Technical note

Improving the optical characteristics of a polycarbonate visor for use in a fencing mask

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Abstract

A fencing mask with a transparent polycarbonate visor has recently been introduced which replaces the conventional metal mesh mask. The visor is constructed using two polycarbonate sheets, one forming the structural layer and the other a removable scratch plate. This multilayer system has inherent disadvantages with regard to optical transmission, since the intensity of reflected light is related to the difference in refractive index of the materials. As such, a large step change in refractive index leads to greater reflective losses, thereby lowering the intensity of transmitted light. The magnitude of this reflective loss may be calculated using the Fresnel equations.

Light scattering and the appearance of a 'ghost' image are a manifestation of the Fresnel reflections. Light reflected at one surface undergoes internal reflection and thus appears to originate in a different optical plane. Since there are reflective losses at every interface, it is essential to reduce the reflectivity at each step.

Results presented here show that the optical properties of an air-filled multilayer system offer substantially lower transmission than a liquid-filled structure. Modelling of this simple modification to the existing mask design has been shown to increase the theoretical transmission of light by a minimum of 7%, with experimental work substantiating these findings.

Keywords: fencing mask, reflective loss, polycarbonate visor

Introduction

A new fencing mask (Leon Paul Equipment Company, 2000) has been developed to fulfil one of the FIE (Federation International d'Escrime) and Olympic Association requirements for the modernization of fencing as a sport. The major difference between the existing fencing mask designs and the new mask is the presence of a transparent polycarbonate (PC) visor which allows unobstructed vision by the wearer.

The visor comprises two sheets of polycarbonate, an internal structural layer 3-mm thick, and an outer scratch plate 0.5-mm thick clamped on top. Whilst this allows the scratch plate to be replaced when damaged, the multilayer polycarbonate structure affects the transmission of light since reflective loss occurs at each boundary where there is a change in refractive index. The magnitude of reflective loss increases as the refractive index step height increases, and may be calculated using the

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Fresnel's equations. The multilayer structure doubles the number of reflective boundaries and this significantly reduces the transmission of light.

Light reflected at an internal boundary may undergo internal Fresnel reflections due to the multilayer structure and this can give rise to 'ghost' images or outlines which may be observed by the wearer. This is especially true for highly illuminated objects.

Since reflective loss is determined by the refractive index step height, it follows that a reduction in the step height can reduce the magnitude of reflective loss at each boundary. If the refractive index of the gap layer can be increased to a value that is nearer to that of polycarbonate, the Fresnel reflections will be much weaker, and as a consequence any ghost images would be less intense. One method of achieving this is to coat the inner polycarbonate surfaces with a thin polymer film, an antireflective coating. For this system, the AR Coating would have a refractive index between that of polycarbonate and air. This method is expensive and complex, and as such will be discussed for the purposes of comparison only. Theoretical modelling of a visor with a 0.1-mm thick Teflon AF coating ($n = 1.31$) has been included; however, most low index materials suitable for use as antireflection coatings are very soft, and would be easily damaged in the circumstances in which fencing masks are used.

We have concentrated on a novel liquid-filling method for reducing reflective loss. This involves replacing the air layer with a suitable liquid to increase the refractive index between the polycarbonate sheets. This could be sealed using a narrow rubber gasket; however, capillary action was found to be sufficient during trials. Several liquids are available which have refractive indices approaching that of polycarbonate ($n = 1.585$); however, we will show that the reflective losses can be significantly reduced, and hence the transmission of light over a broader angle of incidence increased by using a cheaper and more common alternative, water. This has a refractive index of 1.333, and is significantly closer to that of polycarbonate than air ($n = 1.0$), thereby reducing Fresnel reflections significantly.

Calculating the reflective losses

When light is incident on a boundary between two dielectric media with different refractive indices, a portion of the light is reflected and the remainder is transmitted. This transmitted portion is also refracted since the change in refractive index affects wavefront velocity, as shown in Fig. 1.

