# Mechanical probe systems for precision machines

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# Mechanical Probe Systems for Precision Machines

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# Contents

# 1. Introduction

Nowadays precision machines show a high geometric accuracy to perform their tasks. The most important representatives of this class of machines are machine tools and coordinate measuring machines (CMMs). Both machine types can be used to control objects on their geometric performance, using a probe to obtain coordinates of the object.

An object coordinate will be determined by contacting an object with, for example, a ball, mounted on the stylus of the probe. The resulting deflection or translation of the stylus will activate a sensing mean which will generate a signal on which the machine's scales will be read. An important condition to realize accurate measurements is that the center of the stylus ball is known in relation to a coordinate system of the machine, so the touched points can be related to this known position.

In the final result are included errors introduced by the machine and errors introduced by the probe system.

The contribution of geometric errors to the machine's unaccuracy, due to imperfections of slideways of precision machines, are getting smaller. In respect to the total accuracy of precision machines, the uncertainty in the measuring results introduced by (touch-) probe systems unfortunately are getting more important.

An additional problem is introduced by the demand of industry for faster precision machines. This means higher accelerations of machine components and probe system combined with faster probing. This introduces effects which have, in contrary to slow probing, their impact on the measuring results. Therefore dynamic behaviour of probes needs to be studied more extensively.

To get a better understanding of the behaviour of (touch-) probe systems and to develop and built a suitable (touch-) probe system based on this knowledge, the Eindhoven University of Technology, Laboratory of Precision Engineering has started, in collaboration with Mitutoyo Laboratory Europe, Helmond, a research project covering this field.

In this interim report the results are presented of a literature study on mechanical touch probe systems for precision machines. The literature study covers scientific publications of approximately the last decade and published patents dealing with this subject.

As a result of this study a summary of error sources are presented. Based on this study a proposal for modeling mechanical touch probes will be presented. Additionally a proposal for verification measurements will be done. In these experiments the dynamical behaviour of the probe will be emphasized.

## 2. Classification of Mechanical Probe Systems

This report will focus on probes in use on precision machines, especially coordinate measuring machines. Only probes suitable for measuring in three orthogonal directions will be described. Actually, this means that only probe types, able to measure in the corresponding 6 directions (3D-probe) or probes able to measure in 5 directions ($2\frac{1}{2}$D-probe) are taken into account.

From a probe a few main parts or functions can be distinguished.
The probe housing is the reference of the other probe parts because it is fixed to the machine. The probe house protects the more vulnerable components of the probe and it defines in many cases the position of the stylus carrier. The probe house is thus the frame to which a stylus carrier is mounted in a defined way. The stylus carrier is provided with a stylus holder to which a stylus can be attached. The stylus is a cylindrical bar, which is generally terminated by a ruby ball, the latter also called stylus tip. The stylus should ensure that the stylus tip is held as rigidly as possible in space.
To obtain coordinates some sensing device is coupled with the stylus carrier, so after contact between stylus tip and the object coordinates are generated.
To allow the machine to come to a stop after contacting the object, the stylus carrier can displace or deflect. This function is called overtravel and prevents the machine, probe and object for damage [12].

Two different types of contact probes can be distinguished [1, 8, 11, 13]. The classification of these two types is based on how each type determine, in collaboration with the CMM, the real coordinates of a probing point.
The two major probe types are :

1) Analogue probe or measuring probe;
2) Touch trigger probe.

Ad 1) An analogue probe system possess a sensor to detect a magnitude change of a quantity. The word " analogue " does not always mean in this case that the measuring mean generates a continuous function of the value of the quantity to be measured. This quantity can represent for example a change in intensity of a light beam, a displacement or an angle. The change in magnitude is an indication for the displacement of the stylus tip.

This displacement is added to the machine readings to obtain the real coordinates of a probing point. The probe can be equipped with real analogue sensing means or with digital ones.
Most of the analogue probes have a mechanism to adjust the measuring force during probing. A minority of the probes in use on coordinate measuring machines is of this type. This type of probe is not in use on machine tools because the probe must be exchangeable with tools and this probe type is at the moment too complex to integrate easy in the machine's system. Also the at the moment commercial available analogue probe systems are not adequate to use on machine tools, due to the high accelerations and the aggressive environment of the machine. In most cases these probes are slowing down the measuring process. Typical measuring speeds are 0,1-10 mm/s.

Ad 2) Touching trigger probe systems generate a trigger signal which latches the counters of the machine's scales to read the coordinates of the machine.
The vast majority of these probes are performed with a reseating mechanism to which a stylus is connected. Thus the reference position is mechanically defined. Most of these probes are suitable for fast probing. Typical measuring speeds are 8-20 mm/s.

To get a better understanding of the two classes of probes, a typical representative of each group will be briefly described.

