

# Probes for spot measurement of surface conductivity on polluted insulators

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**Abstract:** The surface conductivity of insulators in the field is often non-uniformly distributed. In this case the integral surface conductivity is not an appropriate parameter of pollution severity. A better evaluation can be achieved on the basis of local conductivity measurements by means of special probes, for example, the rod probe or tissue strip probe. In this work the form factors of different probes are given and the form factor for the rod probe was calculated. The influence of wet-contamination area, the meniscus and the pollution layer thickness on the measured value of surface conductivity are shown. It was found that the surface conductivity on polluted silicone rubber measured by a tissue strip probe is proportional to the equivalent contamination deposit density (ECDD).

## 1 Introduction

The problems arising from pollution of insulators have been recognised by utilities for nearly a century. With the aim of predicting flashover and improving insulator design, considerable research work has been done towards understanding insulator surface contamination processes and flashover mechanisms under pollution conditions [1]. In service, an insulator will carry a resident contamination layer, accumulated since its installation or the last cleaning operation. This layer, which may fluctuate as a result of depositing and wetting events, is more or less stable. Whatever their nature, the pollutants, when dry, are rather inactive. However, when exposed to random occurrences like condensation, frost and onshore gales, water and/or ionisable materials are added. This, depending on the design of the insulator, will increase its surface conductivity possibly leading to flashover and consequent power outages.

The surface conductivity is, together with equivalent salt deposit density (ESDD) and leakage current, a very important parameter of contamination severity. For ceramic and glass insulators, specially designed probes appear to be accurate for surface conductivity assessment, because field pollution accumulation is generally non-uniform. ESDD measurement is a reliable method for assessing contamination severity for porcelain, glass and polymer. It involves washing the contaminants off from the insulator surface, and measuring the conductivity imparted by the contaminants. Polymer materials, on the contrary to porcelain, resist wetting because of hydrophobicity and their molecular chains known to be non-stationary. For example, a thin film of silicone fluid literally engulfs contaminants thus preventing dissolution of the ionic species in the water and thereby providing a very low surface conductivity. Thus,

for insulators made of silicone materials, ESDD rather than surface conductivity seemed to be a better parameter of pollution layer. However, during the washing of insulator all soluble components of the contaminant are dissolved. Therefore so measured ESDD value does not take into account the particular properties of silicone rubber. A new equivalent contamination deposit density (ECDD) parameter was introduced to replace ESDD for silicone insulators. The measurement procedure of ECDD is rather complicated. We show that surface conductivity, measured very simply by means of strip probe, is proportional to ECDD. The strip probe has an important advantage, it can be used both for porcelain and silicone insulators.

## 2 Insulator surface conductivity and flashover prediction

It is possible to evaluate the flashover voltage  $U_f$  of an insulator as a function of surface conductivity  $\kappa_s$ . The experimentally well confirmed equation is [2]

$$U_f = K_f \cdot \kappa_s^{-n_\kappa} \quad (1)$$

where  $K_f$  and  $n_\kappa$  are constants influenced by the insulator profile and other factors. The surface conductivity is related to the conductivity  $\kappa$  and layer thickness  $h$  of the pollution layer by

$$\kappa_s = \frac{1}{R_s} = \kappa \cdot h \quad (2)$$

If the surface conductivity is uniformly distributed on the insulator as in the case of artificial layers then its value can be calculated from the current measurement. Usually the current is measured at a voltage lower than the operating voltage (e.g. 700 V per 1 m of leakage distance) which causes no partial discharge or substantial temperature increase [3]. The so-called integral surface conductivity of a polluted insulator is then calculated from

$$\kappa_{si} = f \cdot \frac{I}{U} \quad (3)$$

where  $f$ ,  $U$  and  $I$  represent respectively the form factor of the insulator, the applied voltage and leakage current.

The form factor is calculated as

$$f = \int_0^L \frac{db}{2\pi \cdot r} \quad (4)$$

where  $L$  represents the leakage length of the insulator,  $db$  the incremental leakage length and  $r$  the radius at distance  $db$ .

The distribution of surface conductivity on insulators in the field is usually very non-uniform. In this case, the integral surface conductivity is not a proper parameter of contamination severity. For the same integral surface conductivity the flashover voltage of the non-uniformly polluted insulator, can be either lower or higher than in the case of uniform pollution [2].

