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On the linearity of the PS Closed Orbit Display pick−up electrodes

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Abstract

The PS is equipped with 40 electrostatic Pick−Ups (PUs), constituting the first element in a signal processing chain which allows reconstruction of the orbit of the beams circulating in the accelerator. The signals produced by these PUs are ideally a linear function of the position of the beam with respect to the centre of the vacuum chamber.

This report describes measurements to assess the precision and linearity of the PU electrodes with the associated sum and difference circuits.

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Introduction

The Pick−Ups (PUs) of the PS consist of four plates, or electrodes, arranged symmetrically around the centre of the vacuum chamber. As the beam traverses the PU, the image charge, which accompanies it around the machine, is induced onto the electrodes. The image charge is distributed in relation to the proximity of the beam to each of the electrodes. The electrodes are shaped such that the difference of the signals induced on a pair of opposite electrodes is linearly dependent on the beam position [1]. Obviously, the induced charges are also dependent on the beam intensity and therefore a sum signal, which ideally does not depend on the beam position, is used to normalize the difference signals, thus resulting in intensity independent position information.

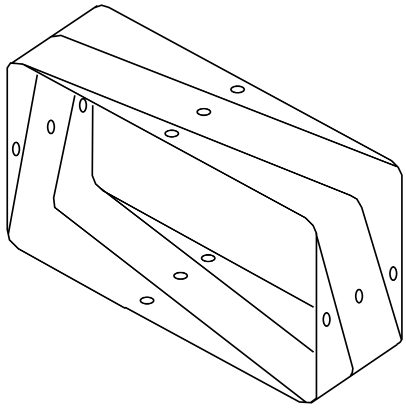

Fig. 1 The Pick−Up electrodes

If we denote the electrode signals as y^+, y^-, x^+ and x^- respectively, the position of the beam in the horizontal plane can be expressed as:

$$X = S_x \frac{x^+ - x^-}{x^+ + x^- + y^+ + y^-} = S_x \frac{\Delta_x}{\Sigma}$$

where S_x is a proportionality constant expressed in millimetres. Similarly, the beam position in the vertical direction can be expressed as:

$$Y = S_y \frac{y^+ - y^-}{x^+ + x^- + y^+ + y^-} = S_y \frac{\Delta_y}{\Sigma}$$

The constants S_x and S_y are called the *position sensitivity* for the horizontal (or radial) and the vertical axis respectively. Typical values for these PUs, measured at 5MHz and using a sum−and−difference circuit built with hybrid transformers, are S_x=174mm and S_y=82mm [1].

Measurement set−up

The PU is mounted in a pump manifold such as those used in the PS ring. The manifold is mounted above a computer controlled test bench specially constructed for the purpose of mapping out the PU response [2,3]. To simulate a particle beam, a wire carrying an electrical signal is strung through the PU. The test bench allows the wire to be moved along two perpendicular axes, thus simulating displacements of the beam. The arrangement is depicted in Fig. 2. The drive mechanics and the supports of the manifold have been left out for clarity. The highest resolution of the displacements is the ’micro−step’, of which 8192 fit into a millimetre. The positioning accuracy of the bench is about 50μm [3]. Each axis is controlled by a DC servo motor with an incremental encoder for position feedback. The motors drive precision ball screws attached to the wire supports. The bench is controlled via GPIB (IEEE−488), using simple alphanumeric commands. A computer, running a program written in the C language, controls the movements of the table and acquires the measurements. After a few sanity checks and some filtering, the data are written into a file using a format suitable for further analysis.