- *The analogue probe*
  This probe (patent DE 2 242 355) exists of three leaf spring constructions (see figure 1). Each construction has two leaf springs (3a, 5a, 7a) to realize a pure translation. Each of these constructions has a perpendicular orientation to the other two, resulting in a real 3D probe system. To prevent vibrations each unit has a visco-hydraulic damper.
  This construction, a combination of three translation units, has a big torsional stiffness and has no back lash. Each translation unit is equipped with an independent measuring system, its orientation is in the direction of displacement of the unit. The measuring system can be e.g. based on the inductive principle.
  Because of the leaf springs, each translation unit has its own rest position, which is defined as the reference position. A displacement of the unit is related and quantified to this point. The central unit, to which the most upper translation unit is connected, is equipped with three coils and lever mechanisms to adjust the measuring force. Additionally each unit has a precision blocking mechanism for special features like contour scanning of surfaces.

This blocking mechanism gives the opportunity to drag the stylus tip along the surface with only one possibility of deflection, so the scanning line can be described as a function of two coordinates.

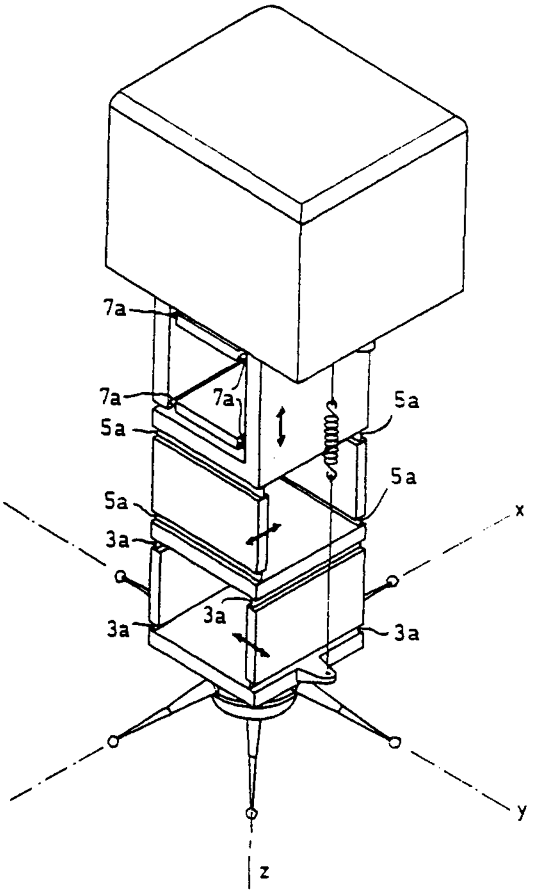


Figure 1 : Analogue probe with three leaf spring constructions.

- *The touch trigger probe*

  In figure 2 is shown the most simple version of a touch trigger probe (patent EP 0 423 307). The stylus is connected to a stylus carrier which includes three cylindrical seating elements in the form of rods spaced at 120° intervals around the stylus axis.

  The seating elements are supported in confronting seats, each of which e.g. consists of a pair of balls fixed in the housing of the probe. This construction defines kinematically a reference position, which is maintained with a light spring preload when no external forces act to the stylus.

The three seat constructions are electrically wired in series, and a constant current source is connected. A measurement is taken when the stylus is deflected, resulting in a change of resistance in the electric circuit, but a contact breakage is not necessary for a reliable trigger [6, 12].

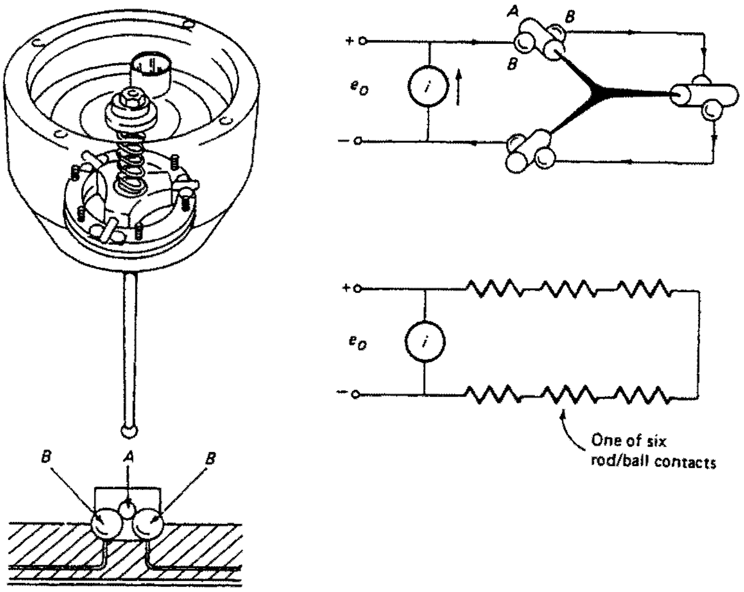


Figure 2 : Details of touch trigger probe. The schemes on the right show the principle of the electric circuit and, in this case, also the sensing mean.

