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Research Progress on Micro-vibration and Thermal Stability Control of Vehicle-mounted Optomechanical Systems

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Abstract

Vehicle-mounted optomechanical systems are optoelectronic equipment that integrate precision optical payloads, servo-stabilized platforms, and environmental control units on a mobile chassis, combining the high precision of fixed optical measuring equipment with the rapid deployment capability of mobile equipment. Compared with fixed sites, vehicle-mounted platforms are subjected to multi-source disturbances during transportation and operation, including road-surface vibration, ground pulsation, equipment heat generation, and diurnal temperature differences caused by solar irradiation. Micro-vibration suppression and thermal-induced optical-axis drift control have become the two core problems constraining the performance of high-precision vehicle-mounted optomechanical systems. Focusing on these two main lines, this paper systematically reviews the disturbance transmission paths of vehicle-mounted optomechanical systems; summarizes the progress of micro-vibration suppression technology from three directions-passive vibration isolation, six-degree-of-freedom active vibration isolation, andfast-steering-mirror precise stabilization -and reviews the progress of thermal stability control technology from athermal structural design, distributed precision temperature control, and thermo-optical compensation; analyzes the magnitude and engineering constraints of these two types of disturbances in typical applications such as mobile precision optical observation, vehicle-mounted high-energy laser tests, and vehicle-mounted optoelectronic measurement; points out existing bottlenecks, including the still-insufficient thermal–mechanical–optical multi-field coupling modeling and online decoupling, the prominent contradiction between the low-frequency performance of active vibration isolation and the weight cost, and the conflict between the precision thermal stabilization time constant and rapid deployment requirements; and finally looks forward to development trends in four directions: lightweight composite-material integrated athermalization, advanced six-degree-of-freedom active vibration isolation, thermal–mechanical–optical joint active compensation, and multi-parameter online monitoring.

Keywords

Vehicle-Mounted Optomechanical System; Micro-Vibration Isolation; Active Vibration Isolation; Optical-Axis Stabilization; Precision Temperature Control; Athermal Design; Thermal–Mechanical–Optical Coupling.

1. Introduction

Precision optical systems impose stringent requirements on ground stability, temperature uniformity, and environmental cleanliness. Traditionally, they have been deployed relying on fixed equipment

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rooms or observation stations, with inherent drawbacks such as limited site locations, difficulty in rapid relocation, and susceptibility to advance reconnaissance. With the growth of demands such as low-altitude security, outfield directed-energy tests, mobile optoelectronic measurement, and mobile precision optical observation, vehicle-mounted optomechanical systems that integrate large-aperture optical systems, high-energy laser emission, and multi-band detection payloads on mobile vehicle platforms have gradually become one of the mainstream forms of mobile precision optoelectronic equipment [1-2].

Vehicle-mounted optomechanical systems cover various forms, including shelter-type integration, vehicle-mounted turrets, vehicle-mounted photoelectric theodolites, and vehicle-mounted optoelectronic payloads, whose common feature is using off-road vehicles as the mobile platform with precision optical payloads and supporting equipment integrated internally. Compared with fixed optical measuring equipment, vehicle-mounted platforms are subjected to more complex multi-source disturbances during maneuvering and operation: random road-surface vibration, ground pulsation, vibration of in-cabin refrigeration compressors and fans, narrowband vibration of diesel generators and servo motors, as well as structural thermal deformation caused by solar irradiation, internal–external temperature differences, and equipment heat generation. The support platform of the vehicle-mounted photoelectric theodolite developed by the Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, adopts a truss–skin structure; under the theodolite angular-acceleration excitation of 0.5°/s²~20°/s², the base response acceleration is only 0.008~0.55 m/s² [2]. The China Academy of Engineering Physics, under the driving condition of a tertiary highway at 40 km/h, used a piezoelectric ceramic fast-steering-mirror to suppress the RMS jitter of the vehicle-mounted optical axis in the X and Y directions by 3.6 and 2.1 times, respectively, with a closed-loop bandwidth greater than 100 Hz [3], reflecting the typical technical level of vehicle-mounted optomechanical systems in achieving high-precision optoelectronic operation under mobile conditions.

