Technical Paper

Setting New Standards for Appearance Measurement of Paint Quality

For many years measuring methods used for characterising the paint quality of automotive surfaces have been highly complex and held mainly in the domain of experts. In order to achieve a quick and uncomplicated quality evaluation, manufacturers would instead prefer to use a fast measurement system that provides quantitative results with fixed, reliable and correlated scales.

After several years of collaboration with specialists from Volkswagen AG, Rhopoint Instruments Ltd have developed an innovative hand-held measuring device that reproduces human perception – the Rhopoint Total Appearance Measurement System (TAMS)™.

The appearance of painted surfaces is of paramount importance to all premium coatings companies and particularly automotive manufacturers, since the first visual impression of the surface quality of a product that the customer gets can have a considerable effect on the subsequent purchasing decision. The quality of painted surfaces should therefore be perceived by the customer as visually appealing, which is influenced by the colour and particularly the structure of the surface.

Conventional measuring instruments rely on users who interpret the highly complex values of several measuring devices as an actual visual appearance. This can lead to ambiguous communication about the nature of surfaces, e.g. between the manufacturer and the companies that supply add-on parts. Difficulties in correlating between measured values and the visually experienced impression can result in a finish that does not fulfil the manufacturer's expectations, even though all of the conventionally measured parameters are within tolerance.

In order to optimise the painting processes, several years ago Volkswagen AG initiated a comprehensive innovation project which dealt with examining and improving the basic procedures in measuring automotive finishes, amongst other things. An important part of the project was intensive investigation of human perception, which was carried out at AUDI AG. The joint development of definitions and computing models was needed for a comprehensive description of the visual impressions of the observer.

The human eye looks at surfaces by running through two different types of focusing – focusing on short distance for evaluating surface structure and defects, and focusing on the reflections and contours of a surface at so-called showroom distance, i.e. the distance of approx. 1.5 m which an observer generally adopts for visual evaluation.

When doing this, the observer's brain runs through various estimations and the basis for their reaction is: "Does the product look good"? or "Do neighbouring parts have a harmonious and homogeneous effect"?, processes which ultimately have an effect on the purchase decision.

The TAMS simulates these processes by imitating the functions of the human eye and mapping the mechanisms that take place in the brain using double focus image technology and imaging and computing systems at a high-tech level.

Measurements are based on the principle of the “human feeling reaction” which can be expressed as:

Vision, Perception, Emotion

With compact format (175mm × 55mm × 140mm) and low weight (1080g), the TAMS (figure 1) is designed for in-line production use for quick appearance measurements on automotive surfaces. The TAMS is easy to handle and can be used on a large range of surfaces on a car thereby covering most of the critical perception points on the body. Image acquisition and computation takes approximately 4sec each. Several measurements can be performed on the target surface by the user after which TAMS provides averaged results. The system is powered by two lithium-ion batteries allowing up to 2000 continuous measurements to be made for more than 5 hours. The innovative “My Car” functionality allows a full car database to be configured in the instrument for easy measurement and data classification, post-analysis and automatic PDF report publication.

Figure 1: TAMS instrument

The TAMS measurement is based on a dual-focus imaging system combined with an image pattern generator (Figure 2). An integrated LCD screen is used to generate fringe patterns and a dual focus camera captures the reflected images (focusing surface or screen). The TAMS records these images at the different focus levels and computes the characteristics with the aid of perception algorithms. A powerful processing unit (1Ghz cortex A8) provides fast image processing and computation.