The angles from the normal for the incident (i), transmitted (t) and reflected (r) components may be calculated using Snell's laws, which state

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \tag{1}$$

$$\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1} \tag{2}$$

$$\theta_i = \theta_r \tag{3}$$

The magnitude of the reflected and transmitted components may be calculated by using Fresnel's equations (Wilson & Hawkes 1989). These equations differ depending whether the electric field vector of the incident light is parallel (||) or perpendicular (⊥) to the plane of incidence and can be used to calculate both reflected (E_r) and transmitted (E_t) components.

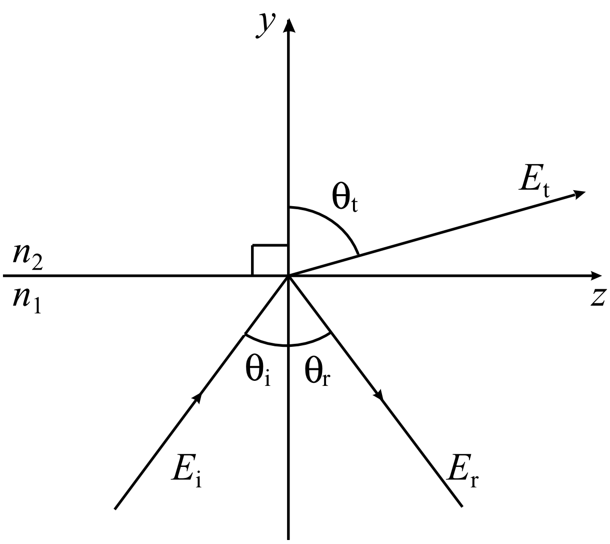

Figure 1 Illustration of a reflection at a boundary interface between two materials with different refractive indices.

The Fresnel equations (Pedrotti & Pedrotti 1997) are:

$$\frac{E_r^{\perp}}{E_i^{\perp}} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \tag{4}$$

$$\frac{E_r^{\parallel}}{E_i^{\parallel}} = \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \tag{5}$$

$$\frac{E_t^{\perp}}{E_i^{\perp}} = \frac{2n_1 \cos\theta_i}{n_1 \cos\theta_i + n_2 \cos\theta_t} \tag{6}$$

$$\frac{E_t^{\parallel}}{E_i^{\parallel}} = \frac{2n_1 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \tag{7}$$

In all cases. the relative intensity of the reflected component, the reflectivity coefficient R, is given by:

$$\left(\frac{E_r}{E_i}\right)^2 = \frac{I_r}{I_i} = R \tag{8}$$

By multiplying this value by 100 it is possible to obtain the intensity of reflected light as a percentage of the incident light.

To apply this model to a real world system, such as the existing Leon Paul Vision 2000 mask, and our new liquid-filled visor, a number of assumptions must be made. These are:

1 The TE and TM field vectors must be treated independently.

2 Light reflected at a surface resulting in internal and multiple reflections is accounted for in the software algorithms used. This change in transmission with angle is actually an interference effect.

3 There are no absorptive processes to reduce the intensity of transmitted light.

Since there is a change in the refractive index at each boundary, the transmitted light undergoes refraction; this results in an angular change which may be calculated using Eq. (1). Since the angle of incidence affects the relative intensities of both reflected and transmitted light, it is important to include these modifications in the calculations.

Using the assumptions stated above, calculations showed a 17.2% reduction in total transmitted light for the vision 2000 system, compared to only 10.1% for the liquid-filled structure. It should also be noted that the largest reflective losses were observed at the air/polycarbonate boundaries, these being 4.3% for both the air/PC and PC/air boundaries. The PC/water and water/PC boundaries gave reflective losses of 0.74% each under the applied conditions. These calculations were performed using an initial incident angle of 10°, with the appropriate refractive indices (PC = 1.585, water = 1.33 and air = 1.0). Layer thickness was not factored into the calculations, as the internal losses in the polycarbonate are insignificant.