Among the many disturbance factors, micro-vibration and thermal deformation are the two mechanisms that most directly enter the optomechanical reference and ultimately manifest as optical-axis pointing drift and imaging quality degradation. In recent years, with the rapid development of six-degree-of-freedom active vibration isolation, composite-material athermal structures, and multi-band shared-optical-path technologies, vehicle-mounted optomechanical systems have continued to progress in long-term optical-axis stabilization and wide-temperature adaptability. Focusing on the two main lines of micro-vibration suppression and thermal stability control, this paper reviews the disturbance transmission, key technologies, typical applications, and existing bottlenecks of vehicle-mounted optomechanical systems on the basis of a systematic review of domestic and international literature and engineering practice, aiming to provide a reference for the overall design and engineering of mobile precision optoelectronic systems.

2. Vehicle-mounted Optomechanical Systems and Environmental Disturbances

2.1 Definition and Accuracy Grades

Vehicle-mounted optomechanical systems generally refer to mobile optoelectronic systems that use off-road vehicles as the mobile platform and integrate precision optical payloads and supporting equipment. According to the load-bearing form, they can be divided into shelter-type integration, vehicle-mounted turret/gondola type, and vehicle-mounted photoelectric theodolite type; according to optical-axis stabilization accuracy and thermal stability requirements, they can be roughly divided into three grades: ① conventional mobile optoelectronic systems, with optical-axis stabilization accuracy on the order of milliradians, equipped with multi-band payloads such as visible light, infrared, and laser ranging, mainly undertaking target search and tracking tasks, with general requirements for micro-vibration and temperature gradients; ② high-precision vehicle-mounted optoelectronic systems, with optical-axis stabilization accuracy on the order of microradians, represented by vehicle-mounted high-energy laser emission and vehicle-mounted photoelectric

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theodolites, with clear index requirements for micro-vibration suppression and in-cabin temperature uniformity [2-3,10]; ③ ultra-precision mobile optical systems, with optical-axis stabilization reaching the sub-microradian order and frequency stability reaching the 10^{-15}order, such as mobile optical clocks and vehicle-mounted large-aperture astronomical telescopes, with the most stringent requirements for ground vibration and temperature stability [6,14]. The higher the accuracy grade, the more prominent the constraint of micro-vibration and thermal deformation on system performance; the subsequent discussion in this paper mainly focuses on the latter two grades.

2.2 System Composition and Disturbance Transmission Paths

In engineering, vehicle-mounted optomechanical systems are usually divided into subsystems including chassis load-bearing, load-bearing structure (shelter or mounting platform), optomechanical payload, stabilization and servo, environmental control, information processing, and power supply/distribution status monitoring. From the perspective of micro-vibration and thermal stability, there are mainly three transmission chains: (1) the vibration transmission chain-random road-surface vibration, ground pulsation, and vibration of refrigeration compressors, fans, diesel generators, and servo motors are transmitted step by step through the chassis, load-bearing structure, optical platform, and mirror mount; angular vibration directly manifests as beam-pointing jitter and image motion; (2) the thermal-deformation transmission chain-solar irradiation, internal–external temperature differences, and equipment heat generation are conducted through the load-bearing structure and support structure, changing the optical interval and optical-axis orientation through two paths: the refractive-index and surface-figure changes of optical elements, and the thermal expansion and contraction of mirror mounts and support rods; (3) the stabilization-tracking chain-the optical-platform vibration isolation, payload coarse tracking, and fast-steering-mirror precise stabilization form a multi-level stabilization closed loop, providing terminal compensation of residual micro-vibration [3,13].

