

# Design and Rapid Prototyping of Affective Shapes with 1/f Fluctuation Characteristics

Katsuhiko MAEKAWA\*, Terutake HAYASHI\*, Yoshiaki WATANABE\*\*

\* *The Research Center for Superplasticity, Ibaraki University, 4-12-1 Nakanarusawa, Hitachi-shi, Ibaraki 316-8511, JAPAN, E-mail: mae@mech.ibaraki.ac.jp*

\*\**Graduate School of Science and Engineering, Ibaraki University*

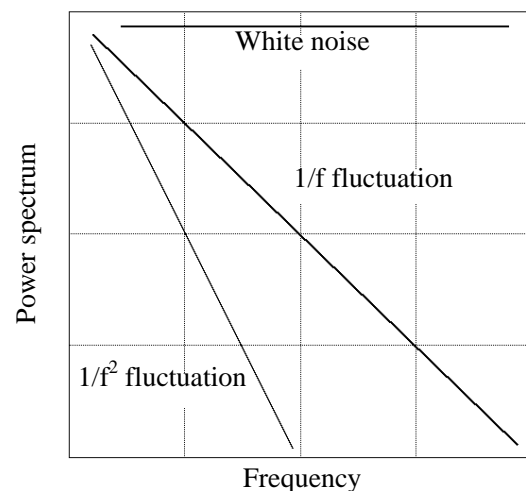
**Abstract:** Methods of introducing 1/f fluctuation characteristics into aesthetic objects are proposed. First, the surface topology of various teabowls is measured using laser metrology, and its wave pattern is then analyzed by the FFT method to clarify power spectrum characteristics. The quantification of an affective factor involved on the outer surface shows that the handmade teabowl has an inclination of  $-1$  on the special frequency-power spectrum diagram, i.e. 1/f fluctuation characteristics. The machine-made one, on the other hand, has an inclination of approximately  $-2$ , which gives a uniform, not to say monotonous impression. Secondly, the 1/f fluctuation characteristics are applied to the design of a model teabowl in which three different methods are illustrated. Finally, the creation of aesthetically pleasing objects is attempted using rapid prototyping technology. The CG images and the three-dimensional objects substantiated show a correlation between 1/f fluctuation characteristics and the aesthetic quality of handmade articles.

**Key words:** 1/f Fluctuation, Shape Design, Affective Design, Kansei Engineering

## 1. Introduction

The value of a product consists of many factors, including functional capability, performance, cost, usability and eco-friendliness. Design to please the eye is another factor that adds value to a product. New products having a high value reflect this trend; we tend to select a product that confirms to our sense of the beautiful, all being equal. The aesthetics of a product are influenced by such elements as shape, texture, color, pattern and visual harmony with the environment. These qualities are related to individual sensitivity or *kansei*, and to the individual's cultural background, so it must be admitted that it is difficult to characterize them quantitatively [1].

The present study concerns the design of aesthetic forms. First, shape fluctuation is investigated using laser metrology and analyzed by the Fourier transformation in order to foreground eye-pleasing characteristics. Fluctuation is a spatial and time change that is difficult to predict. **Figure 1** shows typical patterns of the power spectrum as a function of frequency in a double logarithmic plot. The spectrum is defined as the root-mean-square wave amplitude contained in every frequency. White noise has no dependency on frequency,



**Fig. 1** Power spectrum of typical fluctuations

whereas the spectra of  $1/f$  and  $1/f^2$  fluctuations change with frequency; the inclinations of these characteristic lines are  $-1$  and  $-2$  respectively. It is worth pointing out that these three fluctuations tend to give human beings different impressions: disorder with white noise, aesthetic and affective satisfaction with the  $1/f$  fluctuation, and blandness and monotony with the  $1/f^2$  fluctuation [2].  $1/f$  fluctuation characteristics can be seen in various natural phenomena, such as breezes, streams, candle flames and the luminous patterns of fireflies [3]. They are also introduced into many industrial products, such as the control of the revolutions of electric fans and the control of the oscillations of massage tools. No application to shape design has been reported. The integration of  $1/f$  fluctuation characteristics with shape design is focused on the second part of this paper.

