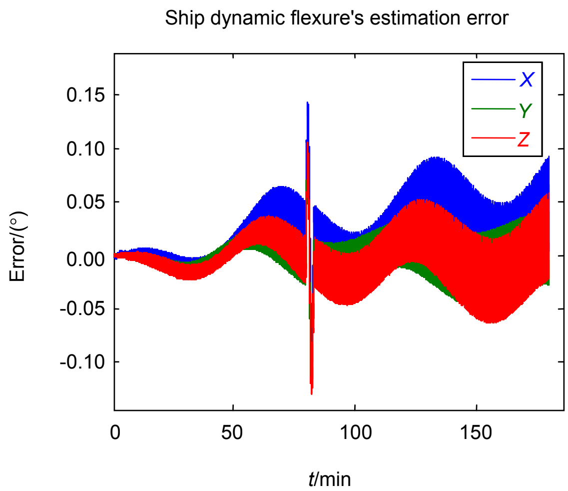


Fig. 4　Estimation error of the dynamic flexure

5.3 Simulations for the proposed quasi-static model

To illustrate the excellent tracking performance of the quasi-static flexure variation, simulations for the proposed model are carried out, with the simulation results shown in Figs. 6~8.

From Figs. 6 and 7, we can see that Model 2 can track both the slow-varying angular flexure (approximately simulated by a linear plus sinusoidal process) and the short-time large-magnitude flexure (simulated by the second sinusoidal process).

Fig. 8 shows that the two LGUs' bias difference can also be estimated effectively, with little coupling with the variation in quasi-static flexure.

6 Conclusions

For ship angular flexure measurement based on the ring laser gyros, a new simplified attitude matching method has been proposed in this paper. The Kalman filter observation provides direct measurement of the desired ship angular flexure plus the 'relative attitude', and the propagation of the 'relative attitude', insensitive to the gyro biases of each LGU, mainly depend on the gyro bias difference and initial ship flexure.

Additionally, considering its slow-varying characteristics, quasi-static flexure may not be modeled as random constants anymore, the angular rate of which may be modeled as random walks. Based on the 'relative attitude' attitude matching method and the 'random walks' model for the angular rate of quasi-static flexure, the state-space dynamic model for Kalman filtering has been developed as well.

Numerical simulations validate that the new simplified attitude matching method can track both the slow-varying angular flexure caused by sunshine heating and the short-time large-magnitude angular flexure caused by factors such as helm's operation.