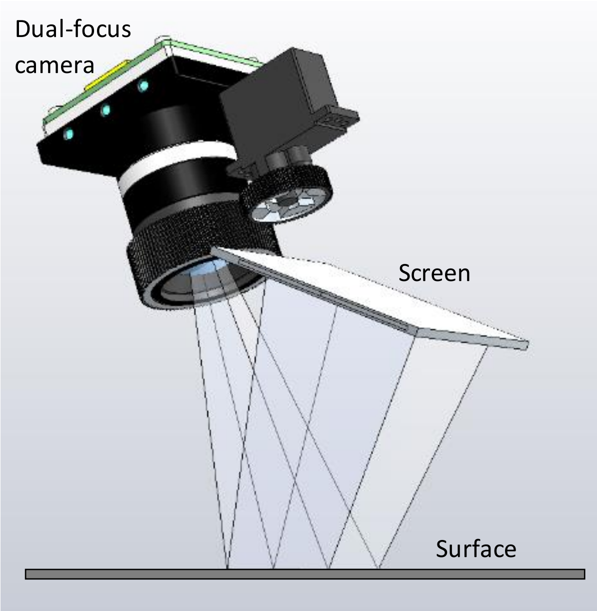

Figure 2: Optical Design

Based on this knowledge, special recording of the visual appearance impression is possible. Easily understandable measured parameter were chosen which make clear communication between all internal and external links responsible in the vehicle delivery chain possible.

The Rhopoint TAMS™ uses four parameters to produce a comprehensive description of the visual sensation:

Contrast (C) – Sharpness (S) – Waviness (W) – Dimension (D)

These characteristics have been selected to be the most involved in visual perception and brain mechanisms mimicking the subconscious process in the observer's brain.

Typically an observer would react either positively or negatively: good or bad, so this is exactly what QC inspection want to predict in production using an effective Quality index that correlates to the observers feeling.

Quality (Q)

The quality value is calculated using a mathematical combination of some of the basic's parameter indicated above. The Quality index ranges from 0 to 100 and uses a combination of Sharpness and Waviness. A contrast correction factor has also been included in the calculation, which will be explained in detail later in this paper. In brief, low contrast surfaces such as white or silver metallic are perceived slightly differently than high contrast surfaces like deep black especially in terms of sharpness. The Quality value helps to give the observer visual preference. In addition, the observer has the visual ability to detect orange-peel texture variation between two parts side by side. For this, the TAMS can also calculate the Harmony value between two parts:

Harmony (H)

The Harmony value represents the statistical "delta appearance" acceptance in terms of *surface texture* between two surface finishes standing side by side. For this calculation TAMS uses Waviness and Dimension values but in case of significant difference of either Contrast or Sharpness (that are not used for the Harmony calculation) a warning can be displayed. Harmony is a positive value which ranges from 0 to 1 if the "delta acceptance" (texture) is statistically acceptable. If not the value is greater than 1.

Finally, when TAMS is used by an operator on a production line they want to know if the paint quality is an acceptable range for a certain car model and if it looks homogeneous using Q and H. Ultimately a paint production engineer who wants to improve the painting process can also directly use the basic parameters C, S, W and D. It is worth noting that with TAMS, automotive manufacturers and paint suppliers can significantly improve the communication using this new TAMS standard visual appearance language to better understand the large variety of perception (Figure 3).

Figure 3: Reflective surface appearance examples

Contrast (C)

The contrast of a reflected image characterises the difference in intensity between dark and light areas. In the case of a painted car body, we refer mainly to the contrast of the glossy coating because of the reflection produced by the surface. Contrast represents the ratio between darker and lighter intensities in the reflected image environment. It is worthwhile noting that in order to perceive contrast an appropriate environment is required containing variable intensity distribution populated with different objects in the surrounding scene. For instance, a black glossy paint can produce deep black and high white colour reflections. Therefore, the contrast is usually high for such surface finish (C > 90%, Figure 4 right). On the other hand, for light paint colours such as white or silver metallic it becomes difficult to distinguish objects in the reflected image, in which case, the contrast is usually low (C < 50%, Figure 4 left).
TAMS incorporates Michelson's definition for the calculation of a global contrast C.

Contrast value is further used in the Quality algorithm allowing a corrective factor to be applied accordingly to compensate for changes in perception sensitivity.
This is defined by the following relationship:

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{\min}} \times C_{max}^{-1} \times 100$$

Where I_{max} and I_{min} represent the maximum and minimum intensities of the reflected image and C_{max} the maximum contrast value obtained for a perfect silver mirror glass by:

$$C_{max} = \frac{I_{max}^{silver} - I_{min}^{silver}}{I_{max}^{silver} + I_{\min}^{silver}}$$

In practice TAMS displays a fringe pattern with a low-frequency (f_0) sinusoidal intensity profile (large black and white bands) and the camera captures the reflected image by focusing onto the screen.

