OPTICAL ENGINEERING

Mastering Asphere Design in CODE V: A Comprehensive Technical Guide to Advanced Optical Systems

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The evolution of optical engineering has been defined by the persistent pursuit of higher resolution, smaller form factors, and superior light-gathering capabilities. At the heart of this evolution lies the transition from traditional spherical lens elements to complex aspheric surfaces. While spherical lenses are easier to manufacture, they inherently suffer from spherical aberration, which limits their performance in high-precision applications. **CODE V**, developed by Synopsys, has emerged as the industry-standard optical design software for addressing these challenges, offering a sophisticated suite of tools specifically engineered for asphere and freeform design.

In modern optical systems, the integration of aspheric surfaces is no longer a luxury but a necessity. From the miniature lens modules in smartphones to the high-performance optics of the Hubble Space Telescope, aspheres allow designers to achieve performance levels that would otherwise require a prohibitively high number of spherical elements. This article provides an in-depth technical exploration of asphere design within CODE V, covering theoretical frameworks, optimization strategies, and manufacturing considerations.

The Theoretical Framework of Aspheric Surfaces

To design effectively in CODE V, one must first understand the mathematical representation of aspheric surfaces. Unlike a sphere, which has a constant radius of curvature, an asphere's local radius changes with the distance from the optical axis. The standard representation used in most optical design codes, including CODE V, is the rotationally symmetric aspheric surface equation.

The Standard Aspheric Equation

The sag (z-coordinate) of a standard aspheric surface is typically described by the following formula:

z(r) = (c*r^2) / [1 + " (1 - (1+k)c^{2}r^2)] + " (Ai * r^i)

Where:
z is the sag of the surface parallel to the optical axis.**c** is the curvature (1/R) at the vertex.**r** is the radial distance from the optical axis.**k** is the conic constant (k = 0 for spheres, k = -1 for parabolas, -1 **Ai**represents the higher-order aspheric coefficients (4th, 6th, 8th order, etc.).

Limitations of Standard Polynomials

While the power-series expansion (Ai * r^i) is widely used, it presents significant numerical challenges during optimization. High-order terms can become non-orthogonal, meaning a change in one coefficient significantly impacts the others. This leads to instability in the optimization damping and can result in surfaces that are mathematically sound but physically impossible to manufacture or measure. To combat this, CODE V emphasizes the use of **Q-type polynomials** (Forbes surfaces).

Advanced Surface Modeling: Q-type and Freeforms

One of the most powerful features of CODE V is its support for **Q-type aspheres** (Qbfs and Qcon). Developed by G.W. Forbes, these polynomials are orthogonal over the normalized aperture. This orthogonality ensures that the coefficients are independent, providing better numerical stability and a more intuitive relationship between the coefficients and the surface slope. This is critical for **manufacturability (metrology)**, as it allows designers to constrain the slope of the asphere more effectively.

Q2D and Freeform Surfaces

As optical systems move toward non-rotationally symmetric designs—such as head-mounted displays (HMDs) and off-axis reflective systems—freeform surfaces become essential. CODE V's **Q2D freeform aspheres** provide a robust framework for designing these surfaces. Unlike standard XY polynomials, Q2D surfaces offer better convergence during optimization and allow for smoother transitions across the aperture, which is vital for reducing scattered light and improving image quality.

Optimization Strategies in CODE V

Optimization is the core of the optical design process. CODE V utilizes a powerful derivative-based optimizer known as **Automatic Design (AUT)**. However, aspheric design requires more than just local optimization; it requires a strategic approach to navigate the complex multi-dimensional error function space.

Global Synthesis (GS)

For complex aspheric systems, local optimizers often get stuck in local minima. **Global Synthesis** in CODE V allows designers to explore a much broader range of potential solutions. By systematically varying parameters and using proprietary algorithms, GS can find non-obvious configurations that utilize fewer aspheric elements or more cost-effective glass types while maintaining performance.

Asphere Expert: Automating Complexity

One of the standout tools in CODE V is the **Asphere Expert**. Designing an asphere involves deciding which surfaces should be aspheric and what order of polynomial to use. The Asphere Expert automates this by:

Analyzing the system to identify which surfaces provide the most significant aberration reduction if made aspheric.
Incrementally adding aspheric coefficients and checking for performance gains vs. manufacturing complexity.
Ensuring that the resulting aspheres remain within manufacturable limits.

Technical Comparison: Spherical vs. Aspheric Systems

To understand the value proposition of aspheric design, consider the following comparison table which outlines the trade-offs in a typical mobile imaging lens design.

Feature/Metric	Spherical-Only Design	Hybrid (Spherical + Asphere)	Full Aspheric (CODE V Optimized)
Element Count	8 - 10 elements	5 - 6 elements	3 - 4 elements
Total Track Length (TTL)	Longer (Harder to fit in phones)	Moderate	Short / Compact
Spherical Aberration	Difficult to correct at low F-numbers	Well-corrected	Excellently corrected
Manufacturing Cost	Low per element	Moderate	High per element (but fewer elements)
Optical Performance (MTF)	Limited off-axis	Good across field	High performance at wide angles

Designing for Manufacturability: The "Easily Measurable Asphere"

A common pitfall for novice designers is creating a "paper design" that cannot be built. CODE V provides specific tools to ensure that aspheres are **easily measurable**. If a surface has too much local slope deviation or if the inflection points are too sharp, standard metrology tools like interferometers or profilometers may fail to characterize the surface accurately.