### 3 Probes for spot measurements of surface conductivity, ESDD or ECDD

Special probes for measurement of surface conductivity can be used for the assessment of artificial layer uniformity in the laboratory. These probes can be applied for the determination of contamination severity of non-uniformly polluted insulators in the field. Pilling proposed a method for calculation of an effective surface conductivity which can be used for estimation of flashover voltage [2]. The measurement of surface conductivity is carried out in different, defined spots (e.g. 36 spots on 110-kV long rod). The effective surface conductivity is then calculated according to a special procedure taking into account the higher values of local surface conductivities. Probes have also been described to measure the ESDD on a small area of insulator in order to determine the distribution of contamination deposition [4, 5].

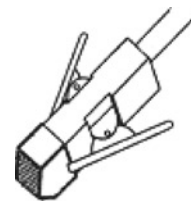
Probes for spot measurement of surface conductivity employ differently shaped electrodes. The measured surface conductivity is proportional to the form factor of the probe  $f_p$  divided by the surface resistance  $R_s$  measured between the electrodes (5). Table 1 lists the form factors of different probes.

$$\kappa_s = \frac{f_p}{R_s} \quad (5)$$

**Table 1: Probes for spot measurement of surface conductivity and their form factors**

Probe type	Wetting method	Form factor $f_p$ (theoretical)
Strip probe (Fig. 1)	Wet strip paper	$a/b$
Coaxial probe (Fig. 2)	Sprayed with distilled water	$\ln \frac{R/r}{2\pi}$
Rod probe (Fig. 3)	Sprayed with distilled water	$\frac{1}{\pi} \ln \frac{a-r}{r}$
IEC probe (Fig. 5)	Sprayed with distilled water	$\frac{1}{\pi} \ln \frac{a-r_c}{r_c}$

$R$  and  $r$  for the coaxial probe – see Fig. 2;  $a$  and  $r$  for the rod probe – see Fig. 9;  $r_c$  – radius of wet pollution in contact with the electrode of IEC probe (the meniscus is not taken into account)



**Fig. 1** Strip probe [2]

#### 3.1 Strip probe

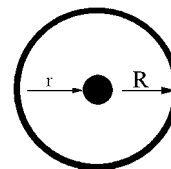
The strip probe described by Pilling is shown in the Fig. 1. The wetting of the measured area is achieved with a special adsorptive paper strip being held between two plate electrodes. When the probe with a wet paper strip is applied to the dry pollution layer the moisture diffuses into the surface contaminants. The distance  $a$  between the plate electrodes and the width  $b$  of electrodes are each 1 cm. Neglecting both the conductivity of the clean paper strip as well as the boundary field established because of broadening of the moisture region, the surface conductivity is inversely proportional to the resistance between the probe electrodes.

#### 3.2 Coaxial probe

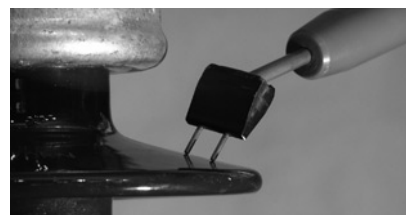
The coaxial probe (Fig. 2) has a construction in which the current flows only between the electrodes so that the result is not influenced by the surrounding pollutants.

#### 3.3 Rod probe

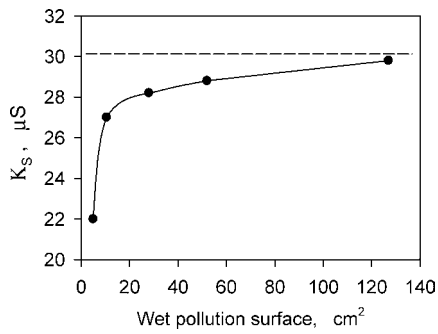
The rod probe, built by Erler, consists of two cylindrical electrodes with radius  $r$  and separation  $a$  (Fig. 3). The area of the wetted pollution has a surface conductivity which is measured to be greater than in the case of the strip probe or coaxial probe. The form factor of the probe in (5) was calculated under assumption that the area of the wet contaminant is large enough. The decrease of the area of wet contaminants results in increase of the measured surface resistance (decrease of measured surface conductivity). Fig. 4 shows that with the area of 100 cm<sup>2</sup> the measuring error is smaller than 3% for the probe with electrodes diameter of 1.5 mm and electrodes distance of 11 mm. The value of form factor of the rod probe estimated during a calibration procedure,  $f_p = 1.0$  differs significantly from the theoretical value of 0.83. These different results