Figure 4: Real-Life Situation, Low Contrast Reflection (Left) and High Contrast reflection (Right)

Sharpness (S)

The sharpness of a reflective surface describes its capability of reflecting the environment with detail. When a surface is viewed closely (<30cm) a sharper and more detailed reflection gives a good feeling to an observer. Also at a typical showroom viewing distance (>1.5m) the sharper and less hazy a surface appears the better the visual sensation.

To quantify Sharpness TAMS uses the Optical Transfer Function (OTF) principle. This function is defined as the relationship between the contrast (as defined previously) of a reflected periodic pattern and its frequency (Figure 5).

$$OTF(f_i) = C(f_i)$$

This function is descending and its rate of fall off and shape depend on the sharpness of the surface. As an example, typical OTF curves are shown in Figure 5 of 10 different panels with sharpness values range from very good (panel #1) to very poor (panel #10).

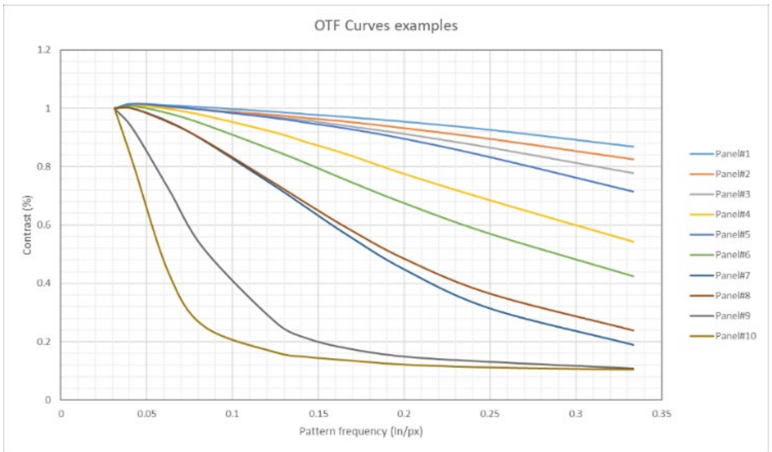

Figure 5: Optical Transfer function examples

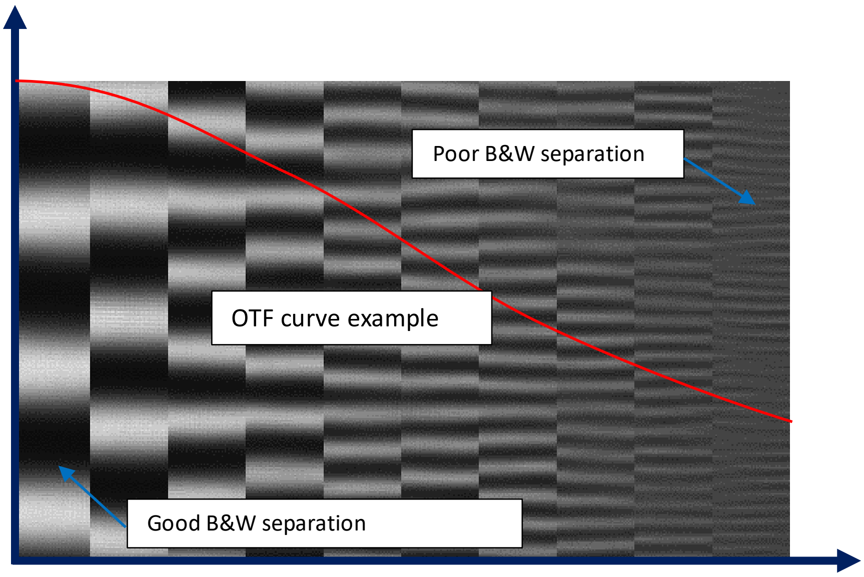

Figure 6: Reconstitution of successive fringe pattern images by TAMS and superposition of OTF curve (Contrast Vs Frequency)