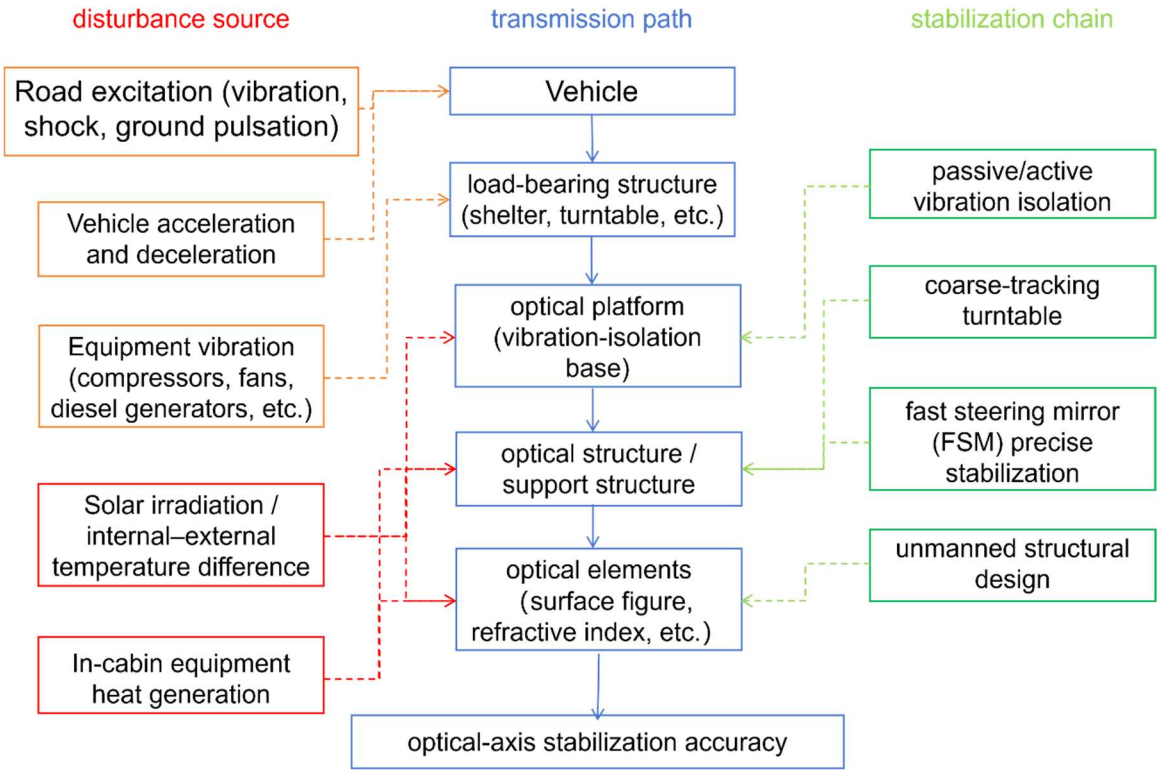


Figure 1. Disturbance transmission path and stabilization chain

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It should be emphasized that the vehicle-mounted platform is not an ideal rigid body. Vehicle driving, equipment vibration, solar irradiation, and in-cabin equipment heat generation all cause quasi-static deformation of the load-bearing structure and the internal optical platform, which is directly transmitted to the optomechanical reference and introduces time-varying optical-axis drift. Therefore, the overall accuracy of a vehicle-mounted optomechanical system is not determined by a single optical payload, but is a multi-disciplinary coupled systems-engineering problem of chassis–load-bearing structure–vibration isolation–thermal control–optomechanics–servo, and micro-vibration and thermal deformation are precisely the two most central and most difficult-to-decouple disturbance types of disturbance. Its disturbance transmission path and stabilization chain are shown in Figure 1.

3. Progress in Micro-vibration Suppression and Optical-axis Stabilization Technology

Micro-vibration is one of the most important disturbance sources of vehicle-mounted optomechanical systems. According to the working stage, it can be divided into transportation vibration and working micro-vibration: the transportation stage is dominated by random road-surface vibration, with low frequency and large amplitude, mainly testing the impact resistance of the load-bearing structure and optomechanical equipment; the working stage includes narrowband vibration of ground pulsation, refrigeration compressors, fans, diesel generators, and servo motors; angular vibration directly causes beam-pointing jitter and imaging blur, and is the primary factor constraining the performance of high-precision vehicle-mounted optomechanical systems [3,11]. The existing technical routes can be summarized as a three-level chain of passive vibration isolation, six-degree-of-freedom active vibration isolation, and compound-axis tracking technology.

3.1 Passive Vibration Isolation Technology

Traditional rubber vibration isolators have a simple structure and low cost, but limited low-frequency isolation capability. Zheng Fengzhu et al. [5] proposed an external metal vibration isolation system for airborne optoelectronic equipment; compared with the built-in rubber vibration isolation system, both can control the stabilization accuracy within 25 μrad, but the external metal vibration isolation systemincreases the effective in-cabin space and maintainability; Qi Yuan et al. [4] symmetrically arranged 8 flexible vibration-isolating connections on both sides of the centroid of the inner-frame beam of the optoelectronic platform, forming a new line-of-sight vibration-isolating stabilization frame that can provide both medium- and low-frequency vibration isolation and static support; an external passive vibration isolation platform based on the Hexapod configuration can achieve a natural frequency of less than 8 Hz under three-directional linear excitation, with a coupled angular-rocking response RMS of less than 200 μrad.