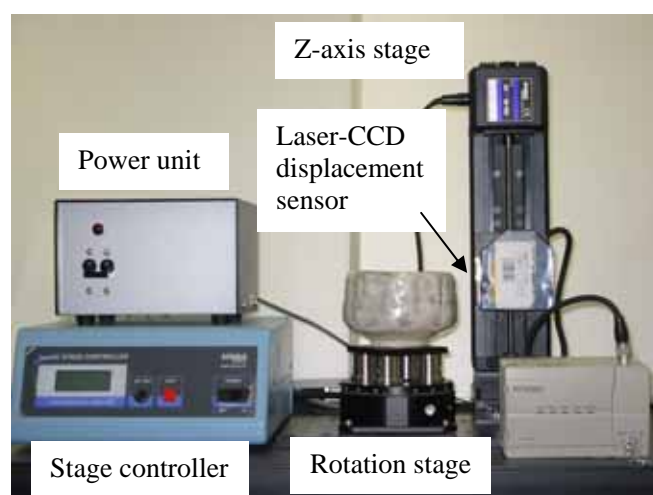
The final part of the paper describes the realization of an affectively satisfying shape with *kansei* features. Rapid prototyping technology, incorporated with computer-aided design, has been utilized to generate mock-ups in a shorter lead-time. Since a 3D-CAD model may be decomposed into layers as thin as  $100\ \mu\text{m}$  and then substantiated layer by layer, any complicated shape can be generated with a high degree of precision. Mock-ups of a teabowl and teacup with affective features are created from fine plastic powders.

## 2. Measurement and Analysis of Shape Fluctuations

### 2.1 Experimental

In order to measure the surface topology of various teabowls with high speed and high accuracy, a 3D shape measurement system has been developed. **Figure 2** shows the system architecture, consisting of the Z-axis stage, the rotation stage, the laser-CCD displacement sensor, the stage controller and the personal computer for system control. **Table 1** shows the specification of the sensing part, in which a semiconductor laser with a  $670\ \text{nm}$  wavelength is used for photoflood and a CCD for photo acceptance. Accuracy of measurement depends on the distance between the sensor and the teabowl. It is highest when the standard distance of  $30\ \text{mm}$  is maintained, diminishing as the distance deviates from the standard. The displacement of  $\pm 5\ \text{mm}$  generates changes in wavelength of  $170\ \mu\text{m}$ , which corresponds to a dimensional error of  $14.5\ \mu\text{m}$  in the radial direction. Sampling conditions depend on the performance of the sensor and the PC used for A-D transformation and power spectrum analysis. We take 2048 data for one peripheral contour, and it takes about 42 seconds to complete one rotation.

Assuming that the contour of a teabowl is a perfect circle, the laser-CCD displacement system measures fine concavities and convexities on the surface as well as deviations from the circular form. These data are regarded as



**Fig. 2** 3D shape measurement system

**Table 1** Specification of laser-CCD sensing apparatus

Photoflood lamp	Semiconductor laser with 670 nm wavelength
Photo acceptance	CCD
Standard measurement distance	30 mm
Measurement range	Standard distance $\pm$ 5 mm
Power input	100 V AC
Output	0.95 mW maximum
Laser beam spot	30 $\mu$ m at standard distance
Resolution in Z-axis	1 $\mu$ m
Sampling cycle	512 $\mu$ s

waves involved on the perfect circle, for which the power spectrum analysis is carried out. The first Fourier transformation (FFT) enables us to decompose complicated waves into frequency components. As a result, a diagram of the relationship between the power spectrum and the spatial frequency is obtained. The spatial frequency is defined as the number of wave periods per unit distance. In this case the unit distance is circumference or the length of the bowl's peripheral contour.

