Aspheric testing

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This report briefly reviews and discusses various possible methods for testing aspheric surfaces with emphases on those of interferometry-based and other contour-based noncontact measurement techniques. Merits and weaknesses of each kind of method have been presented.

It has been pointed out that it is the slope of the aspheric departure not the actual departure itself from the best fitting surface that determines the difficulty of the test. There is no perfect solution up to date for all aspheric testing problems.

After examining and investigating, a proposed conceptual plan is presented for the project of aspheric shape measurement in the virtue of fieldsensing noncontact phase shifting interferometry by the aid of fine mechanical means.

1. INTRODUCTION

The production and uses of lenses, mirrors and products with spheric and aspheric surfaces, as well as with other symmetric and/or asymmetric curved surfaces are increasing very fast, while high precision is required. Especially, the production of lenses, such as those of soft and hard contact lenses, those used in compact disc players, those utilized in many kinds of recorders and those employed in diverse astronomical equipment has expanded enormously.

Though it comes, there have been limitations or difficulties in using aspheric elements. This is mainly due to the fact that they are difficult to fabricate and test. During the last two decades there have been a great deal of improvements in the fabrication or manufacturing of aspheric surfaces, the most benefits being the acceptance of single-point diamond turning and the moulding.

Aspheric surfaces are often manufactured by displacement controlled machines based on processes, such as diamond turning and ductile grinding, or by conventional optical technologies. Therefore, precision measurement of such kind of curved shape is a must for manufacturing process control and product quality validation. For example, it is highly needed for the manufacturers who fabricate the toric lens and so-called "insight lens" which consists of three different shaped zones to possess a kind of reliable technique for accurate shape measurement.
Suppose measurements with lenses are carried out on-machine so that the lenses can be corrected before removal from the lathe and setting error caused by attaching and detaching the workpieces can be avoided. To do so we have to treat troubles worse than in a laboratory. On the other hand, when measurement work is done after the removal of workpieces from the lathe, the validation of workpiece quality can be made under better conditions, but it is hard to correct the lens deviation from desired shape in-situ easily.

In any test of an aspheric surface, the difficulty of the test is determined by the slope of the aspheric departure from the best fitting spheric surface. Considering that conventional contact measurements are restricted due to probable scratch or other shortcomings, and that profilometric measurements are limited to lines or rather smaller field of measurement, interferometrically based methods might be the best choice when the whole aspheric surface must be measured accurately. However, the interferometric measure of aspheric surfaces may be very hard to perform. In fact, if the aspheric surface has a large departure of slope from the best fitting reference surface, an interferogram made without some sort of aspheric null contains too many fringes to analyze or detect.

Furthermore, while much work has been done on the measurements of aspheric surfaces, no outstanding technique has been developed yet. The actual measurement techniques to inspect these product ranges are not so sufficient as to satisfy the increasing demands of industry, especially the required measurement accuracy and convenience.

To make the things even worse, all the existing or ready-made measuring instruments, as far as we know, can test only radius of curvature and surface quality for the lens. There is scarcely any existing technique as well as appropriate instrument that performs in such a way to scrutinise whole-field shape of an aspheric and/or asymmetric surface accurately. It is expected to change the picture during this decade, before the end of this century.

The aim of this research is to improve and materialize a kind of suitable method for aspheric shape testing with an accuracy range of micron or sub-micron for the purpose of using in both laboratory and industry cases, so as to make our contributions to the course of aspheric testing.

2. CONTACT MEASUREMENTS AND NONCONTACT MEASUREMENTS

Possible means of contact measurements here might be

- conventional azimuth-elevation measurements
- CMMs with contact probe
- stylus profilers
- template comparison

They hold such virtues as relatively uncomplicated in configuration, explicit in interpreting measured information and universal suitability for various kinds of irregular surfaces. However, critical shortcomings, due to the physical contact and point-sensing nature, such as surface-scratch, dragging measurement period
and positioning error as well as the error introduced by imperfect sampling strategy make us waive these methods.

For precision workpieces and optical objects with micron or even much higher accuracy in shape, a noncontact and nondestructive measurement method is highly recommended and preferentially accepted due to their non-destructive nature.