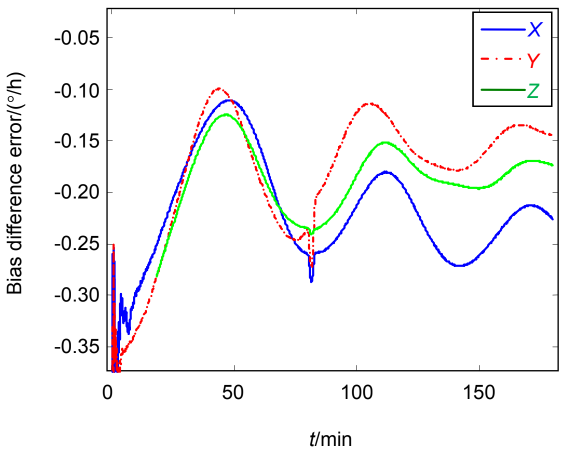


Fig. 5 Estimation error of the gyro bias difference

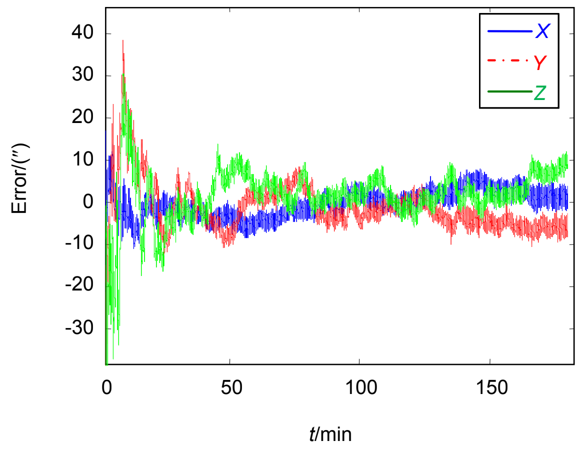


Fig. 6 Estimation error of the ship flexure

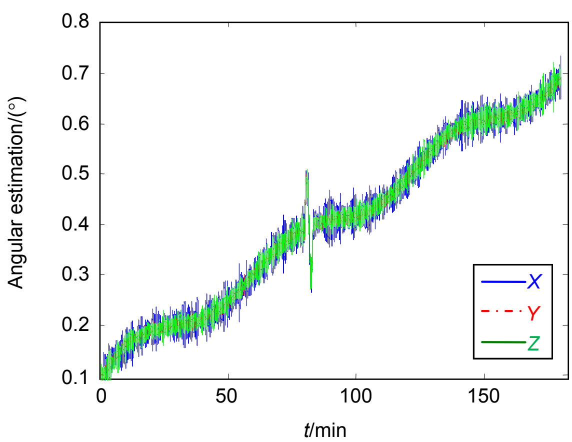


Fig. 7 Estimation results of the ship flexure

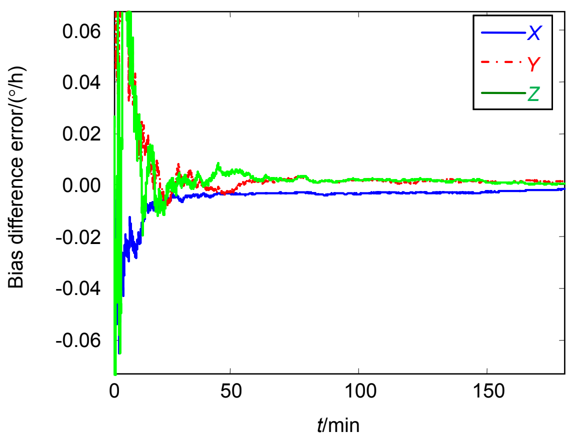


Fig. 8 Estimation error of the gyro bias difference

References

[1] Titterton D H, Weston J L. *Strapdown Inertial Navigation Technology*[M]. London: Peter Peregrinus Ltd, 1997.

[2] Mochalov A V, Kazantsev A V. Use of ring laser units for measurement of moving object deformations[J]. *Proceedings of SPIE*, 2002, **4680**: 85–92.

[3] Carlson N A, Kelley R T, Beming S L. Differential inertial filter for dynamic sensor alignment[C]//*Proceedings of the 1994 National Technical Meeting of The Institute of Navigation*, San Diego, CA, 1994: 341–351.

[4] Kaiser J, Beck G, Berning S. Vital advanced inertial network[C]//*Proceedings of the IEEE 1998 Position Location and Navigation Symposium*, Palm Springs, CA, USA, 1998: 61–68.

[5] Kelley R T, Carlson N A, Berning S. Integrated inertial network[C]//*Proceedings of 1994 IEEE Position*, *Location and Navigation Symposium*, Las Vegas, NV, USA, 1994: 439–446.

[6] Joon L, You-Chol L. Transfer alignment considering measurement time delay and ship body flexure[J]. *Journal of Mechanical Science and Technology*, 2009, **23**(1): 195–203.

[7] Jiang G W. Study on pose relay videometrics method with camera-series and ship deformations measurement[D]. Changsha: National University of Defense Technology, 2010.
姜广文. 像机链位姿传递摄像测量方法及船体变形测量研究[D]. 长沙: 国防科学技术大学, 2010.

[8] Wang S T, Wang Z Q, Zhu Y Z, *et al*. Monitoring on ship hull deformation and correction for heading & attitude information[J]. *Journal of Chinese Inertial Technology*, 2007, **15**(6): 635–641.
汪顺亭, 汪湛清, 朱昀炤, 等. 船体变形的监测方法及其对航向姿态信息的修正[J]. 中国惯性技术学报, 2007, **15**(6): 635–641.

[9] Wan D J, Liu Y F. Summary on removing influence of ship deformation and providing accurate attitude references for warship[J]. *Journal of Chinese Inertial Technology*, 2005, **13**(4): 77–82.
万德钧, 刘玉锋. 消减舰船变形的影响和为全舰提供高精度姿态基准[J]. 中国惯性技术学报, 2005, **13**(4): 77–82.

[10] Zheng J X, Qin S Q, Wang X S, *et al*. Attitude matching method for ship deformation measurement[J]. *Journal of Chinese Inertial Technology*, 2010, **18**(2): 175–180.
郑佳兴, 秦石乔, 王省书, 等. 基于姿态匹配的船体形变测量方法[J]. 中国惯性技术学报, 2010, **18**(2): 175–180.

[11] Zheng J X, Qin S Q, Wang X S, *et al*. Ship hull angular deformation measurement taking slow-varying quasi-static component into account[J]. *Journal of Chinese Inertial Technology*, 2011, **19**(1): 6–10.
郑佳兴, 秦石乔, 王省书, 等. 考虑准静态缓变量的船体角形变测量[J]. 中国惯性技术学报, 2011, **19**(1): 6–10.