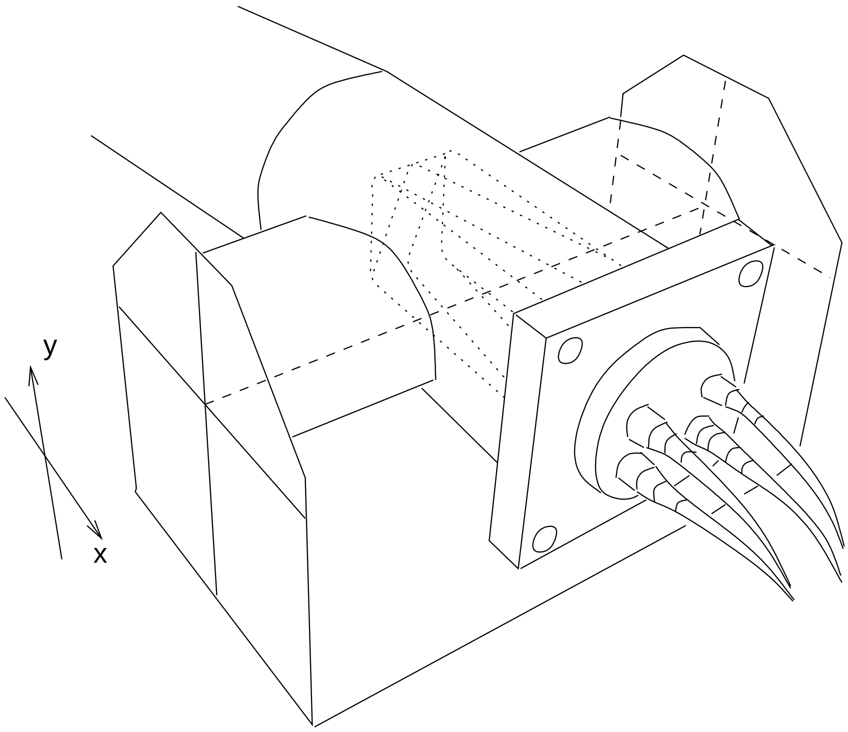

Fig. 2 The computer controlled pick−up test bench

The signal on the wire is a 5MHz sine wave, originating from a Network Analyzer (NA). The four electrodes of the PU are connected to hybrid transformers which elaborate the sum (Σ) and difference (Δ_x, Δ_y) signals [1]. These, in turn, are connected to the three inputs of the NA (Fig. 3). The NA is controlled by the same computer which controls the test bench.

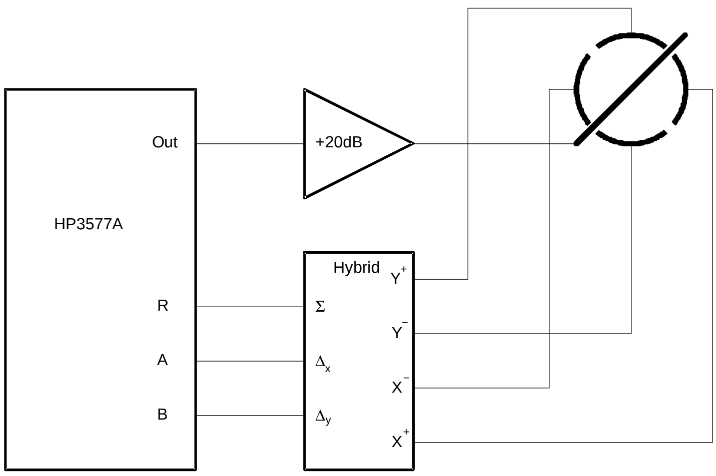

Fig. 3 Measurement set−up

The NA delivers its measurements in the form of complex numbers representing the RF voltage at its inputs. Ideally, these voltages would all be in phase and thus the quotients of the difference and sum signals (Δ/Σ), which represent normalized displacements, would be real. Several imperfections in the system conspire however, to spoil this nice ideal. The hybrid transformers aren't perfect. Even in the electrical centre of the PU, some signal appears on the Δ outputs (about 60dB below the Σ signal). Also, the electrical path length of each of the signals is not perfectly equal. The result is that the value of Δ/Σ as a function of displacement, plotted in the complex plane, traces out an inclined straight line, offset from the centre by some small amount (Fig. 4). The electrical centre of the PU is the point where the line in Fig. 4 makes its closest approach to the centre of the plot. The phase of Δ/Σ at that point is necessarily turned by 90° with respect to its phase for large displacements[1], and reflects the effect of parasitic capacitive coupling between the windings of the hybrid transformers. By way of correction, all measurements are rotated and offset so as to compensate for these imperfections. In fact, this is equivalent to increasing the CMRR of the hybrid transformers up to the noise limit of the NA, in addition to reducing any signal path length differences to a negligible level. Thus the resolution of the position measurement is limited only by noise, and not by the CMRR of the hybrids.

To assess the electrical resolution and reproducibility of the measurements, a number of consecutive acquisitions of the centre position were made with the wire in a fixed position. The scatter plot in Fig. 5 shows the result. The plot has been scaled to millimetres, using S_x=174mm and S_y=82mm [1]. Note that to be able to apply the corrections referred to in the previous paragraph, at least two fairly distant points must be measured, requiring at least one displacement of the wire. This, with the limited precision of the table, explains why one of the points in Fig. 5 stands apart from the others. The standard deviations, ignoring the outlier, are σ_x=5µm and σ_y=3µm respectively. The choice of the position at which these values were measured is purely arbitrary, as the result is the same everywhere. Note also that the position resolution attained is much superior to what can be derived from the *magnitude* of Δ/Σ alone.