Among nondestructive techniques, those based on ultrasonic principle may not be accepted owing to their rather lower resolution; those employing X-ray may not be suitable, too, because of their costliness and radiation. Consequently, the optical noncontact techniques, conceivably being associated with mechanical and electronic means, are therefore our choice. In fact, they are becoming important tools in precision metrology of curved surfaces considering their wonderful possibility and convenience to realize fast, nondestructive, and high accurate measurement.

On the other hand, we should by no means neglect other effective methods and investigate the possibility of their hybrid utilisation.

Perhaps we can group the possible optical methods and their derivatives for the project as followings:

**point-sensing and line-sensing methods**

- profilometer with optical focus sensors
- scanning probe microscopes (STM / SEM / AFM)
- reflect/deflectometry and phase measuring Ronchi testing

**field-sensing methods**

- interferometric optical profilers
- moiré topography
- phase-shifting-interferometrically based methods
  - interferometric null tests
  - interferometry employing high-density CCD arrays
  - interferometry using longer wavelength
- sub-Nyquist interferometry
- two-wavelength or multiple-wavelength interferometry
- shearing interferometry
- subaperture interferometry

Traditional measurements are based on point-sensing methods and even recently developed measurements such as STM techniques are based on linesensing methods. Nevertheless, the phase shifting interferometry and moiré topography are based on field-sensing methods, having attracted much attention of many workers in modern times, as an attractive alternative for measuring the curved and aspheric objects. We are going to deal with moiré topography, reflect/deflectometry and phase measuring Ronchi testing, profilers and phase shifting interferometry respectively, but with much more concentration on the last one.
3. MOIRÉ TOPOGRAPHY

Moiré technique and its derivatives, as a kind of field-sensing methods, have getting many developments in recent years. Besides in-plane occurrences interpreted and measured by moiré technique, the moiré topography can be used to determine the shape of an object. It has been done mainly by two kinds of techniques:

- deflection / reflection moiré
- shadow / projection moiré

Deflection moiré and reflection moiré are based on the same principle. They are used for objects which give specular reflection. Moiré deflectometry and appropriate instruments have been used for the measurements of such specular or optical surfaces as buttons of contact lenses.

The information provided by moiré deflectometry is a ray deflection map of a light beam and the method is of a pure ray tracing. In other words, measured quantity is the slope of the surface. Compared with interferometry, this method is insensitive to tilt, relative height is observed directly, mechanical stability requirement is not so strict as interferometry, and sensitivity is tunable. It suffers, however, from restrictions of measurement accuracy within the range of several microns, for example 5 μm-accuracy of Rotlex OMS 101 system, which would be insufficient to the want.

Both shadow and projection moiré methods are based on the same principle and usually being accepted for objects which reflect light diffusely. With both types moiré fringes become contour lines of surfaces in specific geometrical conditions. The former has relatively higher sensitivity but smaller range of measurement, while the latter lower sensitivity but larger range of measurement.

The most important factors which dominantly determine the sensitivity or accuracy in moiré technique are the pitch and quality of gratings as well as the availability to divide and then identify the fringe patterns as fine as possible. A much higher density grating can be made by inserting refractive medium instead of air.

The sensitivity with this method generally is within the range of micron. Theoretical upper limit of moiré interferometry is approached as grating pitch approaches half wavelength of employed light. Nevertheless, it could be improved by virtue of fringe shifting and fringe sharpening techniques.

4. REFLECT/DEFLECTOMETRY AND PHASE MEASURING RONCHI TESTING

After discussing over the project with mathematicians, we have got following idea. Mathematically, an arbitrary curved surface could be defined entirely as its normal and location of each point on the surface are known. Since the direction of a normal is of right retroreflection, profile measurement of an aspheric surface might be realised in light of reflection and deflection.
Direction of the surface normal and location of the surface slope to be measured could be defined by the retroreflection or deflection beam by means of ray tracing method; slope of the surface could be found by analyzing components of the surface normal. As long as retroreflection or deflection information on the direction of the surface normal at special points is acquired, the profile shape can be determined mathematically.