Theoretical modelling

All theoretical data presented here have been calculated using our in-house software, LPRO. This is designed to model waveguiding structures, and may also be used to determine reflective losses and total transmission using Fresnel's equations. The software is based on a transverse matrix algorithm. Modelling parameters were an air/water layer of 0 → 1 mm thickness, with the effects for a range of incident angles (0 → 45°) monitored using a 0.1-mm thick layer.

Air-filled visor

The air-filled visor is in essence a three-layer system, with the structural and sacrificial polycarbonate layers ($n = 1.585$), being 3-mm and 0.5-mm thick, respectively, surrounding a thin air gap ($n = 1.0$). The large refractive index step height gives rise to reflective losses at each boundary interface, and the transmission intensity is shown as a function of layer thickness (0 → 1 mm) in Fig. 2. This demonstrates a mean transmission value of 91% ± 9%. However, Fig. 3 indicates that the transmission intensity also varies with incident angle, with intensity of transmission approaching a maximum as the incident angle approaches 30°.

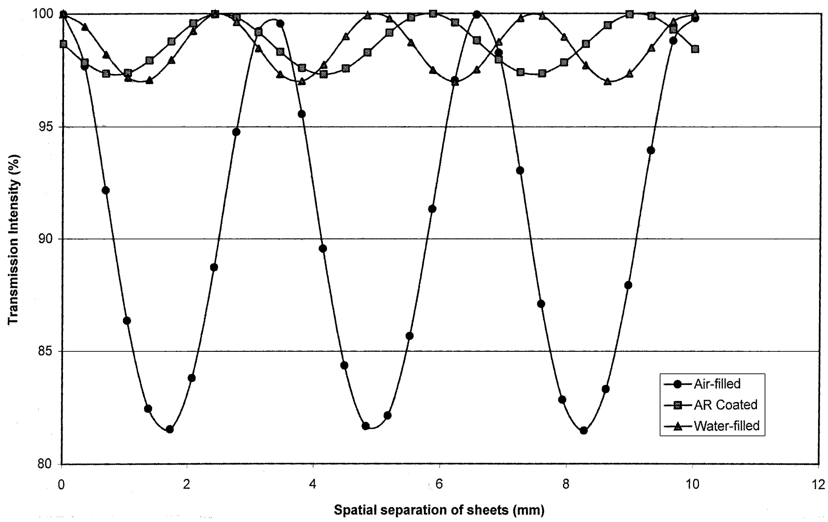

Figure 2 Modelling the effect of spatial separation of the polycarbonate sheets as a function of transmission intensity.

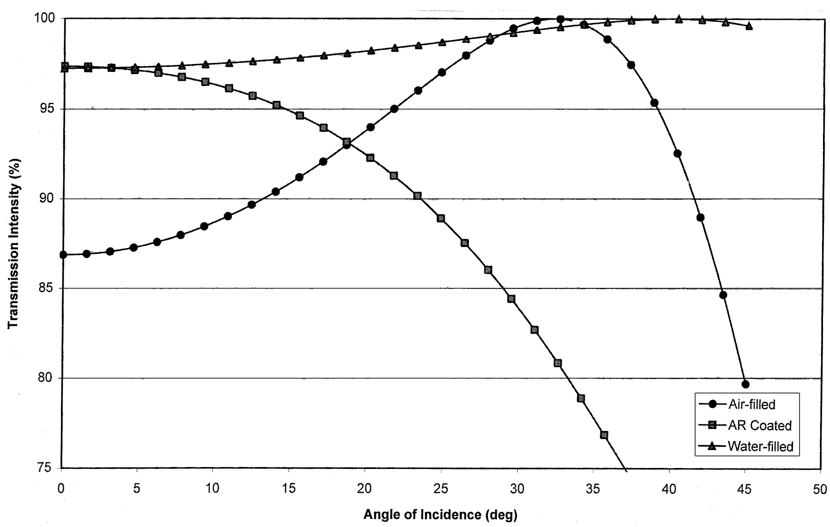

Figure 3 Modelling transmission intensity as a function of incidence angle.