**Fig. 2** Electrodes of coaxial probe [6]



**Fig. 3** Rod probe on the porcelain insulator



**Fig. 4** Influence of pollution area on the value of surface conductivity measured by means of rod probe [7], electrode diameter 1.5 mm, electrodes distance 11 mm; the real value is 30  $\mu\text{S}$

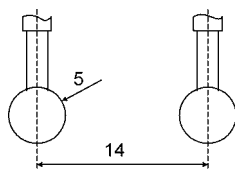
are caused by the meniscus which is formed at the electrodes. The meniscus changes the effective radius of electrodes and the layer thickness. This procedure error depends on the viscosity of pollution layer.

### 3.4 International Electrotechnical Commission (IEC) probe [3, 8]

The IEC probe has two rod electrodes with spherical tips (Fig. 5). Thanks to such a shape, the probe can be inclined to the insulator surface with different angles. The rod probe should be perpendicular to the contaminated surface because the form factor  $f_p$  given by (5) is valid for this position only. The form factor of this probe depends on the contact radius of pollution layer with the electrode. Neglecting the meniscus formation, this contact radius depends on the layer thickness only. Table 2 shows the form factors of the probe with the very similar dimensions to that recommended by IEC for different contact radii. The real form factor of the probe can be measured during the calibration procedure. The solution of volume  $V$  consisting of water and NaCl was poured on the flat horizontal plate with the area  $A$ . The mean layer thickness can be calculated as  $h = V/A$ .

The calibration test results for different layer thickness are shown in Fig. 6. The form factor of rod and IEC probes is constant for the thickness  $h$  greater than 0.2 mm. In this region the meniscus influence causes no big difference between the theoretical and experimental values of form factors. The theoretical value of form factor for the layer thickness of 1 mm (contact radius of 1.87 mm) is 0.59. The experimental form factor for this thick layer is 0.65. The influence of meniscus is very big in the case of very thin layer, the experimental form factor increases three times for IEC probe and two times for the rod probe for the layer thickness of 0.1 mm. The meniscus decreases the layer thickness around the electrodes and increases the resistance between them. Therefore the form factor of the probe calculated from the (5) increases.

The viscosity of wet contaminants becomes important for thin layer. The form factor of the probes evaluated with the contaminants consisted of 30 g Aerosil per litre of



**Fig. 5** IEC probe with spherical tips

**Table 2: Form factor of the probe with spherical tips for different contact radii between the electrode and contamination layer**

Contact radius $r_c$ (mm)	Form factor $f_p$	Remarks
1.0	0.79	Sphere diameter 4.5 mm
1.5	0.65	Distance between sphere centres 13 mm
1.87	0.59	
2.2	0.51	

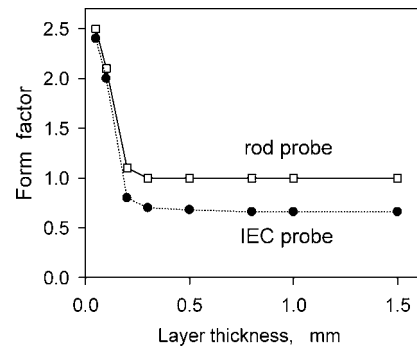
water (highly dispersed fumed silicon dioxide, called also Cabosil) depends less on the layer thickness. Similar effect is expected for the pollution layer consisting of kaolin used in laboratory tests.

### 3.5 Probes for spot measurement of ESDD or ECDD

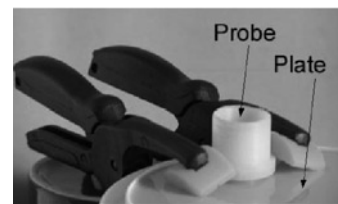
The tool consists of a measurement cell which can be fixed to the upper surface of polymer, glass or porcelain insulator surfaces. The measurement cell is a small tube sealed by an O-ring at the lower perimeter to make it water-tight when attached to the insulator surface. A small amount of de-ionised water (e.g. 2 ml) can be poured in the cell. After few minutes approximately 0.15 ml of solution is removed from the cell by a pipette. A conductivity meter is used to determine the conductivity and salinity of this solution. Fig. 7 shows the cell built by Besztercey [4] fixed on a round silicone plate using two clips. Liang Xidong used a small conductivity cell, a tube with two electrodes [5]. The meter directly connected to this probe measures continuously the increase of water conductivity in the cell.