Constraint Management

In CODE V, designers can use **User-Defined Constraints (UDC)** to limit the maximum slope or the change in curvature (Delta-C) across the surface. By incorporating these constraints directly into the optimization macro, the software ensures that the final design adheres to the fabrication capabilities of the chosen vendor (e.g., molding, diamond turning, or magnetorheological finishing).

Cost-Effective Use of Aspheres

Aspheres are more expensive than spheres due to the complexity of the grinding, polishing, and testing phases. The **CODE V Glass Expert** and Asphere Expert work in tandem to find the most cost-effective solution. Sometimes, using a slightly more expensive high-index glass with a simpler aspheric profile is cheaper than using a low-index glass with a highly complex, difficult-to-measure aspheric surface.

Practical Implementation: Step-by-Step Workflow

To successfully implement an aspheric design in CODE V, engineers typically follow this structured workflow:

Step 1: Establishing the Spherical Baseline

Always start with a functional spherical design. Attempting to optimize a system from scratch with aspheric coefficients enabled often leads to divergent solutions. Use the **Step Optimization** feature to gradually introduce complexity.

Step 2: Sensitivity Analysis

Use the **Field Map** and **Aberration Curves (Ray Aberration Plots)** to identify which surfaces are contributing the most to the overall error function. Usually, the surfaces closest to the stop or the image plane are prime candidates for asphereization.

Step 3: Running Asphere Expert

Invoke the Asphere Expert to determine the optimal number of coefficients. Start with a low order (e.g., 4th and 6th) and only increase if the MTF requirements are not met. Over-specifying coefficients leads to "wavy" surfaces that are a nightmare for fabrication.

Step 4: Tolerance Analysis (TOR)

An aspheric design is only as good as its tolerances. CODE V's **Tolerance Analysis tool** uses Monte Carlo simulations to predict the yield. Aspheres are particularly sensitive to **decenter** and **tilt**. If the tolerance analysis shows a low yield, the designer must use the **Tolerance Optimization (SAB)** feature to desensitize the design.

Case Study: Mobile Camera Lens Design

In mobile phone optics, the space is extremely constrained (z-height). A typical 7-element (7P) lens utilizes aspheres on almost every surface. CODE V enables the design of these plastic molded aspheres by providing specialized tools for **thermal analysis**. Since plastic refractive indices change significantly with temperature, CODE V's multi-configuration capability allows the designer to optimize the aspheric coefficients to maintain focus from -20°C to +60°C.

Challenges with Stray Light

Highly curved aspheres in mobile lenses can cause internal reflections (ghosting). CODE V's **Beam Synthesis Propagation** and integration with **LightTools**allow designers to analyze how the aspheric shapes contribute to stray light, enabling the addition of mechanical baffles or surface coatings early in the design phase.

Troubleshooting Common Errors in CODE V Asphere Design

Even with advanced tools, designers often encounter hurdles. Here are common issues and their technical solutions:

- Optimization Stagnation: If the error function stops decreasing, try switching from the standard dampening (DAMP) to Levenberg-Marquardt or use Global Synthesis to jump to a different solution space.
- Non-Physical Surfaces: If a surface "self-intersects" or develops a hole, check the clear aperture settings and apply Edge Thickness (ET) constraints in the optimization macro.
- Metrology Failure: If the manufacturer complains they cannot measure the part, use the Q-type polynomial conversion and limit the higher-order terms.

Future Trends in Aspheric Design

The future of asphere design is moving toward **Artificial Intelligence (AI) and Machine Learning (ML)** integration. Synopsys is increasingly incorporating automated heuristics that can predict the best starting points for aspheric designs based on vast databases of previous optical systems. Furthermore, the rise of **Metalenses**(flat optics with sub-wavelength structures) represents the next frontier, though CODE V continues to be updated with modules to handle these hybrid refractive-diffractive systems.

Strategically, the mastery of CODE V for asphere design requires a balance between mathematical rigor and manufacturing pragmatism. By leveraging tools like Asphere Expert, Global Synthesis, and Q-type polynomials, designers can push the boundaries of what is possible in optical performance while ensuring that the resulting products can be manufactured reliably and cost-effectively. As the demand for compact, high-resolution imaging grows in sectors like autonomous vehicles, AR/VR, and medical devices, the role of the CODE V optical designer remains more critical than ever.

In conclusion, the effective use of aspheres within CODE V is a multi-faceted discipline. It begins with a deep understanding of surface mathematics, moves through the rigorous application of optimization algorithms, and culminates in a design that is robust against manufacturing tolerances. For the modern optical engineer, these tools provide the capability to transform complex light-steering requirements into tangible, high-performance hardware.

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