In practice, TAMS displays several periodic fringe patterns with different frequencies and then calculates the contrast value $OTF(f_i) = C(f_i)$ for each of them (Figure 6). After having calculated the OTF curve of the surface, the TAMS then performs a pseudo-integration computation of the area under the curve that defines the sharpness value. To be colour independent, a correction coefficient is applied all along the curve, in such a way that the curve always starts with $OTF(f_1) = 1$ for the lowest frequency. Finally, the sharpness value is obtained by the following relationship:

$$S = \sum_{i=1}^{n} a_i OTF(f_i) \times \left(\sum_{i=1}^{n} a_i OTF^{silver}(f_i) \right)^{-1} \times 100$$

The original Sharpness value S has no waiting in the curve so $a_i = 1 \; \forall i \in (1; n)$. But recently a new Sharpness value called S_Q (Sharpness for Quality) has been introduced to include a contrast correction and now S_Q depends onto $a_i(C)$ coefficients, where C is the first TAMS parameter calculated. In the real-life, low and high sharpness values would look as shown in Figure 7.

Figure 7: Real life situation, Low (Left) and High Sharpness (Right)

Waviness (W)

Waviness describes the disturbance level of the reflected image caused by orange peel. This phenomenon is mainly caused by two parameters: the paint process and the under layers (e-coat aspect and raw material quality). Both can lead to either a very wavy (Figure 12 left) or very smooth (Figure 12 right) surface finish. TAMS quantifies the global waviness level that produces image deformation and the non-smooth aspect of the surface. To quantify waviness, the TAMS employs an innovative approach that uses a line deformation analysis technique designed to replicate the human eye process and brain mechanisms. TAMS displays perfectly straight lines onto the surface and the camera captures the deformed line reflection images (Figure 8).

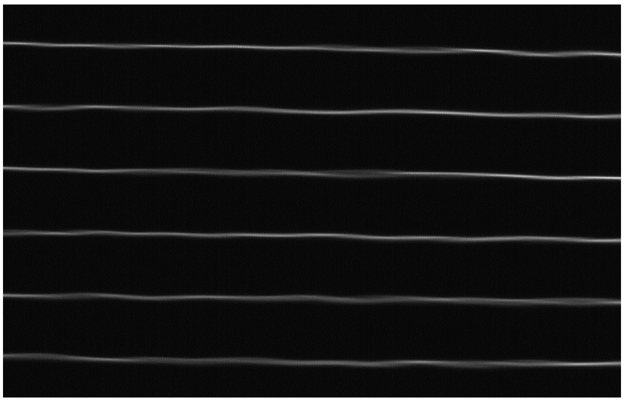

Figure 8: Reflected line images captured by TAMS

Post processing compares the displayed and reflected lines and computes the deformation amplitude. The field of view and optical design of the TAMS was configured to be compatible with the visual perception at a viewing distance of 1.5m.

Practically, the internal screen of the TAMS displays several parallel and straight lines toward the surface. The camera is focused onto the internal screen and an image of the reflected straight lines is acquired (Figure 8). A specifically tailored algorithm is then used to detect and track the lines across the image (Figure 9).

Figure 9: Reflected line images + detection results by LDA algorithm

After full line detection has completed TAMS performs more computations to isolate and extract deformation all along the lines (Figure 10).