Antireflective-coated air-filled visor

The modelling of an antireflective coated structure has been included here to illustrate the type of results which could be expected if this method was to be considered. However, as stated before it is not cost effective when compared to other methods. The antireflective layer acts as an index-gradient cushion between that of the polycarbonate and the air. This results in lower intensity Fresnel reflections and an increase in the intensity of light transmitted by the visor. Teflon AF ($n = 1.31$) with a layer thickness of 0.1 mm was used here as the antireflective coating on the two internal faces of the polycarbonate visor.

It can be seen from Fig. 2 that the use of an antireflective coating significantly improves the transmission characteristics of the visor, giving a mean transmission intensity of 98.6% ± 1.4%. However, it can be seen from Fig. 3, that the transmission intensity decays rapidly as the incident angle is varied, such that the transmission is below 75% before a 40° change in angle has been achieved.

Liquid-filled visor

The novel aspect of this work involves the use of a water layer to act as a refractive index-cushion between the polycarbonate layers, thereby replacing any air between the two layers.

Again, this intermediate material increased the transmission of light over most angles of incidence, resulting in a theoretical mean transmission of 98.5% ± 1.5%, as shown in Fig. 2. Figure 3 shows that the effects of incident angle are significantly less than for both the air-filled and antireflective-coated structures. The transmission intensity remains above 98% over the entire 45° scan range with a steady increase in transmission up to 42°.

Experimental results

Measurement of transmission

The transmission intensity profile for both air- and water-filled polycarbonate structures was monitored over a range of wavelengths (400 → 900 nm) using a dual beam Perkin-Elmer Lambda 5 UV/visible spectrometer. The polycarbonate sheets were separated by layers of adhesive tape, resulting in spatial separation of 45 μm, 90 μm and 135 μm. The transmission values were averaged for each structure, and the final data is plotted in Fig. 4. The intensity of light transmitted by the liquid-filled structure is significantly higher than that observed for the air-filled layer, with a mean improvement of 8.5% over the scan range. The deviations from linearity for the transmission plots are a direct result of the absorption characteristics of polycarbonate.

Light scattering experiment

A white light source (1.5 V Maglite pocket torch) was positioned 3 cm below the polycarbonate structure with a layer gap of 45 μm, and images were captured using the Motion Picture capture card (ATM, UK) and a Baxall CD9752 CCD camera with 12.5-mm focal length Computar lens. Windows Media Player and Paint Shop Pro 4 (JASC Software, USA) were used for image extraction and formatting, respectively. Both air- and liquid-filled structures were examined.

It can be seen from Figs 5 and 6, than there is significantly more scattering of light through the air-filled structure compared to the liquid-filled structure. The histogram function of Photoshop 4