It is difficult to align the center of the rotation stage with the center of the teabowl since the form of the object to be measured is not a perfect circle. The influence of this eccentricity may appear in the measured data. However, it is found that the power spectrum increases with the deviation at a low frequency of less than 3. Since the higher frequency region is the matter of interest, the influence of eccentricity can be neglected [4].

## 2.2 Results and Discussion

**Figure 3** shows the teabowls and teacup measured in the present study: (a) - (c) are handmade articles produced by ceramic artists whereas (d) and (e) are mass-produced ones. The maximum outer diameter of the teabowls is about 120mm and that of the teacup is 70 mm. The vertical measurement range covers from 45mm to 75mm from the bottom. The topology of the outer surfaces was measured at vertical intervals of 210  $\mu$ m.

**Figure 4** shows the analytical results: there are five power spectrum-spatial frequency diagrams, in which (a) - (e) correspond to (a) - (e) of Fig. 3. The straight line in the double logarithmic chart is the least mean square



(a) Teabowl A



(b) Teabowl B



(c) Teabowl C

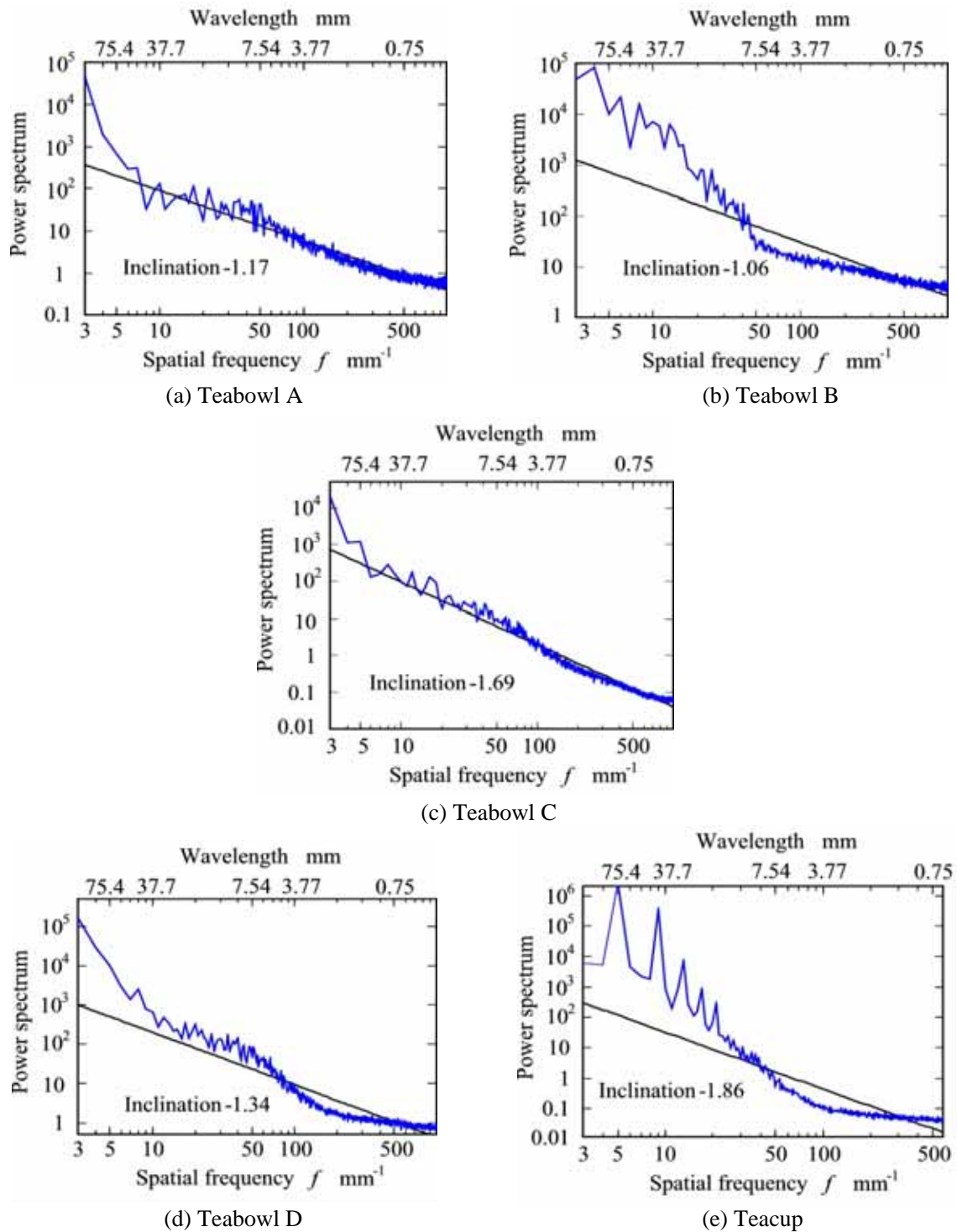


(d) Teabowl D



(e) Teacup

**Fig. 3** Teabowls and teacup measured



**Fig. 4** Topological characteristics of power spectrum vs. spatial frequency

approximation, in which the spatial frequencies of less than 3 and of more than 1000 are omitted, due to the influence of eccentricity and the resolution of the displacement sensor respectively.