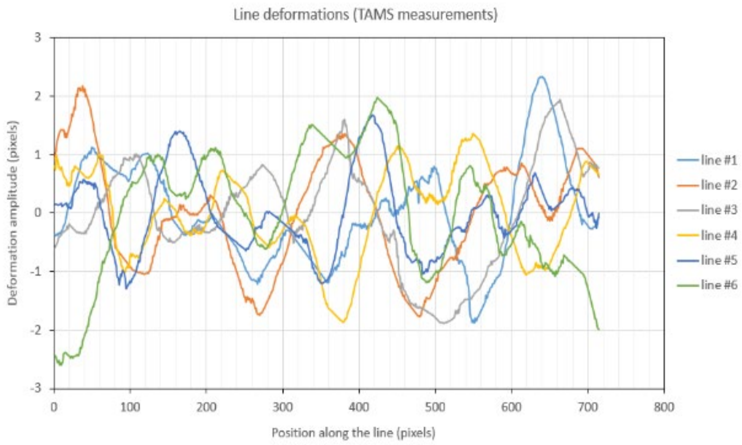

Figure 10: Line Deformation Curves

It then computes the Fourier Transform to get the spectrum representing the energy contained in the deformations (Figure 11).

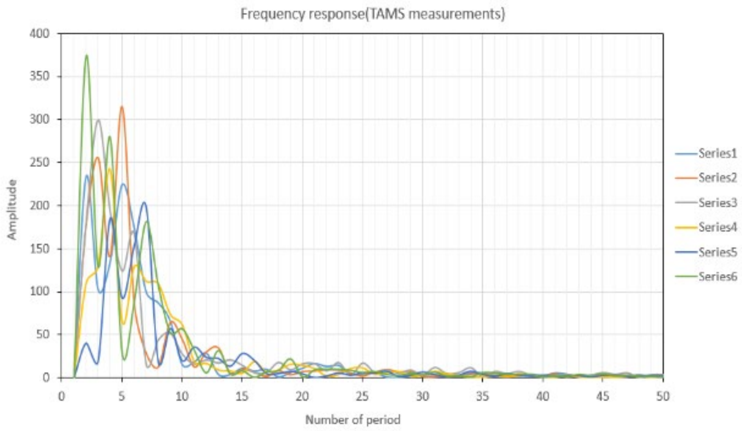

Figure 11: Line Deformation Spectrum

Finally, the pseudo-integration of the spectrum along a specific frequency range provides the waviness value of the surface:

$$W = \left(\sum_{i=1}^{n} F(p_i) \right) - W_{min}$$

Where $F(p_i)$ represents the deformation spectrum, $(p_1; p_n)$ the range of integration and W_{min} the minimal Waviness value obtained for a perfect silver mirror glass by:

$$W_{min} = \left(\sum_{i=1}^{n} F^{silver}(p_i) \right)$$

The advantage of this technique is that TAMS is directly measuring the visible deformation of a real image pattern after reflection, as the human eye would do naturally.

In comparison to measuring the surface topography, the TAMS “sees” and quantifies the same optical deformation to the human eye, taking into account the reflectivity of the surface and many other real-life parameters that could influence the final waviness perception like pigment effects, contrast, microstructures etc.

In the real-life, high and low waviness perception would look as shown in Figure 12.

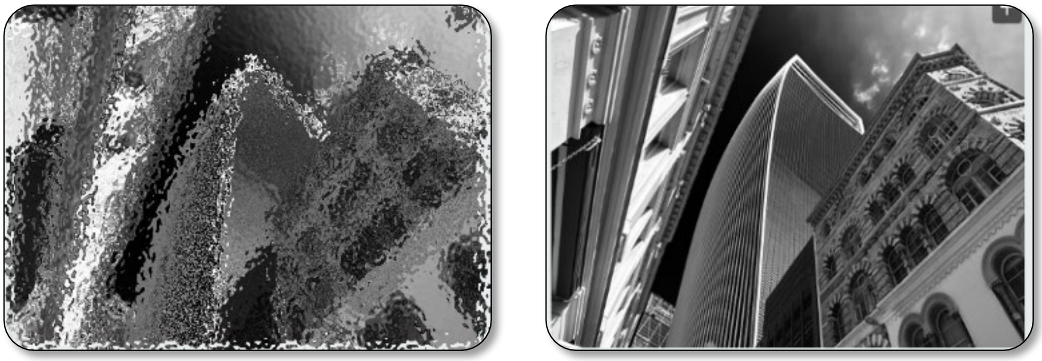

Figure 12: Real-life situation, high (left) and low Waviness (right)

Dimension

As previously detailed waviness is a very important parameter to measure as waviness describes the overall level of visible waves or structures that are affecting the surface appearance quality. It is well known that in this visible wave spectrum the human eye can discriminate one dominant structure size among the mix of wavelengths when looking at a glossy surface finish.