Two types of light beams can be employed to illuminate measured surface on which the beams are supposed to be reflected off. A single light beam could be accepted with association of a position sensing detector (PSD) which provides continuous position data of a light spot travelling over its surface to identify the scanning loci on the surface accurately. The method may holt some drawbacks due to its non-field-sensing nature and imperfectly positioning. As an alternative, collimated beam could also be accepted with the aids of rotation of a reflection mirror which is inspected precisely, in case that interferometry is accepted to acquire data regarding normal and position of the surface slope where the ray has a minimum optical path. A fundamental problem is that a suitable way should be found otherwise the slope of the wavefront must be small enough that the entire wavefront can get reflectively back into the interferometer.

Actually, there have been some relevant research already, for instance phase measuring Ronchi test and phase detection deflectometry. In a Ronchi test, a binary grating with equal spacing of transparent and opaque strips, called a Ronchi grating, is positioned near the focal plane. Through the grating the exit pupil is observed so that a pattern corresponding to the aberration of the surface or system under test is observed. The phase of the Ronchigram measures the first derivative of the surface aberration. By numerical integration of the phase, the shape of the surface can be reconstruct.

A so-called phase detection deflectometry is an application of phase detection to the Ronchi method. It is based on the measurement of the deflection of light rays, after reflection on every point of the surface under test. It is possible to obtain an extensive slope mapping of the surface and then to rebuild the altitude mapping by integration means as long as deflection direction and position of each point on the surface are known. This can be materialized by precisely monitoring and measuring the translated Ronchi grating which is placed between tested objects and the acquisition system.

The accuracy will be restricted mainly by the resolution of detecting system and positioning accuracy.

5. PROFILERS

Profilers are instruments that are used to measure surface roughness and the geometry of small features on an object. They are different from instruments that are meant to measure large surfaces or the overall form of an object. Typically, a profiler has a maximum field of view of about 10 mm. Rather than only providing qualitative data, profilers usually providing quantitative data in the form of a surface height map over the measurement area.
Profiler types can be split into contact and noncontact devices. A contact profiler scans a probe across the surface and determines height by looking at the height variations of the probe as it scanned. Usually the surface is moved under the stylus, but the stylus may also be moved over the surface. As the foregoing statement, we confer less attention to it although we could get benefits and inspiration from it to fabricate our measuring system.

Noncontact devices measure surface height without coming in contact with the surface. Most of them are optical microscopes, being used to determine surface roughness or geometries of small features. Although they are very sensitive and can measure heights with a precision of a few angstroms rms or even much high, the fact that they hold much smaller field of measurement than what we desire downgrades their position in our selection. Scanning probe microscopes such as STM, AFM, that move a fine tip in close proximity to a surface and optical focus sensors that sense focus at a single point on the surface and adjust the height of the focusing lens until focus being achieved hold the same picture.

6. PHASE-SHIFTING-INTERFEROMETRICALLY BASED METHODS

6.1 Phase shifting interferometry (PSI)

In any modern interferometric test of an aspheric optical surface some means is required to get the interferogram data into the computer for analysis. Phase shifting interferometry (PSI) is the best. The relatively simple concept behind PSI is that a time-varying phase shift is introduced between the reference wavefront and the test or sample wavefront in the interferometer. A time-varying signal is then produced at each measurement point in the interferogram, and the relative phase between the two wavefronts at that location is encoded in these signals. In PSI, the phase difference between the two interfering beams is made to vary at a known rate, and as the phase difference is varied the resulting intensity distribution is detected and fed into a computer. If three or more intensity measurements are made while the phase difference is varied, the phase variation across the interference pattern can be calculated.

The advantages of the PSI technique includes high measurement accuracy, rapid measurement, good results even with low-contrast fringes, results that are independent of intensity variations across the pupil and phase obtained at a fixed grid of data points.

Over the years this general technique has been known by several names including phase measuring interferometry, fringe scanning interferometry, real-time interferometry, alternate current (AC) interferometry and heterodyne interferometry. All describe the same basic technique.

6.2 The fundamental problems and solvability

Aspheric surfaces of optical elements and other high-precision objects are generally tested using profilometer or interferometer, although other kind of
measurements are also being accepted simultaneously. Since profilometric measurement is limited to lines, interferometry is then the best choice when whole surface must be tested. However, the interferometric measure of aspheres may be very hard to perform if the aspheric slope departure from the best fitting reference surface exceeds several micron-meters, considering that such method is originally designed for the measurement of plano or spheric surfaces.