The inclination of the approximation line is -1.34 for Teabowl A, -1.06. for Teabowl B and -1.17 for Teabowl C. The slope becomes flatter and approaches -1 in the high-frequency region of more than 100 for Teabowl A and 50 for Teabowl B. The spatial frequency of 100 corresponds to a wavelength of 3.77 mm when the outer diameter of the teabowl is 120 mm. The value of around  $-1$  means that the surface has  $1/f$  fluctuation characteristics. As can be seen in Figs. 3 (a) - (c), the surface topology of the teabowls contains a moderate combination of regularity and

irregularity. According to the aesthetic criteria adopted here, the handmade objects provide an eye-pleasing impression.

In the mass-produced objects, on the other hand, the inclination of the approximation line becomes larger: -1.69 for Teabowl D and -1.86 for the Teacup as shown in Figs. 4 (d) and (e). The five prominent peaks in Fig. 4 (e) indicate that the surface of the teacup contains specific periodic components. Taking  $1/f^2$  characteristics into consideration, the machine-made products present a monotonous, rather bland impression.

### 3. Design of Affective Shape with $1/f$ Fluctuation

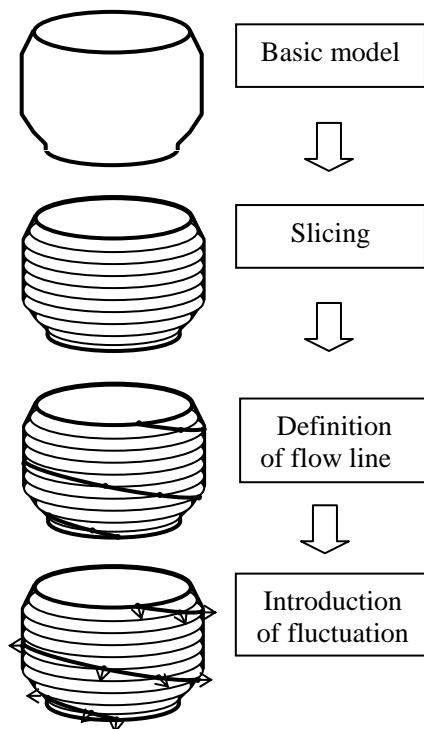
#### 3.1 Design Methods

In terms of the application of  $1/f$  fluctuation characteristics to product shape design, the present paper proposes two methods: one is the use of mathematical  $1/f$  waves and the other is the use of natural  $1/f$  ones.

