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Review

Fluctuation scaling of color variability in automotive metallic add-on parts

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ABSTRACT

Color matching between the car body and assembled add-on parts is a complex process that increases the costs and time in automotive manufacturing. We have investigated the statistical properties of color coordinates for color matching in automotive metallic coatings. CIELAB lightness L^*, red-green a^*, and blue-yellow b^* coordinates were calculated by using multi-angle spectrophotometric reflectance measurements from a broad range of metallic coatings from different manufacturers. We found that trial-to-trial L^* variations are related to a self-similar stochastic process. The sample variance and the sample mean value of L^* calculated over different viewing angles are correlated across painted pieces. A power function model describes the data quite well. This power function corresponds to a wide spread phenomenon known as fluctuation scaling in many engineering process. We also found that the sample skewness and the sample kurtosis of L^*, a^*, and b^* follow a U-shaped pattern and a generalized version of fluctuation scaling. The exponent of fluctuation scaling in the skewness–kurtosis plane depends on the cardinal directions, L^*, a^*, and b^*. This suggests that different flake-shaped pigments mediate trial-to-trial correlations of color coordinates. We conclude that fluctuation scaling provides a powerful approach for better prediction of lightness flop variations and for better color quality control between car manufacturers and suppliers of add-on parts.

Contents

1. Introduction

The metallic appearance of modern automotive exterior finishes is driven by color trends created by flake-shaped pigments [1–4]. Some examples of flake-shaped pigments are aluminum flakes, mica-based interference flakes, etc. with an average particle size of a few microns [5,3,4,6]. A crucial aspect in the automotive industry consists of color matching between car bodies and assembled add-on parts from different suppliers of door handles, bumpers, fenders, etc. (also called "color harmony") [7]. This is a complex issue because the appearance of metallic coatings depends on the

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Abbreviations: DIN, The Deutsches Institut fuer Normung; ASTM, American Society for Testing Materials; OEM, Original Equipment Manufacturer; CIE, Commission Internationale de l'Éclairage; CIELAB, CIE-1976 $L^*a^*b^*$ perceptual color space; L^*, CIE-1976 lightness, CIELAB units; a^*, CIE-1976 red-green, CIELAB units; b^*, CIE-1976 blue-yellow, CIELAB units; D65, CIE standard illuminant D65; A, CIE standard illuminant A; F2, CIE standard fluorescent illuminant F2; F11, CIE standard fluorescent illuminant F11.

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illumination and viewing angles and each supplier has its own paint procedure and manufacturer parameters. Therefore, incomplete color harmony is undesirable and delays car manufacturing in the production line. Fig. 1(a) shows an example of color harmony of a typical metallic-gray coating.

For each metallic-paint formulation, process monitoring of color harmony by direct visual inspection is insufficient and quantitative colorimetric methods are demanded. Multi-angle spectrophotomers evaluate reflectance spectra of surface coatings at different viewing angles as exemplified in Fig. 1(b). In automotive coatings containing metal flakes, the illumination angle is fixed at 45° from the perpendicular to the surface. The detection or viewing angle δ is defined from the specular reflection (usually called "aspecular" angle). At least three different aspecular angles are recommended [8]. DIN (The Deutsches Institut fuer Normung) prescribes the aspecular angle δ of 25°, 45°, 75° and optionally 110° [9,6]. The ASTM (American Society for Testing Materials) prescribes the aspecular angle δ of 15°, 45° and 110° [10,6]. Other industry standards for flake-shaped pigments have been proposed [11–13,6].

Reflectance spectra are transformed to color coordinates in the CIE-1976 $L^*a^*b^*$ (Commission Internationale de l'Éclairage) or "CIELAB" perceptual color space [14,6]. The CIELAB space is a three-dimensional abstract representation of color properties of surface materials and is recommended for industrial pigmented coatings [14,15,7,6]. There are three orthogonal axes in the CIELAB space: the luminance axis or L^*, related with brightness (i.e., white and black) ($L^* \geq 0$), and the red-green a^* and blue-yellow b^* axes that are related with chroma and hue properties of surface materials [14,15,6]. Both red-green and blue-yellow axes define the (a^*, b^*) color plane perpendicular to the L^* axis. $a^*>0$ and $b^*>0$ indicate reddish and yellowish, respectively whereas $a^*<0$ and $b^*<0$ indicate greenish and bluish, respectively [14,15,7,6].