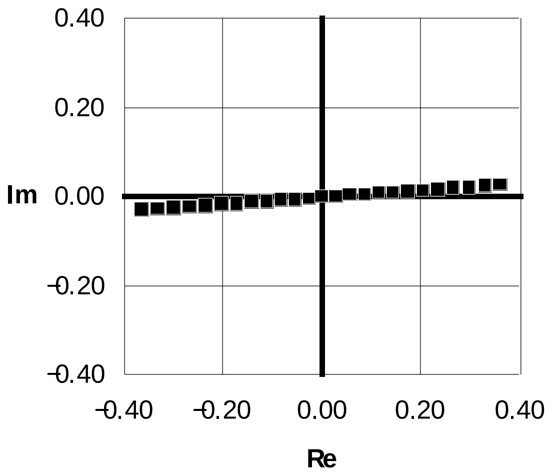

Fig. 4 The complex value of Δ_X/Σ at 5mm intervals

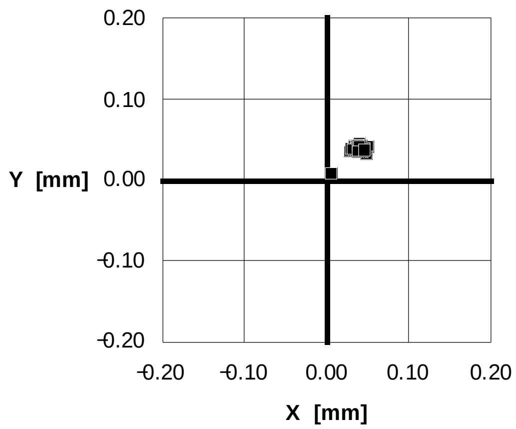

Fig. 5 Electrical precision of zero position

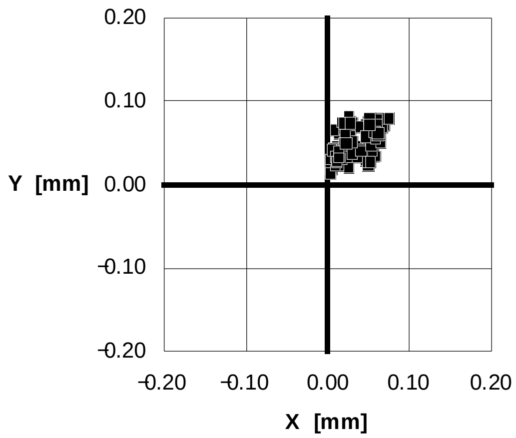

Fig. 6 Precision of mechanical positioning

The scatter plot of Fig. 6 gives an idea of the positioning precision of the table. The measurement is similar to the previous one, but this time the wire is randomly moved around between acquisitions. The uncertainty in the mechanical position of the table is seen to dominate the electrical noise. In addition, the horizontal axis appears to suffer

[1]Appendix A

from some hysteresis. The precision is still well within 0.1mm though, better than the resolution required of the PUs. The linearity of the table displacement has not been measured and is accepted on faith. In conclusion, in the data which follow, the mechanical and electrical positioning errors are neglected.

Measurement results

For the next two plots (Fig. 7 and Fig. 8), all accessible points in a 5mm grid inside the elliptical aperture of the vacuum chamber were scanned. The displacements were kept well within the internal dimensions of the chamber to avoid collisions of the wire suspension with the chamber walls. The values for both Δ_x/Σ and Δ_y/Σ were acquired simultaneously. The plots have been scaled to mm, using the sensitivities derived from a least squares fit through the centre of the appropriate data. The sensitivities so obtained were S_x=170mm and S_y=79mm. Ideally, the plots therefore show inclined planes with unit slopes. One clearly recognizes the elliptical outlines of the vacuum chamber in which the PU is mounted.