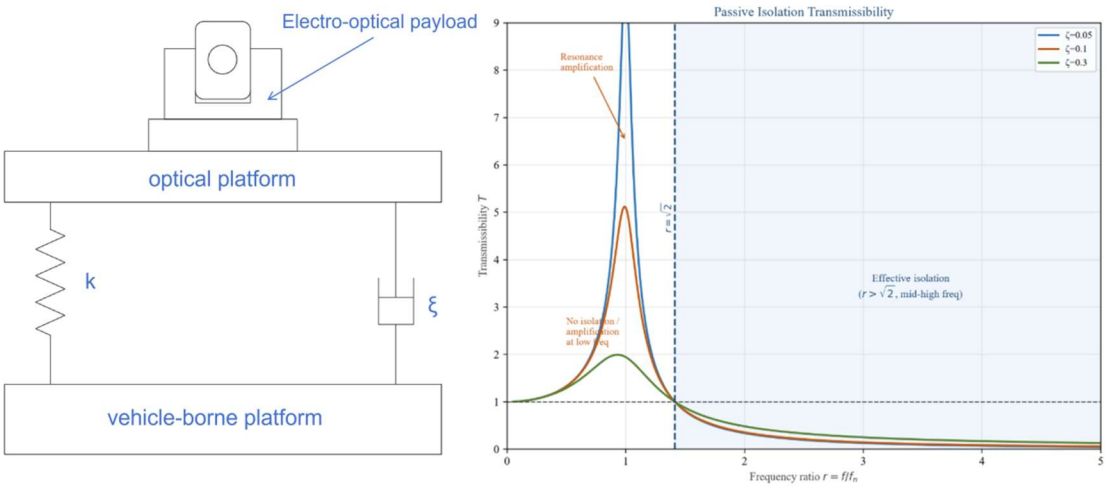


Figure 2. Model and transmissibility characteristics of the passive vibration isolation system of a vehicle-mounted optomechanical system

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Passive vibration isolation has a simple structure, no power consumption, and high reliability; it is the basic vibration isolation means of vehicle-mounted optomechanical systems, but limited by the physical constraint of "the lower the natural frequency, the larger the static deformation," it is difficult to simultaneously balance the low-frequency vibration isolation performance and the static support stiffness of the optical platform; it therefore mainly targets medium- and high-frequency disturbances, and its isolation characteristics are shown in Figure 2.

3.2 Six-degree-of-freedom Active Vibration Isolation Technology

Six-degree-of-freedom active vibration isolation based on the Stewart/Gough platform has been a research hotspot in recent years. Kong Yongfang et al. [12] combined Skyhook damping with notch filters, causing the resonance peaks of a flexible Stewart platform near 17.4 Hz and 34.8 Hz to drop by about 12.2 dB and 10.19 dB, respectively; Liu Renhong et al. [11] constructed a parallel six-degree-of-freedom active vibration suppression platform using piezoelectric ceramics as actuators, established a dynamic model based on the Newton–Euler method, and designed a decoupling control strategy, showing good suppression effects on low-frequency micro-vibration. Such active–passive combined vibration isolation schemes for precision space optical payloads provide a direct reference for the six-degree-of-freedom active vibration isolation design of vehicle-mounted precision optical systems.

Active vibration isolation senses base vibration through accelerometers or inertial reference elements and drives actuators through closed-loop control to cancel the disturbance, enabling effective isolation in the low-frequency band while maintaining high static stiffness: unlike the natural-frequency limitation of passive vibration isolation, active vibration isolation can provide effective isolation starting from a low-frequency band of about 0.5~5 Hz, making up for the inherent shortcoming of passive vibration isolation in the low-frequency region, and is the mainstream approach to solving the "insufficient low-frequency performance of passive vibration isolation." Its engineering cost is the weight, power consumption, and reliability problems introduced by actuators, sensors, and control systems; especially in vehicle-mounted outfield long-term unattended scenarios, the long-term stability of the active vibration isolation chain still requires engineering accumulation. In the application of ultra-precision mobile optical clocks, Yao Jiamin et al. [6] adopted a TS-300 active vibration isolation platform and a 500BM-1 passive vibration isolation platform to form an active–passive combined vertical vibration isolation system, reducing the contribution of vibration to optical-clock stability from $5.8\times10^{-15}\tau^{(-1/2)}$ to $1.12\times10^{-15}\tau^{(-1/2)}$, representing a relatively high level of vehicle-mounted micro-vibration suppression. The closed-loop control principle of six-degree-of-freedom active vibration isolation is shown in Figure 3.