Fig. 2(a) shows an optical micrograph of a typical metallic yellow coating containing aluminum flakes and conventional iron oxide absorption pigments [5,6]. Fig. 2(b) exemplifies for the same metallic yellow coating the CIELAB L^*, a^* and b^* color coordinates at the aspecular angle δ of 15°, 25°, 45°, 75° and 110°. Aluminum flakes act as tiny mirrors at the micron scale and produce specular reflection and scattering at the borders. Their size, morphology, and relative orientation mainly characterize the metallic effect [5,16,6,17]. Parallel alignment of metal flakes is the main responsible that the lightness L^* decreases as the angle δ increases by producing a "lightness flop" as shown in Fig. 2(b) [5,6]. Variations in a^* and b^* are also observed due to the presence of aluminum flakes covered by iron oxide but to a lesser extent as indicated in Fig. 2(b). The addition of iron oxide pigments produces selective light absorption and isotropic scattering and can also alter the steepness of the lightness flop curve [5,6]. Other flake-shaped pigments such as interference flakes can produce marked hue variations or a "color flop" in the (a^*, b^*)-plane [6].

Once CIELAB color coordinates of painted pieces are obtained from reflectance spectra, a selective criteria is implemented. For each metallic-paint formulation, a set of thresholds or color tolerance values are calculated from a reference or "master" panel [6,18]. Therefore for each painted piece, if CIELAB L^*, a^* and b^* values fall within the tolerance limit at each aspecular angle δ, then the piece is accepted in the color batch production otherwise it will be rejected [6,18]. However, process control of acceptability by defining color tolerances is limited because tolerances are specific for each metallic color and they are often valid only for a given illumination spectrum and certain viewing angles [6,18], ignoring texture effects [6,18], metameric comparisons [14,19], and trial-to-trial correlations of color variations in time series [20–22].

In previous studies, we have investigated trial-to-trial color variations in metallic coatings in the Fourier domain [21,22]. We have also investigated trial-to-trial reflectance variability by using principal components analysis [23–27]. In this paper, we use a very different approach to color harmony. We investigate whether color coordinates follow fluctuation scaling over a broad range of automotive metallic coatings from different manufacturers. Fluctuation scaling asserts that the sample variance σ^2 and the sample mean μ follow approximately a power function in many physical and engineering processes [28–31]:

$$\sigma^2 = \beta\mu^\alpha, \tag{1}$$

being β and α the amplitude and the scaling exponent, respectively. In Eq. (1), the larger the value of μ, the larger the variability σ^2 will be and this invariant scaling behavior leads to a power-law function dependency with $\beta>0$ and $\alpha \approx 2$ for a broad range of complex systems [29,28,32]. In comparison with previous works where color coordinates were analyzed by using Gaussian distributions [15], fluctuation scaling implies that the distribution of color coordinates does not necessarily follow a Gaussian shape as well as the existence of long-range correlations. This is plausible because CIELAB coordinates are derived from the CIE system by using a non-linear transformation [14,15,6], and reflectance spectra in metallic coatings change smoothly as a function of the

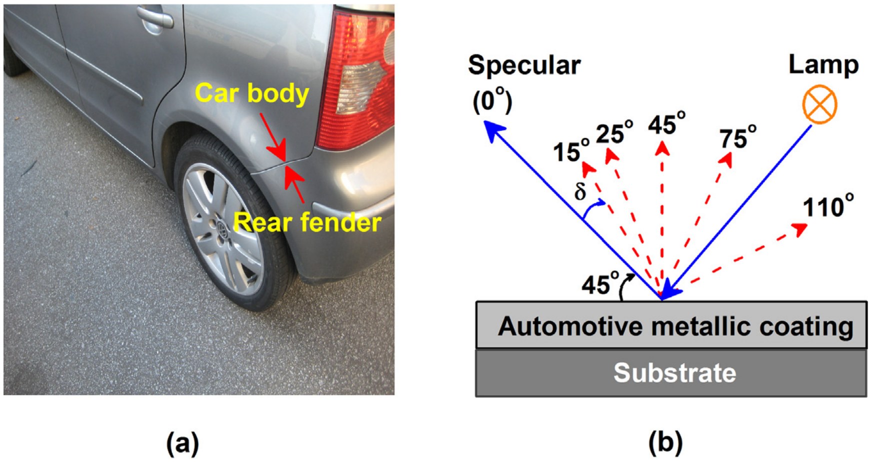

Fig. 1. (a) Example of color harmony in a metallic-gray coating. Color differences between external parts must not be perceptible by the naked eye, specially at the intersection of accentuated curved parts such as between the car body and the rear fender. (b) Schematic representation of a typical multi-angle spectrophotometer for automotive metallic coatings. The directional illumination is fixed at 45° from the perpendicular to the surface. The detection positions are defined as a function of the angle δ from the specular reflection at 15°, 25°, 45°, 75° and 110°, respectively.