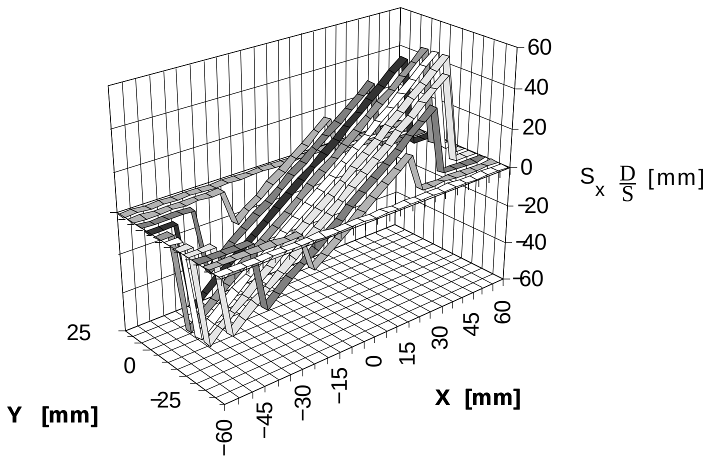

Fig . 7 Measured horizontal position as function of actual position

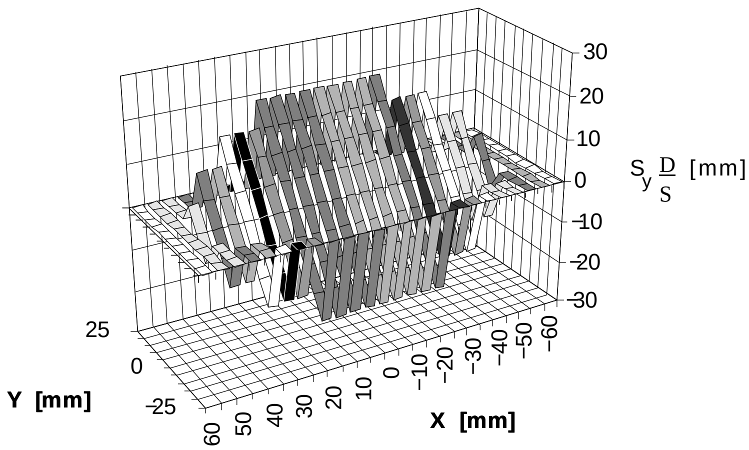

Fig. 8 Measured vertical position as function of actual position

If the linear approximation is subtracted from the actual response, the residual errors become apparent. Fig. 9 and Fig. 10 show plots of these residuals, using the same perspective as the previous plots. Fig. 10 shows a clear linear tendency along the x−axis, indicating that the horizontal axis of the table is not perfectly perpendicular to the vertical axis of the PU, as it is mounted in the set−up. Although not as evident, a similar tendency exists in Fig. 9 and further analysis shows that the whole PU is tilted by about 7 milliradians with respect to the table. No attempt was made to correct this. Several different electrode sets have been measured, using two different hybrid circuits, and the shapes of the plots below appear to be typical.