Therefore it is important to define which wavelength is dominant. As the waves and structures are "randomly" distributed the brain computes a sort of average in the field of view. Consequently, it is possible to get two surface finishes that have a similar waviness value (global disturbance level), but different visual structure appearance to the human eye. This situation usually happens when the Dimension value is different between each surface. This is the reason why TAMS also includes Dimension as a measurement parameter. This parameter will be further used for harmony calculation.

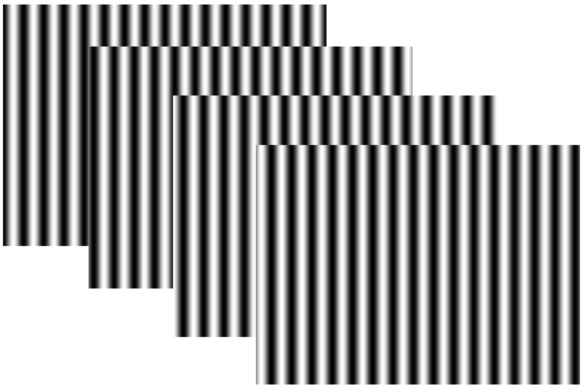

Figure 13: Shifted fringe pattern used for PMD

To quantify the dimension value, TAMS uses the Phase Measurement Deflectometry technique. This technique uses a series of sinusoidal fringe patterns all shifted by a pi-multiplier (Figure 13).
The camera acquires images while focusing on the surface and after computation the 2D curvature field is finally obtained (Figure 14).

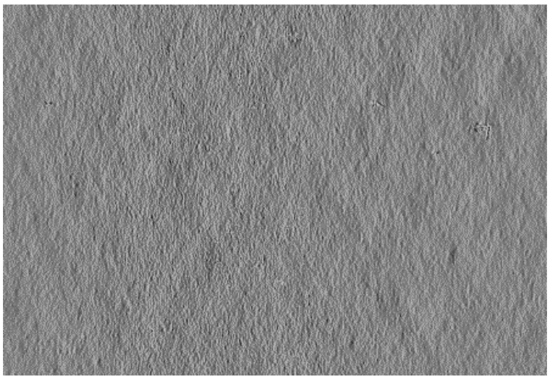

Figure 14: Surface Curvature Map

Using the 2D field, TAMS computes a global horizontal Fourier Transform to obtain the spectral response which is a function of the wavelength on the surface (Figure 15).

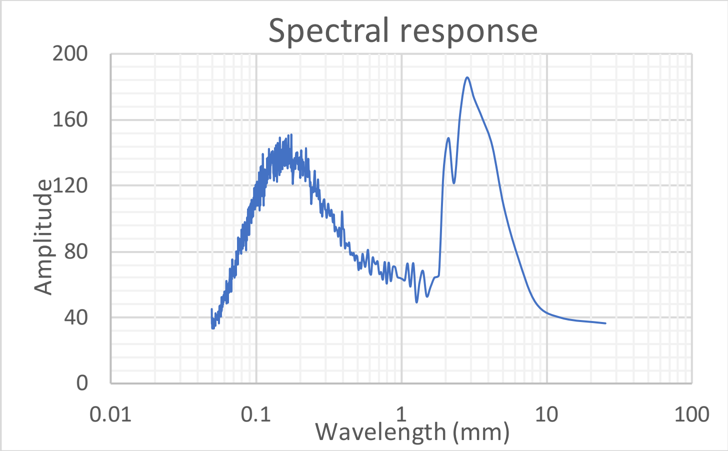

Figure 15: Spectral response of the surface

This spectrum is like a "fingerprint" of the surface and is the result of TAMS looking at the surface, but using the instrument sensitivity instead of the human one. Therefore, to correlate with human perception, a sensitivity correction is applied. This function called Contrast Sensitivity Function (CSF) is applied onto the initial spectrum or "Raw spectrum".