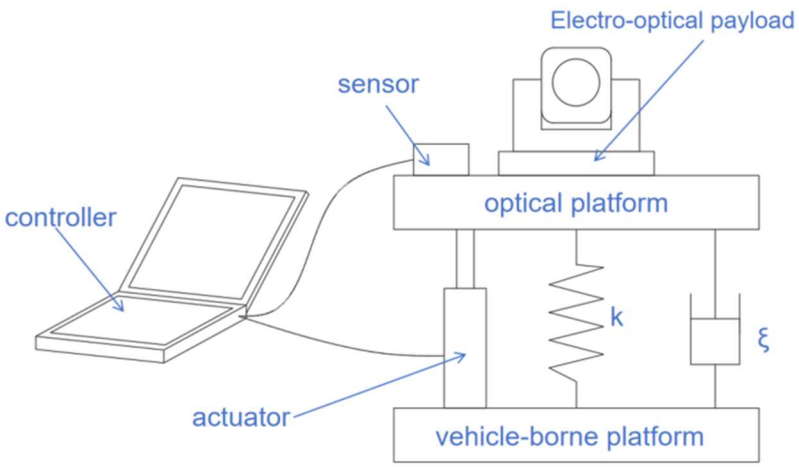


Figure 3. Six-degree-of-freedom active vibration isolation platform and closed-loop control principle of a vehicle-mounted optomechanical system

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3.3 Compound-axis Tracking Technology (Gimbal Servo and Fast-Steering-Mirror Precise Stabilization)

Compound-axis tracking is the core technical route for optoelectronic tracking and aiming systems to achieve high-precision line-of-sight stabilization and target tracking, consisting of two nested control loops-coarse tracking and fine tracking. Coarse tracking uses the optoelectronic tracking-and-aiming gimbal (tracking turntable) as the carrier, driving the azimuth and elevation axes through frame motors, with rate gyros forming the inertial-stabilization inner loop and optoelectronic miss-distance forming the position-tracking outer loop, undertaking large-range target search, acquisition, and tracking; limited by the large rotational inertia of the gimbal, its tracking bandwidth is usually on the order of several hertz, mainly suppressing low-frequency large-angle disturbances and target maneuvers. Fine tracking uses the fast-steering-mirror (FSM) as the terminal actuator, with small rotational inertia, small field of view, and high closed-loop bandwidth: Li Guohui et al. [3] used a piezoelectric-ceramic-driven fast-steering-mirror with a resolution of about 0.4 μrad and a closed-loop bandwidth greater than 100 Hz, significantly suppressing optical-axis jitter within 20 Hz under the driving condition of a tertiary highway at 40 km/h, thereby eliminating coarse-tracking residuals and residual angular vibration of the platform..

The key to the compound-axis system lies in the coordination of the coarse and fine loops: the miss-distance sensor feeds the coarse-tracking residual into the fine-tracking loop; coarse tracking brings the target into the fine-tracking field of view; fine tracking eliminates the residual error and outputs the line of sight; in bandwidth, coarse is low and fine is high; in field of view, coarse is large and fine is small; in the frequency domain, they connect with each other, jointly raising the line-of-sight stabilization accuracy to the sub-microradian order and, cooperating with the vibration isolation chain, forming full-band suppression of micro-vibration. Wang Huilin et al. [13] introduced a high-precision line-of-sight inertial stabilization technology based on reference light into the inertial stabilization platform, further providing a new approach for long-term optical-axis stabilization under strong vibration environments.

4. Progress in Thermal-deformation Suppression and Precision Temperature Control Technology

Temperature changes affect the performance of vehicle-mounted optomechanical systems through two paths: one is the change of the refractive index and surface figure of optical elements with temperature; the other is the optical-interval and optical-axis offset caused by the thermal expansion and contraction of mirror mounts, support rods, and load-bearing structures. Even if the overall temperature inside the cabin is constant, temperature gradients formed by solar irradiation, equipment heat generation, and internal–external temperature differences still cause structural bending, which is the most important source of static optical-axis drift [7,9]. The existing technical routes can be summarized at three levels: athermal structural design, distributed precision temperature control, and thermo-optical closed-loop compensation.