It has been suggested that PSI could make accurate measurement of "mild" aspheres that departure from the base sphere by a few micrometers and at most does not cause fringe densities on the detector greater than the Nyquist limit of one fringe per two pixels. It seems difficult to employ an existing measuring system to measure a "deep" aspherical surface whose departure exceeds such a narrow range.

The main problem to measure aspheric surfaces generally is that the fringe density is too high to be detected. In other words, the fringe frequency is over Nyquist frequency. From a testing point of view, the prime characteristic of an aspheric surface is that it has a large departure from a best fitting reference sphere, and an interferogram made without some sort of aspheric null contains too many fringes. The Nyquist condition of having at least two pixels per fringe provides a limit to the amount of asphericity that can be measured with a PSI system. The maximum wavefront slope is limited to \( \pi \) per pixel. The fringe frequency is proportional to the wavefront slope, and even a "mild" aspheric surface will violate this condition when test against a spheric reference surface with instrumentation available today. Typically, these systems are limited to testing surface with no more than 10-20 waves of asphericity.

Another problem in case of measuring aspherical surface with a PSI system is that a compensation for error introduced by non-zero fringe densities should be performed in order to correct the primary, significant errors arising from the imaging system.

As a result, a suitable technique must be developed in such a way either being able to reduce the density down till that below Nyquist frequency or able to handle fringes that occur above Nyquist frequency. Consequently, we have taken two groups of such methods into consideration:

**group a:**
- interferometry null test
- employing high-density CCD arrays
- rescale wavefront by longer wavelength

**group b:**
- sub-Nyquist interferometry
- two-wavelength or multiple-wavelength interferometry
- shearing interferometry
- subaperture interferometry

Also, there is a possibility to design a special kind of grating onto a spheric surface instead of a plane for the same purpose to reduce the fringe density.
6.3. Interferometry null tests

The principle behind interferometry null test is to compensate or correct wavefront shape of aspheric aberration individually by means of either material null elements or simulation.

In case of testing an aspheric surface with an ordinary spheric testing system, a diverge lens is used that produces an aspheric wavefront that has the property that the wavefront exactly matches the aspheric surface under test, instead of using a diverge lens that produces a perfect spheric wavefront, then we will still have the null condition of obtaining straight equally-spaced fringe. Any deviation from the condition measures shape or texture error in the aspheric surface. Reflective, refractive and other types of null optics are usual choice of null elements.

Besides, a zone-plate can be used too. A zone-plate is a photo plate with a circle grating that has a pattern calculated to reproduce the shape of the designed surface. In this case, a real reference surface is unnecessary because the reference wavefront produced by a zone-plate can be used as a reference surface. Therefore a symmetrical spheric or aspheric shape can be measured. However, careful adjustment and precision alignment are required here.

Holography provides another methods of performing a null test. More or less as a zone-plate, if a perfect aspheric element is present, a hologram can be made of the element, and the wavefront stored by the hologram can be used later in the interferometric testing of the supposedly identical aspheric elements.

In many situations where master optics are not available for making a real hologram to serve as a holographic test plate, a synthetic computer-generated-hologram (CGH) can be made. Since CGH is of being simulated and designed according to the desire theoretical shape, it could be used much widely than material null lenses. Positioning error, distortion in the hologram plotter and costliness of time and expense are critical problems with the method.

Although null test methods have been widely used in optics they suffer from the drawback of costliness since we have to design particularly for a set of aspheric tested. Furthermore, these methods have a common disadvantage of reserving difficulties for manufacturing.

6.4 Employing high-density CCD arrays and longer wavelength source

Definitely, as long as there are two or more detector elements per fringe it should be possible to test an aspheric surface promptly. If the commercial introduction of high-density CCD arrays for example 4096x4096 CCD arrays or other new type detectors could come into practical use at reasonable lower price, then many aspheric elements would be tested directly.

Another way to reduce the number of interference fringes is to use an interferometer with such a source that has a longer wavelength than that common-used He-Ne laser has as a carbon dioxide laser operating at a wavelength of 10.6 μm, to rescale the tested wavefront so as the fringe frequency will not exceed the Nyquist condition. Unfortunately, the sensitivity will decline simultaneously.
As for the methods listed in group a, none of these is entirely satisfying; each involves a trade-off that places long lead time on the design of the test, requires additional fabrication, increase the difficulty in using and calibrating the instrument, decrease its precision, or greatly increase the instrument cost. In order to test aspheric surfaces without resorting to one of these methods, a PSI system must be capable of handling fringes that occur above the Nyquist frequency and therefore aliased. Four possible methods listed in group b are going to be discussed particularly.