A typical example of the CSF is shown below on Figure 16.

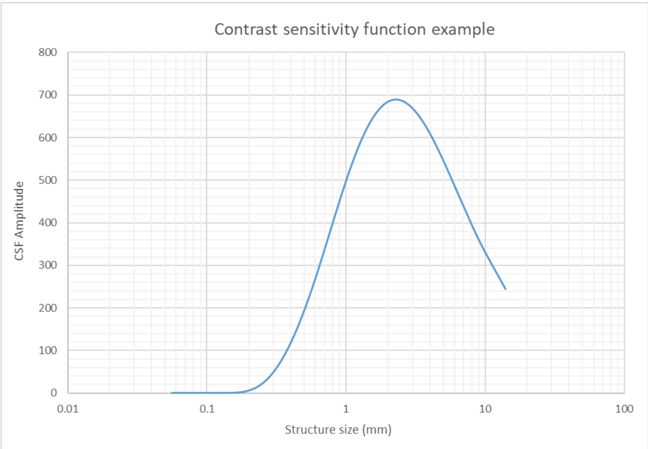

Figure 16: Contrast sensitivity function

CSF reduces the influence of non-visible structure areas and increases the more visible part, mimicking human vision capability. After correction, a new spectrum is produced and TAMS extracts the dominant peak position which represents the dominant structure size. The Dimension value D is given by the following relationship:

$$F_c(D) = \max(F_c)$$

Where F_c is the corrected spectral response and $\max(F_c)$ its maximum. In the example in Figure 17 the Dimension is equal to 3mm.

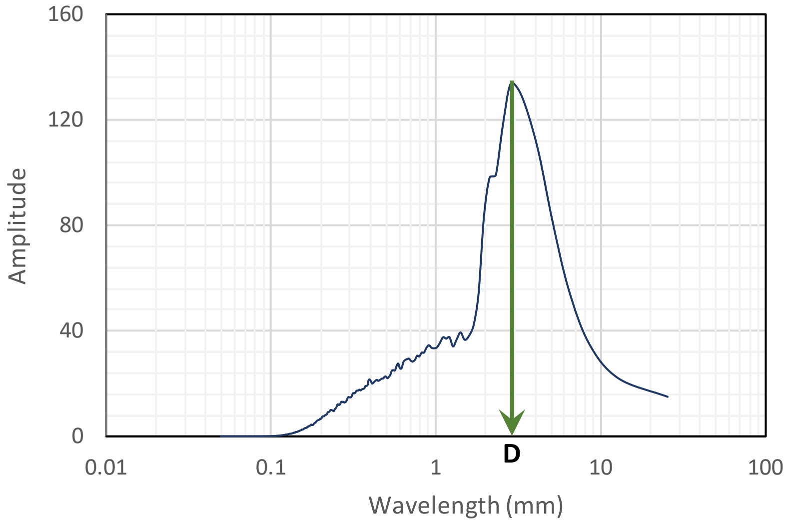

Figure 17: Spectral response corrected with CSF

In real-life, low and high dimension values would give the perception shown in Figure 18.

Figure 18: Real-life situation, small Dimension (left) and large Dimension (right)

Quality

As explained at the beginning of this paper, the main objective of TAMS is to provide a quick and uncomplicated quality evaluation. To achieve this the four parameters described above are used to define two new quality metrics - Quality and Harmony.

The Quality value intends to be used to obtain the "observers visual quality preference", in fact an observer will invariably always prefer a high glossy smooth surface. Also, the car and paint manufacturer want to know the paint quality in terms of "expected customer point of view" when related to their paint process allowing them to adjust it according to different quality grades depending on car model.

To get the "preferred feeling", the human brain subconsciously mixes Sharpness and Waviness together to obtain a quality emotion. In fact, a "flat surface finish" is likely to be preferred in comparison to a "wavy surface finish". Also, a "sharp and clear" reflected image is preferred in comparison to a "hazy and blurred" reflection. There is no evidence that the Dimension value is involved in the surface finish preference, therefore this parameter is not used for Quality calculation.