# 3. Main error sources of mechanical probes

## 3.1. Introduction

To measure an object accurate with a mechanical probe a few conditions must be fulfilled. These conditions for a probe system can be derived from the mean condition that every probing point on an object to be measured must be taken with the same force and the same reference point on the probe. This is the basic idea of correct probing, but consequently this includes some deformation of the object surface and the stylus tip. Elastic deformations of the object surface are inevitable because a certain force is needed to be sure there is real contact between the object and the stylus tip. But undesirable are differences in elastic deformations of the surface or stylus tip after repeatedly probing one point of a surface.

Not included in above mentioned condition is any error compensation by means of software. This means that every error of the total set of errors of the probe system must be mapped or predicted with an adequate model. So when a probe is in use, a correction can be done on every coordinate generated by the probe to obtain a good approximation of the real coordinates [5].

Not for every probe system and stylus combination it is possible to make an error map on which a correction can be based. On the one hand this is not possible for reasons of practicality because e.g. there are to many possibilities to contact a surface with a stylus tip. On the other hand there is in most cases not an adequate model available to predict, with a certain degree of reliability, errors as a function e.g. of the stylus-performance, direction of contact between stylus tip and surface or contact speed.

## 3.2. Probing conditions

For accurate and faultless probing four conditions must be fulfilled by a probing system based on the condition that every probing point on an object to be measured must be taken with the same force and the same reference point on the probe :

1) the magnitude of the probing force must be independent of the direction of probing and must have the same magnitude for every probing direction. This garantees that the use of the probe is not limited to certain directions or certain directions of approach of objects;

2) the probing force must be repeatable, so repeatedly probing of an object on the same spot will not result in different coordinates due to differences in deformation of the object and the stylus;
3) the reference position, to which every measuring point is related, must be unambiguous defined. This is necessary to combine accurately a read-out of the probe system with the readings of a machine;
4) the detection sensitivity or resolution of the probe system must be at least as accurate as the CMM.

Both mentioned classes of probe systems, analogue and touch trigger probe systems, cope with sources of errors. Most of these error sources are type independent. This means that described errors can occur both in analogue probe systems and touch trigger probe systems.
With above defined conditions, current error sources in existing probe systems can be analyzed and described. First a general description will be given of the important error sources. Later an overview of relevant error sources will be given for existing probe systems.

The basic function of a probe including the machine is to transform a discrete object into coordinates to compare this information with specified dimensions and tolerances. A number of influences on this transformation are responsible for errors in the final determination of the dimensions of the object. An overview of the main influences is shown in figure 3.

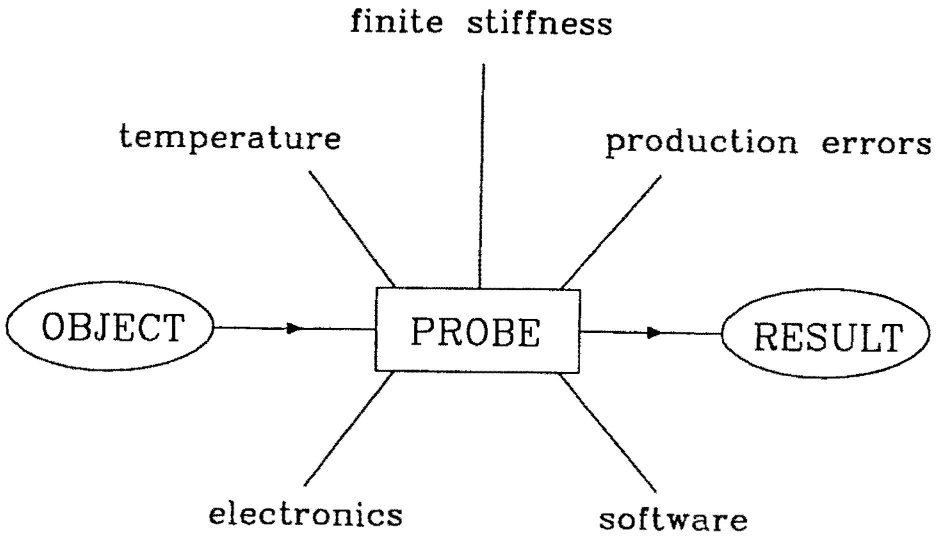


Figure 3 : Main influences acting on the probe accuracy.