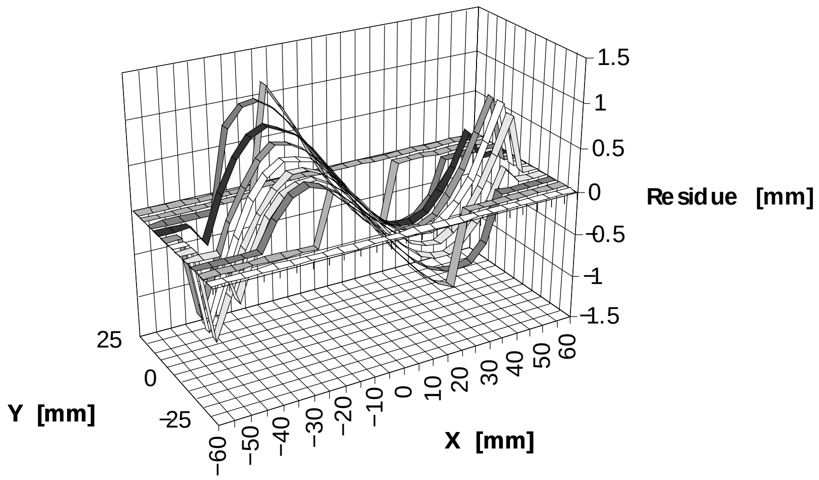

Fig. 9 Horizontal residuals

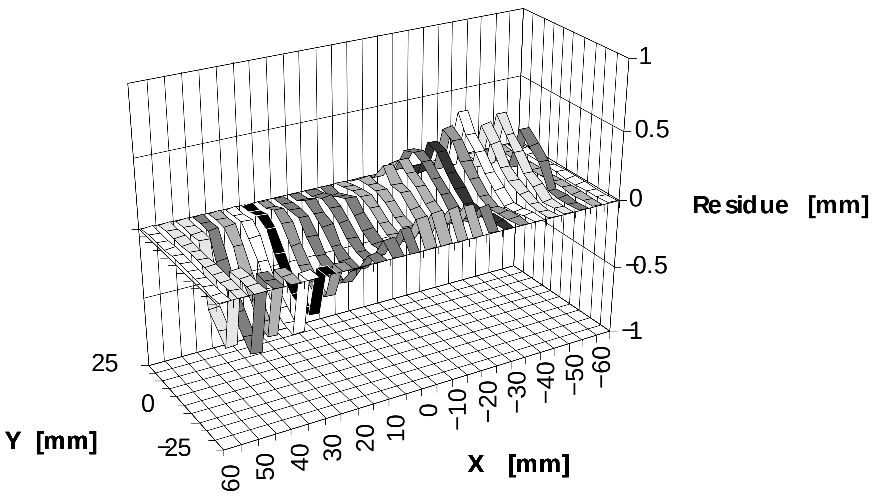

Fig. 10 Vertical residuals

More on resolution

The PS PUs treat pulse−like signals rather than continuous sine waves. Here also, there will be some capacitive leakage from the Σ to the Δ signals within the hybrid transformers. After amplification, the Σ and Δ signals are integrated to find the centre of charge of the particle bunches, before being digitized (Fig. 11) [4].

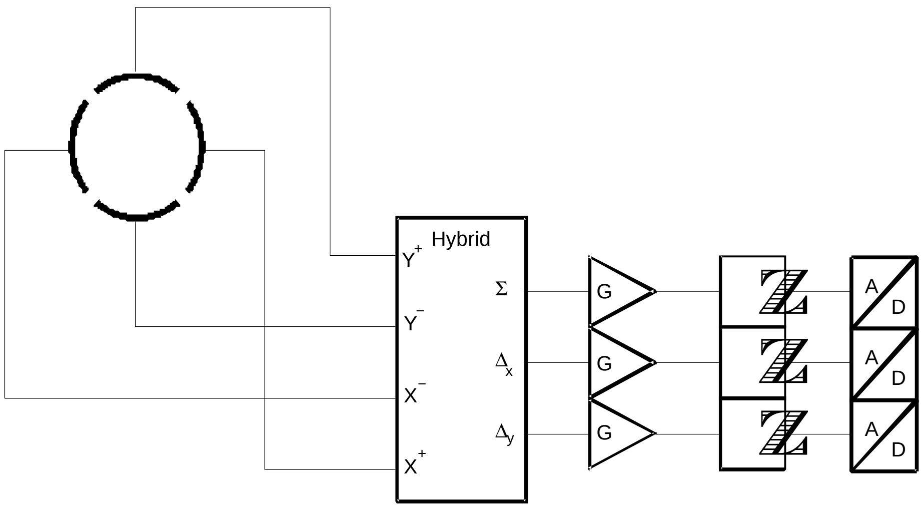

Fig. 11 Pick Up signal processing

The integrators are gated to accept only one pulse per acquisition. The signal level in between pulses is kept at zero by base line clamping. Since the leakage is essentially a differentiated and attenuated Σ signal, its integral yields zero. In Fig. 12, one can see the result of a simulation for a beam in the electrical centre of the PU where the time integral of the Δ signal clearly tends to zero. Thus here too the resolution is not limited by the CMRR of the hybrid circuits, but only by the noise