## 4 Relation between the surface conductivity $K_s$ measured by strip probe and ECDD

The flat plates made from glass and plates with silicon coating were polluted by Kaolin suspension in such a



**Fig. 6** Experimentally estimated form factor of the IEC probe and the rod probe as a function of layer thickness



**Fig. 7** Besztercey's probe fastened to the silicone rubber plate by two clips

manner that the ESDD and dust deposit density (DDD) amounted to 0.1 mg/cm<sup>2</sup> and 1 mg/cm<sup>2</sup>, respectively. The conductivity of the NaCl solution ( $K$ ) was 3500  $\mu\text{S}/\text{cm}$  and the used thickness of the layer ( $h$ ) was 0.05 cm. Therefore the surface conductivity of the liquid contamination amounted

$$K_S \text{ max} = K \cdot h = 175 \mu\text{S} \quad (6)$$

The plates were left to dry. After 1, 10 and 14 days the surface conductivity  $K_S$  was measured by strip probe and ECDD was measured by means of Besztercey's probe. Additionally, the ESDD on glass plate was also evaluated. The procedure for ESDD or ECDD measurement was described in [4].

1. The measuring cell is attached to the insulator surface and filled with 2 ml of de-ionised water.
2. The water is allowed to remain on the surface for 10 min.
3. Approximately 0.15 ml of the solution is removed from the cell by a pipette.
4. The salinity of the removed water is measured using the HORIBA B-173 compact conductivity meter.
5. ECDD or ESDD in [mg/cm<sup>2</sup>] is determined from (9) [9]

$$\text{ESDD} = \frac{S}{A} = \frac{0.42 \cdot V}{A} \cdot \kappa^{1.039} \quad (7)$$

where  $S$  is the salt mass in [mg] on the area  $A$  under the probe in [cm<sup>2</sup>],  $V$  is the water volume in the probe in [litre] and  $\kappa$  is the solution conductivity in [ $\mu\text{S}/\text{cm}$ ]

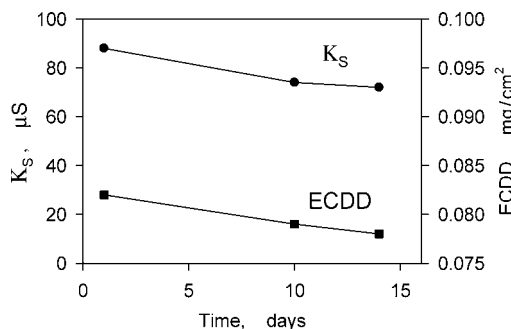
The measurements were repeated on spots where the pollution layer was not changed by earlier measurements. The mean value of surface conductivity measured by strip probe on polluted glass surface calculated from 10 points amounted to about 100  $\mu\text{S}$ . This result does not depend on time (10). On the contrary, the surface conductivity and ECDD measured on silicone coating decrease slowly with time (Fig. 8). The simple correlation is found between both surface conductivity and ESDD or ECDD.

$$K_S \simeq 1000 \cdot \text{ESDD} \quad (8)$$

$$K_S(t) \simeq 1000 \cdot \text{ECDD} \quad (9)$$

where  $K_S$  is the surface conductivity measured by the strip probe in  $\mu\text{S}$  and ESDD or ECDD is in mg/cm<sup>2</sup>.

The strip probe enables the quick evaluation of ESDD on porcelain insulators or ECDD on silicone rubber insulators. The important advantage of the strip probe is the possibility to measure the surface conductivity in many points



**Fig. 8** Surface conductivity measured on silicon rubber (SIR) plates by strip probe and equivalent contamination deposit density measured by Besztercey's probe as a function of time after contamination

including that on the rod and under sheds. The Besztercey's probe can only be used for measurements on horizontal or nearly horizontal surfaces.

## 5 Conclusions

The measurement of surface conductivity of polluted insulators can provide valuable information on several aspects of insulator performance. Probes appear to be very useful tools for measuring of spot contamination severity of outdoor insulators.

The values of form factors for different probes were given as a function of their dimensions. The dependence on layer thickness and area of wet pollutants was estimated.

The surface conductivity measured by means of strip probe is proportional to the ESDD on porcelain insulators and to the ECDD on silicone insulators. The strip probe is therefore a universal tool for measurement of pollution severity on polluted insulators.