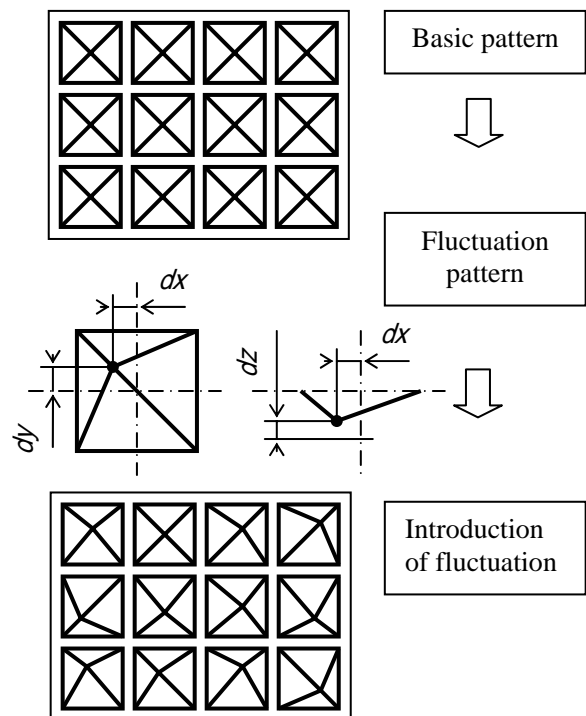
Regarding the mathematical  $1/f$  waves, we use the following equation derived from a chaos model [5]:

$$\left. \begin{aligned} x_{t+1} &= x_t + 2x_t^2 & (0 \leq x_t \leq 0.5) \\ x_{t+1} &= x_t - 2(1 - x_t)^2 & (0.5 < x_t \leq 1) \end{aligned} \right\} \quad (1)$$

Assume a process analogous to making a ceramic teabowl on the wheel. The process can be applied to realizing the surface with a  $1/f$  fluctuation on a 3D-CAD basis; wheel-thrown pottery has the possibility of incorporating fluctuations through manual pressure and/or rotational wheel noise. **Figure 5** shows the concept of the proposed method. A reference shape without fluctuations is first defined and sliced into thin layers. A spiral flow line is then assumed on the circumference. Shape fluctuations given by Eq. (1) are copied radially onto the intersections between the spiral and sliced planes. The arrows in the figure denote the direction of translation. An interpolation is necessary to obtain smooth surface fluctuations, because sudden changes in waveform are included in the  $1/f$  waves given by Eq. (1). The smoothing function used is defined by



**Fig. 5** Concept of generating shape fluctuations



**Fig. 6** Two-dimensional mapping of fluctuations

$$\left. \begin{aligned} r &= (1.0-s) r_1 + s r_2 \\ s &= (1.0 - \cos \pi t) / 2.0 \end{aligned} \right\} \quad (0 < t < 1) \quad (2)$$

where  $r$ ,  $r_1$ , and  $r_2$  are the radial coordinates on the polar coordinate system.

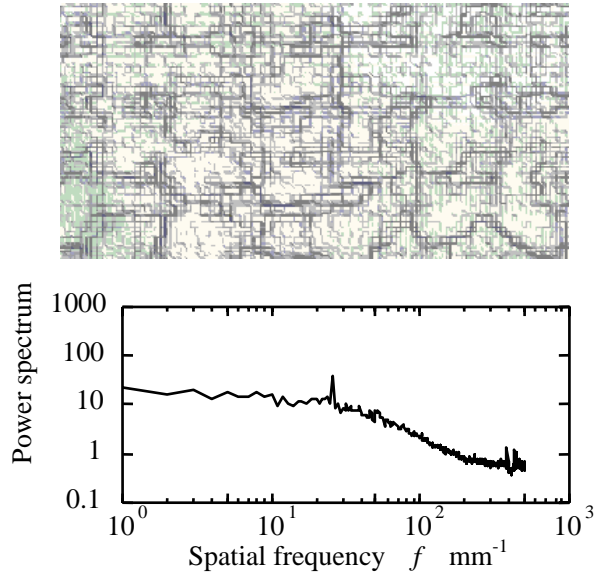
**Figure 6** schematically shows another way of incorporating  $1/f$  fluctuation characteristics. A reference shape without fluctuations is first defined: an equally-spaced array of quadrangular pyramids in this case. The apex of each pyramid is translated by  $dx$ ,  $dy$  and  $dz$  in the  $x$ ,  $y$  and  $z$  directions respectively. Note that the displacements given by Eq. (1) are composed as a three-dimensional vector quantity.