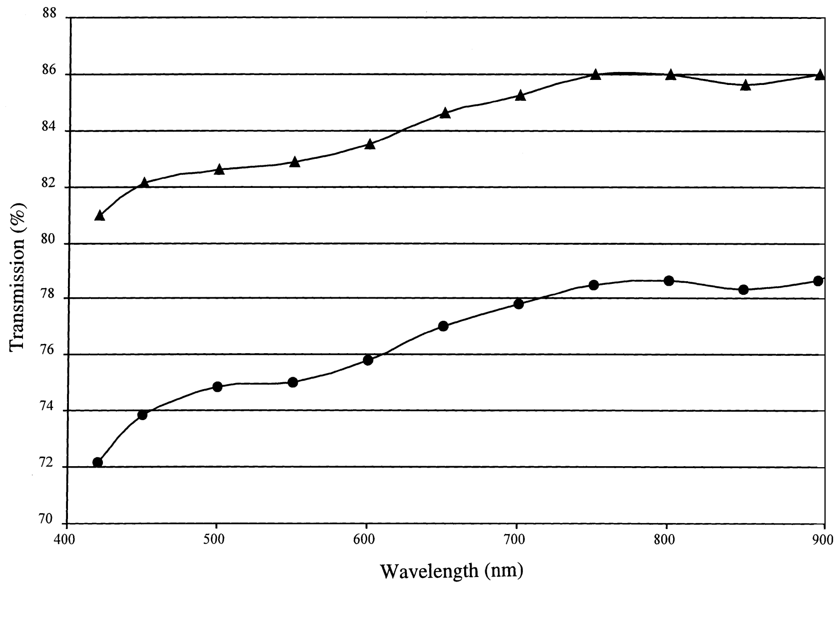

Figure 4 Comparison of the transmission profiles between 400 and 900 nm for air- (●) and liquid-filled (▲) structures.

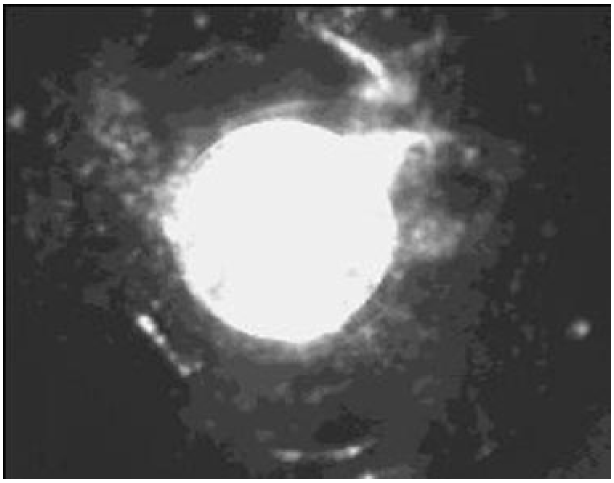

Figure 5 Light source viewed through the air-filled polycarbonate structure.

Figure 6 Light source viewed through the liquid-filled polycarbonate structure.

(Adobe Co., USA) was used to count the number of pixels at colour level 240, which related to the largest white peak on both histograms. The number of pixels for the air-filled structure was counted as 4243, compared to 3858 pixels for the liquid filled structure. This represents a 9.1% increase in pixels at this colour level for the air-filled structure, relative to the liquid-filled structure. This not only indicates that there is significantly greater scattering of light through the air-filled structure, and as such that light is confined to a greater extent using the liquid-filled structure, but also that the experimental results confirm the theoretical results.

Conclusions

Theoretical modelling illustrates that the air-filled visor structure is not an ideal optical design to allow the maximum transmission of light. The combination of reflective losses and Fresnel reflections using an air-filled polycarbonate structure have been modelled to show a decrease in transmission intensity of up to 18%.

The antireflective-coated liquid-filled structures present comparable transmission characteristics, with a maximum reflective loss of 3.2% along the normal. The benefits of using a liquid-filled structures become apparent when the incident angle changes, with the transmission intensity dropping rapidly for the AR coated structure compare to the liquid-filled structure, where the transmission intensity remains above 97% over a significant proportion of the scan range.

Owing to absorbance by the polycarbonate sheets, the actual transmission profile is significantly lower for both air- and water-filled visors. However, the transmission intensity is significantly lower for the air-filled sandwich than for the water-filled structure, as can be seen from Fig. 4. Scattering of incident light due to internal reflections, which in turn relate to the initial magnitude of reflective loss, is also greater with the air-filled structure. This is illustrated in Figs 5 and 6, with the 9.1% increase in pixel count at level 240 confirming a greater dispersion of light around the source than observed through the liquid-filled structure.

Whilst the improvement over the air-filled structure is only 9%, it is felt by the authors that this equates to a significant gain in the overall quality of vision through the visor, one which can be obtained with relatively little cost. The experimental data supports these conclusions, since although the transmission is lower than the theoretical results suggest, the enhancement using a liquid-filled structure is also approximately 9%.

Acknowledgements

The authors would like to acknowledge Mr Barry Paul at Leon Paul Equipment, London for the initial insight into the visors. They would also like to thank UMIST and DIAS for funding R.H. during his work.

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