4.1 Athermal Structural Design

In terms of structural athermalization, adopting materials with low coefficients of thermal expansion is the mainstream approach. Replacing traditional metals with carbon-fiber composite materials as the main support structure and titanium alloy as the external interface can reduce the variation of the axial optical interval by 84.9% under a uniform temperature rise of 60 ℃, with a lightweighting rate of 33.5%; Wang Xuan et al. [8] optimized the carbon-fiber composite support structure for missile-borne optical systems, reducing the axial front-end thermal expansion deformation by 87.8% compared with titanium alloy within a temperature-rise range of 50 ℃, with a mass reduction of 63.2%. Huang Jiangqing et al. [1] adopted a composite structure of an aluminum main mirror cell and invar support rods in a vehicle-mounted long-wave infrared linear-array scanning imaging system, with an overall machine mass of 28.3 kg, a first-order natural frequency of 204 Hz, stable imaging in

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the temperature range of −40~60 ℃, and an NETD of 40 mK, verifying the effectiveness of the composite athermal structure in the vehicle-mounted wide-temperature environment.

The essence of athermal design is to maintain the optical interval and focal length unchanged as temperature changes through the coordinated matching of materials and structures. In engineering, carbon-fiber composite materials (low thermal expansion, high specific stiffness) are usually used as the main support, matched with invar or titanium alloy as external interfaces and connecting rods, and a zero-expansion design in the optical-axis direction is achieved through the combination of thermal-expansion coefficients in different directions. The difficulty lies in the anisotropy of composite materials, process consistency, and dimensional stability under long-term cyclic loading.

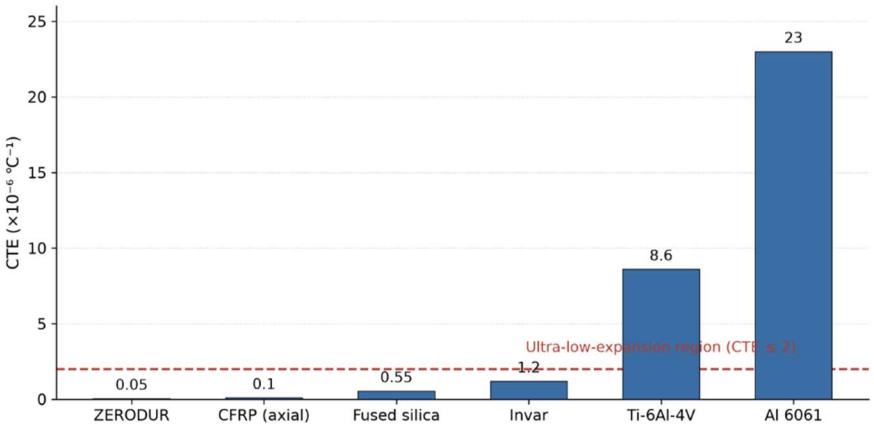


Figure 4. Comparison of thermal-expansion coefficients of commonly used athermal materials

4.2 Precision Temperature Control and Thermo-optical Compensation

The vehicle-mounted integrated temperature-control cabinet developed by Qiu Biao et al. [9] achieved a temperature uniformity of ≤ ±2 ℃ and a temperature fluctuation of ≤ ±0.5 ℃ through Fluent flow-field simulation optimization; Zuo Xiaozhou et al. [7] proposed a regional thermal-control method for the shared-optical-path primary mirror assembly; when the average temperature rise of the primary mirror exceeds 16 ℃, the axial temperature gradient is ≤ 2.5 ℃, the primary mirror surface-figure variation is less than 0.005λ, and the absolute deviation between the simulated and measured temperature fields is less than 1.4 ℃. These studies show that distributed multi-point temperature measurement, zone-independent temperature control, and closed-loop compensation based on thermo-optical simulation have become typical technical routes for the precision thermal control of vehicle-mounted optomechanical systems.

In terms of engineering indicators, the precision temperature control of vehicle-mounted optomechanical systems usually focuses on three dimensions: temperature uniformity (the temperature difference at different positions in the cabin), temperature fluctuation (the temperature drift at the same position over time), and temperature gradient (the spatial temperature difference along or perpendicular to the optical axis). For systems with sub-microradian accuracy, the temperature gradient along the optical axis is often a more difficult indicator to control than overall constant temperature, and is also the most important source of static optical-axis drift. For optical windows on the load-bearing structure, the stress birefringence and surface-figure distortion caused by the internal–external temperature difference are another typical type of thermal-stability problem, usually solved in engineering through electric-heating demisting, flexible window assemblies, and low-thermal-expansion window materials [1].