[12] Schneider A M. Kalman filter formulations for transfer alignment of strapdown inertial units[J]. *Navigation*, 1983, **30**(1): 72–89.

[13] Day D L, Arruda J. Measuring structural flexure to improve precision tracking[J]. ADA364862, 1999.

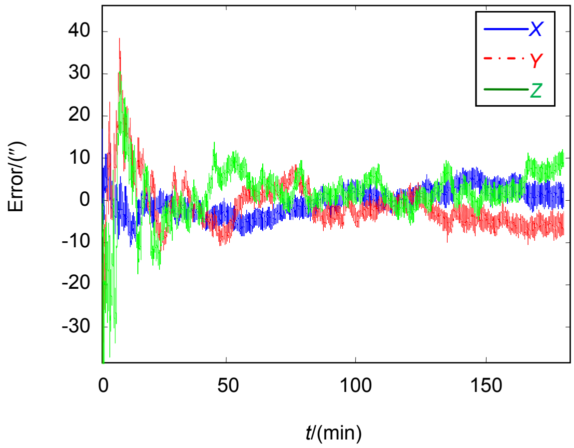
[14] Shin E H, El-Sheimy N. An unscented Kalman filter for in-motion alignment of low-cost IMUs[C]//*Proceedings of the PLANS 2004*. *Position Location and Navigation Symposium*, Monterey, CA, USA, 2004: 273–279.

[15] Liu W T, Liu J Y, Shen Q. Integrated modeling and filtering of fiber optic gyroscope's random errors[J]. *Opto-Electronic Engineering*, 2018, **45**(10): 180082.
刘文涛, 刘洁瑜, 沈强. 光纤陀螺随机误差的集成建模及滤波处理[J]. 光电工程, 2018, **45**(10): 180082.

Ship angular flexure measurement method based on ring laser gyro units

Zheng Jiaxing*, Dai Dongkai, Wu Wei, Zhou Jinpeng

College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha, Hunan 410073, China



Estimation error of the ship flexure

Overview: Ship angular flexure can be segmented into quasi-static and dynamic categories, the difference being time characteristics. Experiments have shown that quasi-static flexure can reach about 1°~1.5° under sunshine heating, and the dynamic flexure may reach about several arc minutes. Consequently, the attitude of shipboard apparatus (such as radar antennas, optical systems), acquired from the central master inertial navigation system, may be corrupted significantly by the existence of ship structure angular flexure. Due to ring laser gyros' reliable performance, the ring laser gyro units (LGUs) can be applied for ship angular flexure measurement. Based on the ring laser gyro units, ship flexure measurement methods, have been developed quickly. To take the advantage of the smoothing effect of the integration process, an attitude matching method has been developed recently, where the Kalman filter observation, not defined by the angular rate difference, is derived from the two LGUs' attitude information. In addition, the model of the ship quasi-static angular flexure has been developed as well, considering the slow-varying characteristic, modeling quasi-static flexure as random constants seems too rough, where its variation may be coupled into other state variables, influencing the measurement accuracy significantly, the angular rate of the quasi-static angular flexure should be modeled as random walks.

Here For ship angular flexure measurement based on the ring laser gyros, a new simplified attitude matching method has been proposed in this paper. The Kalman filter observation provides direct measurement of the desired ship angular flexure plus the 'relative attitude', and the propagation of the 'relative attitude', insensitive to the gyro biases of each LGU, mainly depend on the gyro bias difference and initial ship flexure.

Additionally, considering its slow-varying characteristics, quasi-static flexure may not be modeled as random constants anymore, the angular rate of which may be modeled as random walks. Based on the 'relative attitude' attitude matching method and the 'random walks' model for the angular rate of quasi-static flexure, the state-space dynamic model for Kalman filtering has been developed as well. Numerical simulations validate that the new simplified attitude matching method can track both the slow-varying angular flexure caused by sunshine heating and the short-time large-magnitude angular flexure caused by factors such as helm's operation. According to full-scale experiments in several actual ships, the proposed method can reach an accuracy of 20″.

Citation: Zheng J X, Dai D K, Wu W, *et al*. Ship angular flexure measurement method based on ring laser gyro units[J]. *Opto-Electronic Engineering*, 2019, **46**(1): 180556

Supported by National Natural Science Foundation of China (61573368)

* E-mail: 362422833@qq.com