When using TAMS the user must make several measurements on the target surface so it can compute average values of S_Q and W. The algorithm will then slightly adjust S_Q and W values to correlate to visual sensitivity and also to set a compatible scale:

$$S_Q^* = f_1(S_Q)$$

$$W^* = f_2(W)$$

Where f_1 and f_2 are two non-linear functions that have been experimentally adjusted to get best final perception ranking fit. Finally the quality value is obtain with a combination of S_Q^* and W^*:

$$Q = a \times S_Q^* + b \times W^*$$

Where a and b are two variable coefficients allowing a smart balance between S_Q^* and W^*.

Different real-life quality surfaces are shown in Figure 19.

Figure 19: from left to right; low, medium and high painted surfaces quality

Harmony

The second main target value provided by TAMS is Harmony.

This value quantifies the statistical "delta appearance" acceptance in terms of *surface texture*. In other words, this value statistically answers the question: "Would most of the customer accept the visual texture surface difference between two panels next to each other? Yes, or no". We call that difference sensation the Harmony between two panels. Harmony is independent to Quality. Two panels can have the same quality customer acceptance, but different orange peel perceptions. Also, two panels can have good orange peel acceptance but different quality, because of sharpness variations between each other.

To obtain the visual structure difference (Harmony) the human brain subconsciously concentrates on the Waviness and Dimension characteristics. TAMS uses an algorithm developed in collaboration with AUDI to calculate Harmony. As for the Quality value, the user must make several measurements on the surface to get averaged values $\overline{W}$ and $\overline{D}$.This algorithm is based first on calculating delta-Waviness dW and delta-Dimension dD between two surfaces. The first surface is the surface to check (X) and the second one as the appearance "reference" (R).

$$dW = |\overline{W_X} - \overline{W_R}|$$

$$dD = |\overline{D_X} - \overline{D_R}|$$

Then dW and dD are transformed respectively to dW' and dD' to fit with visual perception and obtain a compatible scale:

$$dW' = a \times dW$$

$$dD' = b \times dD$$

Where a and b are two coefficients obtained experimentally. Then to finish we have:

$$H = \mathrm{c} \times f(dW', dD')$$

Where f is a non linear function of dW' and dD', and "c" a correction coefficient in order to obtain the value $H_{limit} = 1$ as the statistical acceptance limit. Directly from laboratory, experiments values for H< 1 indicates an orange peel difference which is statistically accepted, and for values $H < 1$ are not accepted.

In use operators using TAMS are able to adjust the Harmony limit for their paint process. Experimentally, the value $H_{limit} = 1.5$ is considered in general as an acceptable limit. Figure 20 shows two painted surface finishes whose harmony would not be accepted because of significant differences in waviness and dimension.

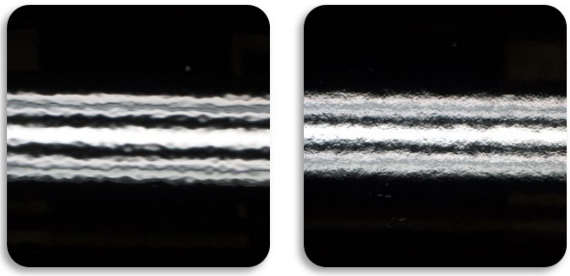

Figure 20: Example of two surface finishes whose harmony would not be accepted

Conclusion

Based on optical metrology, the Rhopoint TAMS™ is a significant step forward in the measurement of automotive and premium high-gloss coatings, because it quantifies the visual experience and makes it easier to interpret and pass on the results. The technology of the Rhopoint TAMS™ provides a comprehensive view of a wide variety of surfaces, from steel as a carrier material to the various intermediate layers such as KTL and filler and as far as the top coat. The Rhopoint TAMS™ therefore helps to optimise the surface finish and provides new quality criteria that are not subject to the subjective influences of visual evaluation.

The universal technology of the Rhopoint TAMS™ will make other customer-specific evaluations methods feasible in the future, whereby Industry 4.0 plays an important role.