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5. Micro-vibration and Thermal-stability Constraints in Typical Applications

5.1 Mobile Precision Optical Observation

Mobile optical clocks, vehicle-mounted astronomical telescopes, and other precision optical observation systems impose the most stringent requirements on vibration and temperature stability, and are typical scenarios for testing the level of micro-vibration suppression and thermal-stability control. Ming Ming et al. [14] adopted near-infrared bands and phase difference technology on a 1.2 m vehicle-mounted telescope, correcting atmospheric wavefront tilt while performing precise tracking, with a detection capability down to 5th-magnitude stars, an imaging resolution close to twice the diffraction limit, and an observation time extended by 6 h compared with traditional adaptive systems; Yao Jiamin et al. [6] established a quantitative relationship between base vibration and beam-deflection angle for the detection optical system of a vehicle-mounted optical clock, and through the combination of a TS-300 active vibration isolation platform and a 500BM-1 passive vibration isolation platform, reduced the contribution of vibration to optical-clock stability from $5.8\times10^{-15}\tau^{(-1/2)}$ to the order of $1.12\times10^{-15}\tau^{(-1/2)}$. Such applications represent the ceiling of vehicle-mounted optomechanical system performance and also impose the most stringent requirements on vibration isolation, thermal control, and ground adaptability.

5.2 Vehicle-mounted High-energy Laser Tests

Vehicle-mounted high-energy laser systems integrate high-power laser sources, beam control, emission optics, and effect diagnosis on a mobile platform, and are the main carrier of outfield directed-energy technology verification. The 2000 W portable laser anti-drone system developed by Hu Haili et al. [10] adopts a scheme combining a lightweight main-axis tracking with large-travel fine tracking and an air-cooled laser source; at 300 m, it statically penetrates a 2 mm stainless-steel plate in only 12 s, and dynamically strikes down a drone in 9 s; Li Guohui et al. [3] developed a fast-steering-mirror optical-axis stabilization system based on a vehicle-mounted platform, providing key support for vehicle-mounted high-energy lasers to maintain beam-pointing accuracy under mobile conditions. This type of system has extremely high requirements for terminal micro-vibration compensation, laser-source thermal management, and the thermal stress of the emission window, and is currently one of the most technically difficult types of vehicle-mounted optomechanical systems.

5.3 Vehicle-mounted Optoelectronic Measurement and Tracking

Vehicle-mounted photoelectric theodolites undertake the tasks of recording weapon trajectories, attitudes, and events in the field, requiring high-precision on-vehicle measurement. The truss–skin high-stiffness support platform designed by Gao Qingjia et al. [2] shows no obvious resonance response under the working angular-acceleration excitation of the theodolite, with a maximum wobble of 7.2″, which can meet the on-vehicle high-precision measurement requirements. The core contradiction of this type of system lies in: how the road-surface vibration when the vehicle travels on tertiary and below roads is effectively isolated, and how the quasi-static deformation introduced by outrigger leveling after stopping converges to the measurement accuracy requirement within a short time.

5.4 Low-altitude Security and Anti-drone

Low-altitude security and anti-drone vehicle-mounted optoelectronic systems usually configure multi-band payloads such as visible light, infrared, and laser ranging to complete the search, recognition, and tracking of low, slow, and small targets, with an optical-axis stabilization accuracy mostly on the order of milliradians, and relatively relaxed requirements for micro-vibration and thermal stability. The engineering focus of this type of system lies in multi-sensor information fusion and target recognition algorithms, which is weakly related to the micro-vibration–thermal-stability main line focused on in this paper, so it is not further elaborated. However, as the largest-scale category in the product family of vehicle-mounted optomechanical systems, its standardized load-

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bearing interfaces and modular payload designs can still provide productization experience for the engineering of high-precision vehicle-mounted optomechanical systems.

6. Existing Problems and Development Directions

6.1 Existing Bottlenecks

(1) The weight–performance–power-consumption triangular contradiction is prominent. Six-degree-of-freedom active vibration isolation requires supporting accelerometer arrays, actuators, and controllers, and precision temperature control requires high-power refrigeration units and heating circuits; the integration of both causes a sharp rise in system weight and power consumption, imposing constraints on chassis load-bearing, road mobility, and outfield endurance. Although carbon-fiber composite load-bearing structures and optomechanical brackets have been applied, their cost is high, and process consistency and long-term stability still need to be verified [8].