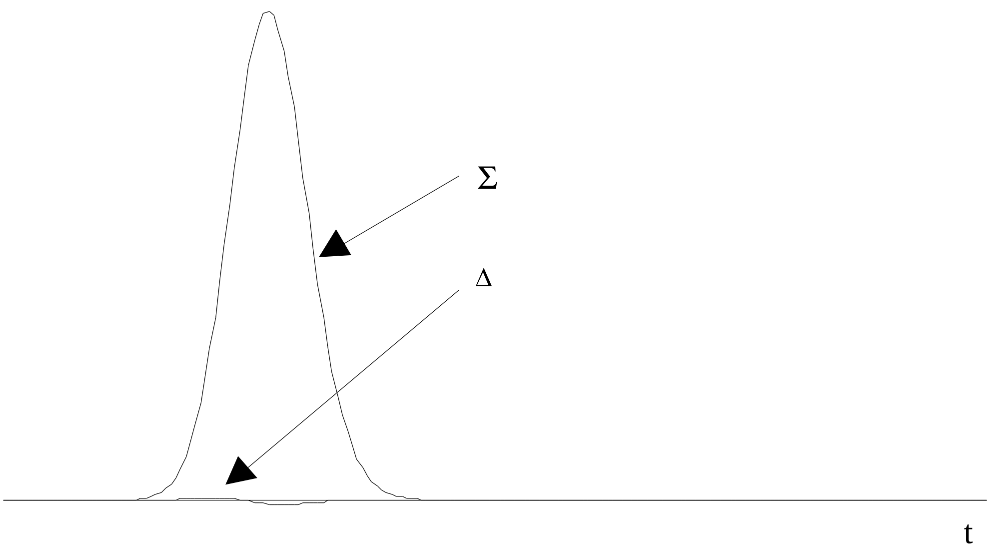

Fig. 12 Simulated Σ and Δ signals at the output of the hybrids for a centred beam in the system.

Conclusions

The PUs of the closed orbit display system show non−linearities in the range of a few percent for displacements of ±50mm in the horizontal, and ±20mm in the vertical direction. The position resolution which can be attained is limited only by the noise in the acquisition system. The present closed orbit display system integrates the PU signals to find the centre of charge of the particle bunches. The input to the Δ integrators is the superposition of the pure displacement and the capacitive leakage of the Σ signal. The latter vanishes after integration, so it does not deteriorate the accuracy of the result. It therefore appears useful to optimize the signal processing electronics so as to increase the signal to noise ratio even to the detriment of the CMRR of the hybrid transformers, if necessary. This may also allow the system to acquire useful data on weaker beams (such as ion beams).

References

[1] J. Durand, J. Gonzalez, E. Schulte, M. Thivent, "New electrostatic Pick−Up electrodes for the PS", CERN/PS 88−42 (PA), June 1988

[2] J. Durand, "Spécification technique d’un banc de mésure pour pick−up électrostatique de type compacte", PS/PSR/Spec. 87−3

[3] Gillièron Electronique S.A., Chemin Buvelot N^{o} 2, CH−1110 Morges

[4] J. Durand, "Intégrateur de signaux rapides bipolaires à porte incorporée", PS/EI/Note 79−11, December 1979

Appendix A

Proof that the closest point to ***O*** on a line *f(x) = ax + b* lies on a line *g(x)* through ***O*** normal to *f(x)*.

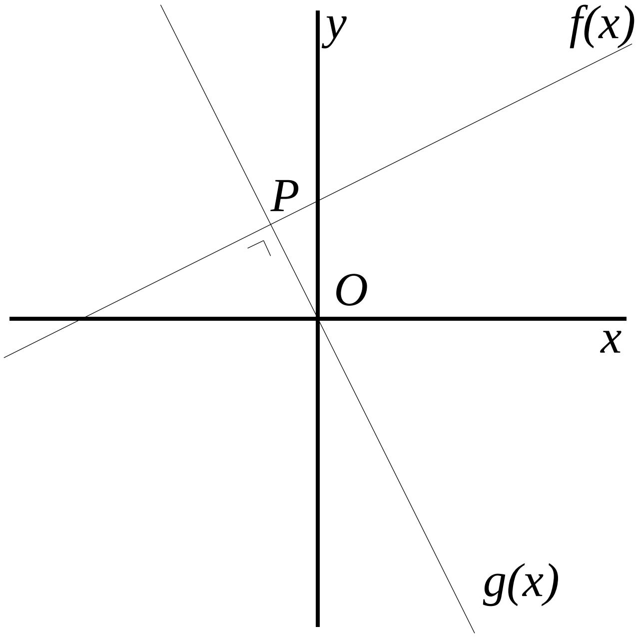

Fig. A1

Consider the point ***P***$=(x_p,y_p)$, lying on *f(x)* at its closest point to ***O***. Its distance to ***O*** is equal to

$$D=\sqrt{x_p^2+y_p^2}=\sqrt{x_p^2+\left[f(x_p)\right]^2}=\sqrt{(a^2+1)x_p^2+2abx_p+b^2}.$$

D is at a minimum for $\frac{d(D^2)}{dx}=0$, that is, $2(a^2+1)x_p+2ab=0$, and thus $x_p=-\frac{ab}{a^2+1}$.

The corresponding ordinate is $y_p=f(x_p)=\frac{b}{a^2+1}$.

It follows that $g(x)=\frac{y_p}{x_p}=-\frac{x}{a}$.