6.5 Sub-Nyquist interferometry (SNI)

Sub-Nyquist interferometry (SNI) is a data collection and analysis method that is capable of extending the measurement range of PSI through the use of a priori information about the tested surface, which is based on the assumption that the surface or wavefront is smooth and therefore has continuous derivatives. The slope continuity constraint correctly reconstruct the surface from the aliased data until the second derivative of the actual wavefront exceeds the limit imposed by the constraint. This additional information allows the analysis to interpret fringes that occur at frequencies well in excess of the Nyquist frequency so as to undersample the wavefront and still perform an adequate measurement. The fundamental limit to the measurement range of an SNI system is in the ability of the sensor to respond to the high-frequency fringes, i.e., the pixel modulation transfer function (MTF). Improving it needs a kind of sensor with a small width-to-pitch ratio or even a point-typed detector.

6.6 Two-wavelength or multiple-wavelength PSI

The additional information that two-wavelength PSI uses to extend the PSI measurement range beyond the Nyquist frequency is a separate measurement at different wavelength. Multiple-wavelength PSI is based on the same principle. In this way, no $2\pi$ phase ambiguities are experienced and sufficient fringe modulation can be obtained if the detector matches the Nyquist condition and each detector element is small enough.

There is an important similarity between SNI and this method for measuring aspheric surfaces: Both depend on being able to measure aliased fringes, and therefore require sparse array sensors with small pixel width-to-pitch ratio. A practical problem that has hindered the implementation of two-wavelength PSI for this application is chromatic aberration in the reference optics and the interferometer. Accuracy with this method will be not as good as that with one shorter wavelength.

6.7 Shearing interferometry

Another approach is to use the shearing interferometry in which two shifted images of the wavefront under test are superimposed to interfere with each other. The attractive feature of using shearing interferometry for aspheric surface testing is that the sensitive of the test can be varied by changing the
shear distance. In this way the number of fringes is reduced. Another advantage of the shearing interferometry is that no reference surface is required. The surface slope is measured with shearing interferometry, and the actual surface then is reconstructed by integration. To measure an asymmetric surface, two sets of PSI data with orthogonal or rotational shears must be collected.

The most important shearing interferometry is of lateral shearing one, although other kinds of shearing interferometry such as radial, rotational and reversal shearing interferometry are used at the same time. Basically, the method of lateral shearing interferometry consists of displacing the defective wavefront laterally by a small amount and obtaining the interference pattern between the original wavefront and the displaced or shifted version of itself.

It has been reported that aspheric surfaces can be measured using lateral shearing interferometry to an accuracy of 1% to 0.1%. The accuracy is generally limited by that the amount of shear is not precisely known and that the noise in the measurement tends to spread across the reconstructed surface as a result of this integration.

The biggest problem with using lateral shearing interferometry for measuring aspheric surface is that it reduces the number of fringes least where the density is highest, working not so effectively as desired.

6.8 Subaperture interferometry

The basic idea behind subaperture testing of aspheric surfaces is to divide the wavefront up into small sections; the wavefront departure in each subaperture is within the measurement range of the instrumentation. The maximum fringe frequency is kept below the Nyquist frequency of the sensor. The problem becomes then that to fit all of these separate measurements, which can contain different amounts of tilt, piston, and sometimes defocus, back into a complete map of the aspheric surface.

The overall surface can be represented by a polynomial expansion, and the subaperture data is analyzed to determine the expansion coefficients. The Zernike polynomials might be the best choice, and a limited number of terms are used. This technique provides the overall aspheric surface shape. Small or localized errors will not appear in the final polynomial fit and must be determined from the subaperture data. It is important that the location of each subaperture within the aperture be precisely known.

The principal difficulties of subaperture testing method are that the results of many subaperture measurements must be combined to yield the full aperture aberrations accurately, and a variable and imprecise amount of focus error and other misalignment errors must be removed from the data properly.