(2) It is difficult to decouple the thermal–mechanical–optical multi-field coupled disturbances. Micro-vibration, temperature gradients, and structural deformation do not act independently in the vehicle-mounted platform, but are coupled into time-varying drift through the optomechanical reference. Existing research mostly addresses a single disturbance: passive/active vibration isolation focuses on the vibration frequency band, athermal structures focus on uniform temperature rise, and fast-steering-mirrors focus on high-frequency residual angular vibration; research on thermal–vibration–optical multi-field coupling modeling, online decoupling of error sources, and joint compensation is still insufficient, and mature solutions for long-term optical-axis stability under complex outfield conditions remain lacking [3,13].

(3) The precision thermal-stabilization time constant conflicts with rapid-deployment requirements. Vehicle-mounted optomechanical systems require wide temperature range, dust prevention, rain prevention, and impact resistance, and also require leveling, temperature-control stabilization, and optical-axis calibration within a short time after stopping. In engineering, the in-cabin temperature converging from the ambient temperature to ±0.5 ℃ usually takes 30~60 min, while rapid-response tasks often require emitting light and working within 5~10 min; there is a quantitative contradiction between the two. The reliability and maintainability of optical windows, leveling mechanisms, and vibration isolation platforms under long-term outfield use still need engineering accumulation.

6.2 Development Directions

(1) Lightweight composite-material integrated athermal design. Carbon-fiber composite load-bearing structures, integrated carbon-fiber optomechanical support structures, and composite–metal hybrid athermal designs will further reduce system weight, improve specific stiffness, and reduce thermal-expansion coefficients, improving mobility while ensuring optical accuracy [8].

(2) Advanced six-degree-of-freedom active vibration isolation and low-frequency performance breakthrough. Composite control strategies based on Skyhook damping, notch filters, adaptive filtering, and inertial references will extend the effective isolation frequency band of active vibration isolation to the low-frequency region (< 5 Hz) while reducing actuator weight and power consumption, and are the core direction for solving the contradiction between “insufficient low-frequency performance of passive vibration isolation” and the “weight cost of active vibration isolation” [11-12].

(3) Thermal–mechanical–optical joint active compensation. Fusing six-degree-of-freedom acceleration sensing, multi-point temperature monitoring, and online optical-axis measurement to establish a thermal–mechanical–optical coupling model, and adopting active vibration isolation, zone thermal control, and servo fast-steering-mirror joint closed-loop control to achieve unified decoupling and compensation of multi-source disturbances, is the core direction for improving long-term optical-axis stability [3,11].

(4) Multi-parameter online monitoring and digital twin. Based on an online monitoring network of in-cabin vibration, temperature, structural deformation, and optical-axis state, a digital twin model of

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the vehicle-mounted optomechanical system is established to achieve fault prediction, remaining-life assessment, and outfield-environment adaptability prediction, promoting the development of vehicle-mounted optomechanical systems toward autonomous operation of "working immediately after stopping."

7. Conclusion

Vehicle-mounted optomechanical systems are the core carrier of mobile precision optoelectronic systems, and their overall performance is jointly determined by multiple disciplines including the chassis, load-bearing structure, vibration isolation, thermal control, optomechanics, servo, and environmental compensation. Micro-vibration suppression and thermal-induced optical-axis drift are the two core problems constraining the performance of high-precision vehicle-mounted optomechanical systems: the multi-level stabilization chain composed of passive vibration isolation, six-degree-of-freedom active vibration isolation, and fast-steering-mirror precise stabilization, as well as composite-material athermal structures and distributed precision temperature control, have become the mainstream technical routes in engineering. The main gaps in current research lie in the online modeling and joint compensation of thermal–mechanical–optical multi-field coupling, and the balance between the low-frequency performance of active vibration isolation and the weight–power cost. With the continued growth of demands for low-altitude security, directed-energy outfield tests, and mobile precision optical observation, vehicle-mounted optomechanical systems will further develop in the directions of lightweight composite-material integrated athermalization, active-vibration-isolation low-frequency breakthroughs, thermal–mechanical–optical joint compensation, and multi-parameter online monitoring, and will play a more important role in future mobile optoelectronic systems.

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