Regarding the use of natural  $1/f$  waves, a  $120 \times 120$  mm square wallpaper sample is selected. A three-dimensional stylus instrument with 0.05 mm-horizontal and 0.025 mm-vertical resolutions measures the unevenness of the surface. Roughness data of  $1024 \times 128$  are collected from a rectangular sample area  $102.4$  by  $12.7$  mm, where the measured points are as small as 0.1 mm in the  $x$  and  $y$  directions. Unexpected discontinuities in unevenness often appear as the stylus traverses the edges of the wallpaper. This may give rise to a high frequency in the spectrum. To avoid this singularity, the measured data are multiplied by the window function. The following Hanning window is used:

$$w(n) = 0.5 - 0.5 \cos \left( \frac{2\pi n}{N} \right) \quad (3)$$

where  $n$  is the number of measured points and  $N$  is the total data per cycle.

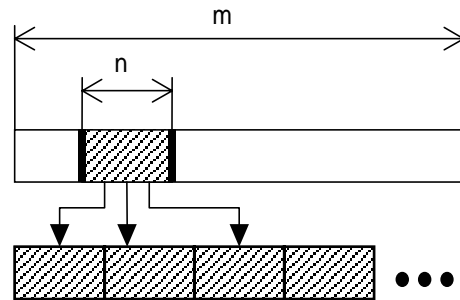
**Figure 7** shows the topological characteristics of the wallpaper tested: the upper picture shows a real CCD image and the lower diagram shows the power spectrum as a function of spatial frequency. The frequency means the wave number that is involved in the length of the wallpaper sample, 102.4 mm in this case. In the power spectrum, an inflection point can be recognized at a frequency of around 25, or a wavelength of 4 mm. The inclination of the characteristic line is approximately  $-1$  at high frequencies above the inflection point.



**Fig. 7** Wallpaper sample and its power spectrum vs. spatial frequency

The topological data sampled from the wallpaper, which includes the  $1/f$  fluctuation characteristics, is applied to the outer surface of a smooth teabowl. In using a part of the  $1/f$  wave data, the problem is how to connect the edges or boundaries of the patches smoothly, as a discontinuity or a large gap disturbs the  $1/f$  fluctuation characteristics.

**Figure 8** illustrates the method proposed for this purpose: selective duplication, where  $m$  is the length of the wallpaper referred to, and  $n$  is the length of the part used. A ‘continuous part’ of the  $1/f$  fluctuation data is



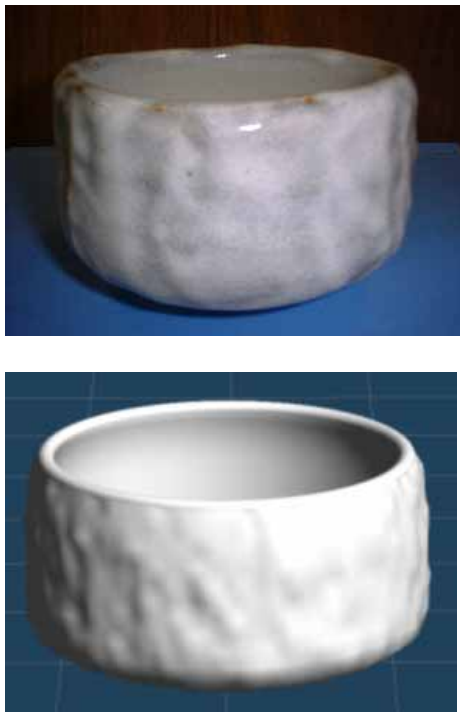
**Fig. 8** Generation of continuous data from patches with  $1/f$  fluctuations

selected and pasted on the periphery of the teabowl. The continuous part means that the sides of the patch have a similar wave pattern. The reference wallpaper is the same as that used in Fig. 7; 12.8×12.8 mm square patches are pasted on the outer surface of 120 mm diameter teabowl.