7. PROPOSED CONCEPTUAL PLAN

After reviewing and examining all preceding mentioned methods, we hold an idea that one of the following three methods might be our suitable choice to accomplish the project:
subaperture PSI by aids of mechanical means
shearing phase shifting interferometry
deflectometry by aids of PSI and precision positioning

The essential considerations are 1) to avoid the use of compensation elements for the measurement of aspheric surfaces; 2) to accepted preferentially noncontact field-sensing method and 3) to employ and modify PSI comprehensively with aids of fine mechanical means as well as SNI technique and other suitable fringe data processing techniques.

From what we have had by means of the previous experiments and the inspiration of PSI method, we get an idea to form a method. The method consists of varying the distance or position of an aspheric surface from the focus of an interferometry reference sphere with a precision translator stage. As the asphere is moved and/or rotated, the radius of curvature of the reference wavefront changes, matching the aspheric surface on rings of increasing or decreasing diameter. After recording a set of partially overlapping annular or other shaped interferograms for different positions of the aspheric surface, their phase maps are sewn together. It might be better for this method to be used with aid of sub-Nyquist interferometry.

8. CONCLUSION

Different kinds of methods for testing aspheric surfaces are reviewed and evaluated in this report. Amongst them, we prefer phase shifting interferometrically based methods.

In any test of an aspheric surface, the difficulty of the test is determined by the slope of the aspheric departure from the best fitting spheric surface. The main problem to measure aspheric surfaces interferometrically is that the fringe density is too high to be detected. There is no perfect solution, at present, for all aspheric testing problems.

Shearing phase shifting interferometry and subaperture phase shifting interferometry by aids of mechanical means as well as deflectometry by aids of PSI and precision positioning could be cultivated and then result in one suitable method to achieve the goal of the project after being improved creatively.

Subaperture phase shifting interferometry by aids of fine mechanical means as well as data such processing methods as sub-Nyquist interferometry is personally proposed. As a result, it seems necessary to pay a visit to Wyko Corp. and university of Arizona or Officine Galileo S.p.A. where the relative research has been robust and successful.

It is to a great extend definite for us to overcome the dilemma between measurement range/depth and accuracy in virtue of the methods so that to accomplish the task for aspheric surface measurement satisfactorily.
Appendix: POSSIBLE METHODS FOR ASPHERIC TESTING

A. CONTACT MEASUREMENTS
- conventional azimuth-elevation measurements
- CMMs with contact probe
- stylus profilers
- template comparison

B. NONCONTACT MEASUREMENTS

point-sensing and line-sensing methods
- profilometer with optical focus sensors
- scanning probe microscopes (STM / SEM / AFM)
- reflect/ deflectometry and phase measuring Ronchi testing

field-sensing methods
- interferometric optical profilers
- moiré topography
  - deflection / reflection moiré
  - shadow / projection moiré
- phase-shifting-interferometrically based methods
  group a: to reduce fringe density
  - interferometry null test
  - employing high-density CCD arrays
  - rescale wavefront by longer wavelength
  group b: to handle high density of fringe
  - sub-Nyquist interferometry
  - two-wavelength or multiple-wavelength interferometry
  - shearing interferometry
  - subaperture interferometry
- hybrid method by combining of lens analysis/design software with interferogram analysis software
POSSIBLE METHODS FOR ASPHERIC TESTING

A. DIFFUSIVE SURFACES

point-sensing methods
- conventional azimuth-elevation measurements
- CMMs with contact probe
- stylus profilers

line- and field-sensing methods
- scanning probe microscopes (STM / SEM / AFM)
- template comparison
- shadow and/or projection Moiré methods

B. OPTICAL/SPECULAR SURFACES

directly profiling methods
- profilometer with optical focus sensors
- scanning probe microscopes (STM / SEM / AFM)
- stylus profiler

indirectly geometric ray methods
- reflect/deflectometry and phase measuring Ronchi testing
- deflection / reflection moiré

indirectly interferometric methods

1. Null test: wavefront shape correction of aspheric aberration
   - stigmatic imaging, aberration compensation & aberration matching

2. Non-null test

   group a: to reduce fringe density
   - interferometry null test
   - employing high-density CCD arrays
   - rescale wavefront by longer wavelength

   group b: to handle high density of fringe
   - sub-Nyquist interferometry
   - two-wavelength or multiple-wavelength interferometry
   - shearing interferometry
   - subaperture interferometry
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