## 6 Acknowledgment

Authors would like to thank Dr. Guyla Besztercey, Furukawa Insulators Ltd., Hungary, for the delivery of his ECDD probe.

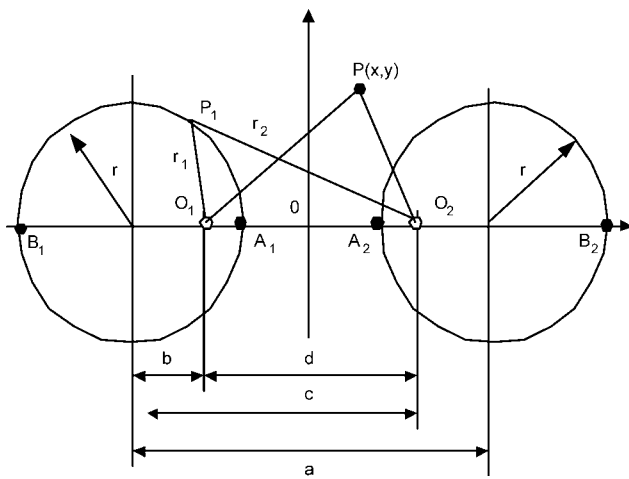
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## 8 Appendix: Form factor calculation for the rod probe

The mirror method is very effective in the modelling of cylindrical arrangements for both electrostatic and stationary current fields. The method utilises the cylindrical equipotential surfaces between two parallel current axes. When both cylindrical surfaces are given, it should be possible to find the equivalent axes for which the surfaces are equipotential. In this case, the electrical field calculated for the equivalent axes is exactly the same as for the cylindrical electrodes.

The potential at any point  $P$  of the field of the parallel axes  $O_1$  and  $O_2$  with the same currents ( $+I$ ) and ( $-I$ )



**Fig. 9** Axes  $\tilde{O}_1$  and  $\tilde{O}_2$  which build the equipotential cylinder surfaces with the radii  $r$  and the distance of their central points  $a$

(Fig. 9) is given by the well known equation

$$\varphi(P) = \frac{I}{2\pi\kappa_s} \ln \frac{r_2}{r_1} \quad (10)$$

where  $\kappa_s$  is the surface conductivity on a plane perpendicular to the current axes, and  $r_1, r_2$  are the distances to  $O_1$  and  $O_2$ , respectively.

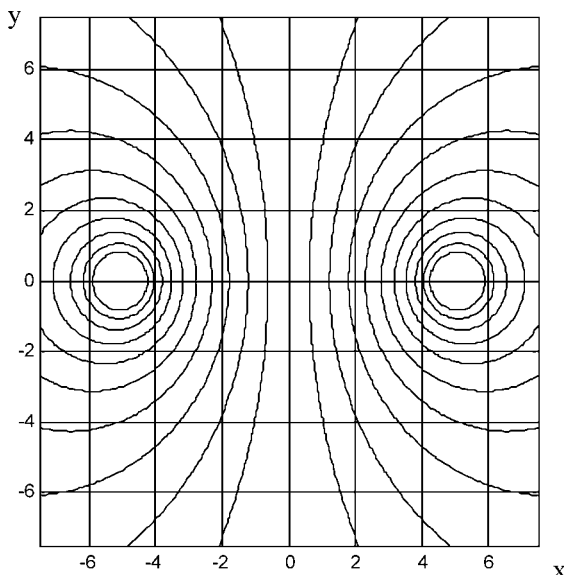
The constant ratio of distances to the points  $O_1$  and  $O_2$  is the condition for the constant potential in point  $P$ .

$$\frac{r_2}{r_1} = k \quad (11)$$

It could be shown that the Apolonius circles fulfill the condition (13) for different  $k$  values.

Taking into account the condition (13) for points  $A$  and  $B$  (Fig. 10) the following equation can be drawn for  $k > 1$

$$\frac{c-r}{r-b} = \frac{r+c}{b+r} = k \quad (12)$$



**Fig. 10** Equipotential lines calculated from (A8)

From (14), the following equation is obtained

$$bc = r^2 \quad (13)$$

Equation (15) expresses the so-called inversion condition of  $O_1$  and  $O_2$  axes with respect to the circle. The expression  $b \cdot c$ , which is the product of the distances,  $O_1$  and  $O_2$ , from the circle central point, is equal to the square of the radius,  $r^2$ . This condition is also called the  $O_1$  and  $O_2$  axes mirror reflex with respect to the circle.