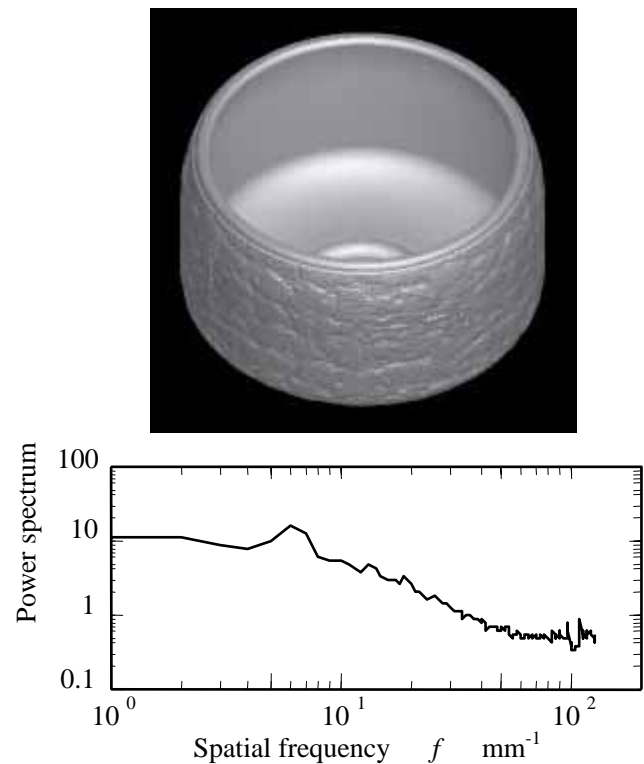
### 3.2 Examples of CG Image

**Figure 9** shows (a) a sample teabowl and (b) a computer graphics (CG) image of the teabowl on which shape fluctuations given by Eq. (1) are copied by the method shown in Fig. 5. A very similar surface pattern to the real one is achieved when 3% fluctuations with 12 orbits and 300 circumferential planes are postulated.

**Figure 10** shows the graphical image of the teabowl on which the surface unevenness of the wallpaper has been copied. The dimensions of the teabowl are: diameter 120 mm, height 77.5 mm and average wall thickness 5 mm. The maximum peak-to-valley roughness is set at 1 mm. Figure 10 also shows the power spectrum of the virtual teabowl as a function of frequency. A fluctuation pattern is produced which is similar to the real surface texture shown in Fig. 7.