Taking into account (14) and (15) the following equations can be established

$$b = r/k, \quad c = rk, \quad d = c - b = r \frac{k^2 - 1}{k},$$

$$r = d \frac{k}{k^2 - 1}, \quad b = d \frac{1}{k^2 - 1}, \quad c = d \frac{k^2}{k^2 - 1} \quad (14)$$

Considering the symmetry associated with identical cylinder radii, condition (15) can be written as

$$c = \frac{a}{2} + \frac{d}{2}, \quad b = \frac{a}{2} - \frac{d}{2}, \quad \left(\frac{a}{2}\right)^2 - \left(\frac{d}{2}\right)^2 = r^2 \quad (15)$$

Thus, in terms of  $a$  and  $r$  the distance  $d$  is

$$d = \sqrt{a^2 - (2r)^2} \quad (16)$$

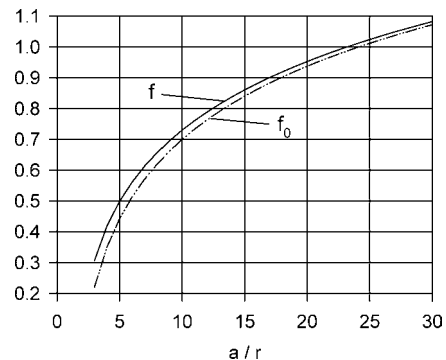
For the assigned position on the axes, the potential at any point  $P(x, y)$  can be derived from (12), with distance expressed as  $x, y$  coordinates

$$\varphi(x, y) = \frac{I}{2\pi\kappa_s} \ln \frac{\sqrt{\left(x - \frac{d}{2}\right)^2 + y^2}}{\sqrt{\left(x + \frac{d}{2}\right)^2 + y^2}} \quad (17)$$

The positive potential electrode determines the coordinates at point  $A_1(-a/2 + r, 0)$  and the negative potential electrode at point  $A_2(a/2 - r, 0)$

$$\varphi(A_1) = \frac{I}{2\pi\kappa_s} \ln \left| \frac{-\frac{a}{2} + r - \frac{d}{2}}{-\frac{a}{2} + r + \frac{d}{2}} \right| = \frac{I}{2\pi\kappa_s} \ln \left| \frac{-a + 2r - d}{-a + 2r + d} \right|$$

$$= \frac{I}{2\pi\kappa_s} \ln \frac{\sqrt{a^2 - (2r)^2} + a - 2r}{\sqrt{a^2 - (2r)^2} - a + 2r} \quad (18)$$



**Fig. 11** Real form factor values  $f$  and calculated values  $f_0$  as a function of ratio  $a/r$

Because of the arrangement symmetry, the potentials at points  $A_1$  and  $A_2$  are identical, that is,  $\varphi(A_2) = -\varphi(A_1)$ , and the voltage between the electrodes  $U = \varphi(A_1) - \varphi(A_2) = 2\varphi(A_1)$  can be written as

$$U = \frac{I}{\pi\kappa_s} \ln \frac{\sqrt{a^2 - (2r)^2} + a - 2r}{\sqrt{a^2 - (2r)^2} - a + 2r} \quad (19)$$

and surface conductivity  $\kappa_s$ , as

$$\kappa_s = \frac{I}{U} \cdot \frac{1}{\pi} \ln \frac{\sqrt{a^2 - (2r)^2} + a - 2r}{\sqrt{a^2 - (2r)^2} - a + 2r} = f \frac{I}{U} \quad (20)$$

where  $f$ , the form factor of the probe depends on the geometric dimension, expressed as

$$f = \frac{1}{\pi} \ln \frac{\sqrt{a^2 - (2r)^2} + a - 2r}{\sqrt{a^2 - (2r)^2} - a + 2r},$$

$$f_0 \simeq \frac{1}{\pi} \ln \frac{a - r}{r} \quad (21)$$

The approximation error of the left equation is smaller than 5% if  $a/r > 10$ . For  $a/r = 5$ , the error of the right-hand formula (23) amounts to 11.5%. Fig. 11 compares the real form factor  $f$  and the calculated one  $f_0$  as a function of the ratio  $a/r$ .