**Fig. 9** Sample teabowl and CG image with 3% fluctuations with 12 orbits



**Fig.10** CG image of teabowl and its power spectrum vs. spatial frequency

### 4. Rapid Prototyping of an Affective Shape with 1/f Fluctuation

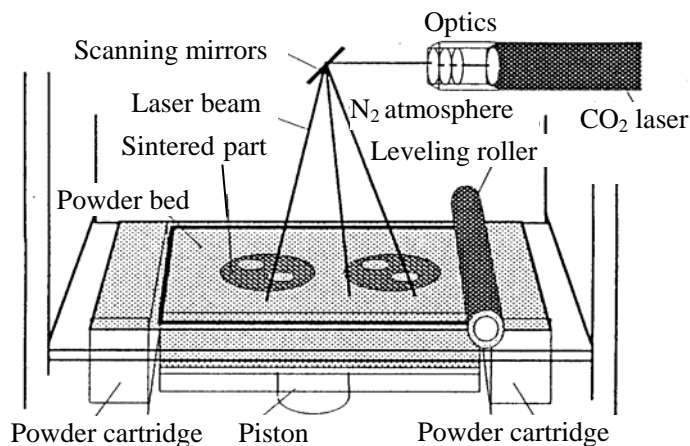
Objects with 1/f fluctuation characteristics have a high degree of complexity, so they are difficult to fabricate by conventional methods such as pressing and machining. Layered manufacturing technology [6], which enables the fabrication of 3D objects from CAD data, has developed rapidly during the past ten years. The method is suitable for the rapid prototyping (RP) of industrial products. The concept is that a model or component is first modeled by a CAD system. It is then converted into an STL file format that approximates the surfaces of the model by polygons. The STL model is sliced into cross-sections by computation, and the cross-sections are then systematically recreated layer by layer through the solidification of either liquid or powder. Besides liquid or powder, sheets of paper, resin or metal can be used to create the cross-section layers. These thin laminations are

glued together to form a 3D model.

Selective Laser Sintering (SLS) [7] is employed for this purpose. **Figure 11** shows a schematic diagram of the apparatus. A thin layer of heat-fusible powder is deposited onto the part-building platform within the process chamber. The cross-section layer of the object under fabrication is selectively scanned on the powder layer by a CO<sub>2</sub> laser. The irradiation of the laser beam raises the temperature of the powder to the melting point, fusing the powder particles to form a solid mass. When the cross-section is completely scanned, additional powder is deposited via a roller mechanism on top of the previously scanned layer. The processes are repeated by depositing successive layers of powder until the part is completed. The SLS process is characterized by the wide variety of powders that can be sintered, including metal, ceramic, sand and wax. The dimensional accuracy of the SLS fabricated part is 100 μm. DTM's Sinterstation 2500 PLUS with a nylon powder of 50 μm mean diameter (DuraForm) was used in the present study.

The reference teabowl's dimensions are: diameter 120 mm, height 75 mm and mean wall thickness 5 mm. The base end surface is divided radially into 60 equal parts, and a spiral line with three orbits is set on its circumference with a height of around 65 mm. In accordance with Eq. (1), a few percent of fluctuations against its radius are copied onto the circular plane.

**Figure 12** shows the rapid-prototyped teabowl when 5% fluctuations with 3 orbits are postulated. A fine pattern is generated by the SLS method, though a loop-like pattern and a polygonal shape can be recognized because of the rough modeling.



**Fig. 11** Schematic diagram of Selective Laser Sintering [7]



**Fig.12** Nylon teabowl with 5% fluctuations and 3 orbits



**Fig.13** Nylon teacup with arrays of 1/f fluctuation patterns

The method of two-dimensional mapping of  $1/f$  fluctuations shown in Fig. 6 is realized by the SLS method. **Figure 13** shows the teacup incorporating an array of square patches. The maximum outer diameter is 60 mm. The bland impression is somewhat improved by the application of the  $1/f$  property.

## 5. Conclusions

Methods of introducing  $1/f$  fluctuation characteristics into aesthetic objects have been developed with a view to designing for eye appeal as part of high-value added production. The major results obtained are as follows:

- (1) The surface topology of various teabowls is measured using laser metrology, and its wave pattern is then analyzed by the FFT method to clarify power spectrum characteristics.
- (2) The quantification of an affective factor involved on the outer surface shows that the handmade teabowl has an inclination of around  $-1$  in the power spectrum-spatial frequency diagram. The machine-made bowl, on the other hand, has an inclination of approximately  $-2$ , which gives a monotonous impression.
- (3) The  $1/f$  fluctuation characteristics are applied to the design of a model teabowl, for which three methods using mathematical and natural  $1/f$  waves are illustrated, and an attempt to create aesthetically pleasing objects is made using the rapid prototyping method.
- (4) The CG images and the three-dimensional objects substantiated show a correlation between  $1/f$  fluctuation characteristics and the aesthetic and affective qualities of handmade artifacts.

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