### 3.3. Systematic errors of mechanical probe systems

The classes of presented error sources (figure 3) can be described more in detail. Hereby no distinction will be made between errors typically for analogue or touch trigger probes. The in this paragraph described errors are typically systematic of nature. Systematic errors are errors which can be quantified and for which can be corrected, in contrary to random errors, described in section 3.4. This means that the type of systematic error can be modeled and thus in theory predicted, but in practical situations this is not always possible or useful. An example of the latter is that it is possible to correct for unroundness of a stylus tip. But in general this error is in the order of magnitude of 0.1 $\mu$m, which is small in comparison to other systematic errors.

- Geometric errors due to imperfect production of probe components.
  For example imperfect production or orientation of probe slideways manifest themselves as position and orientation errors of the stylus tip in relation to the CMM. For touch trigger probes an asymmetric spring, used to provide a preload somewhere, can e.g. cause a probing force variation, dependent on the direction of probing.
- Finite stiffness of materials cause position errors, especially when dynamic operation of the probe is requested. When a probe is used in a measuring environment with accelerations and a fast touch triggering mode, forces are relative high, resulting in deformations of the different components of the probe [22].
  But even in semi-static use with slow measuring speeds, forces are present in the probe construction and therefore cause a position error of the stylus tip. Effects which e.g. contribute to this error are bending of the stylus due to contact forces, and deformation of a seat mechanism of a touch trigger probe.
- Hysteresis is the translation of the apparent origin of the probe in relation to the real, eventually kinematic fixed, origin which must be the reference position. Hysteresis is a direct consequence of a previous probing and is therefore a function of the probing direction. Hysteresis is a result of friction between components [12, 17].
- Expansion of the components of the probe under influence of internal and external heat sources will cause deformation of probe components. Probably this will also influence the behaviour of electric components.
- Software errors are introduced due to the processing of information provided by the probe. The host computer of the machine transforms probing coordinates (= readings of the machine scales plus eventually probe coordinates) to object coordinates, which can introduce some discrepancy between the real coordinates and the calculated ones (see figure 4) [12, 17, 18].

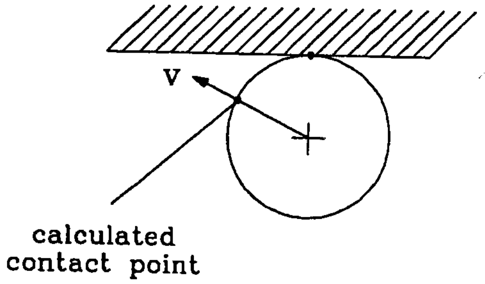


Figure 4 : The contact point on the stylus tip is calculated based on the direction of moving of the machine. When the object is not touched perpendicular to the surface of the object an error will be introduced by the software.

- Delay time effects are not directly influenced by the probe. These errors are a result of the essential electrical or infrared light connection between probe system and machine. Included in this connection circuit are electronic components and wire cables. Consequently it takes some time between generating an electric signal by the probe and the moment in which the scales of the machine are read [12].
- A resolution error is introduced when the sensing means used by the touch probe has a limited resolution in combination with the stylus. This can be illustrated by a touch trigger probe with one rotation point for the stylus carrier. To rotate the stylus carrier over a certain angle, on which the deflection of the stylus is detected, a long stylus needs a larger displacement than a short stylus. Consequently the resolution of the system depends on an external factor.
  The sensitivity of a touch trigger probe system can be interpreted as a resolution error, so this error is a type independent one.
- Scale errors are introduced by the displacement sensors of the probe system. Scale errors are in fact linearity errors. This type of error is a type dependent error which can only occur by analogue probe systems [10].
- The stability of electrical switches can influence the functionality of some probe types, because this is based on the breakage of a electrical switch. The stability of the moment on which the electric circuit is really broken depends on the contact materials, their roughness, the dielectric, the speed of contact breakage, the magnitude of the current, the temperature, the contamination of the contact surfaces, the magnetic field(s) and the pressure of the environment of the electrical switch [13, 14, 19].

### 3.4. Random errors of mechanical probe systems

Random errors are errors which magnitude and sign can not be predicted, i.e. their causes are unknown. An example of an influence which can cause random errors is the contamination of inner and outer contact surfaces of the probe.

An other random effect causing deviations in the probe characteristics are accidents, due to machine or human failure. Due to an unwanted, uncontrolled, collision between probe and object some probe components can deform causing random errors unless these deformations are traced.

Because of the property of random errors these errors must be kept small and must be avoided by checking and datuming the probe.

Above mentioned systematic and random errors will manifest themselves in typical in literature so-called probe errors. In fact it is better to speak about probe characteristics, because they are a consequence of the already mentioned systematic errors and the realized mechanical construction, so in most cases they will manifest themselves as a combination of systematic errors.

These probe errors can be measured to record the status quo of the probe. The errors which can quantify the measuring quality of a probe are :

1) pre-travel;
2) pre-travel variation;
3) repeatability;
4) linearity;
5) clearance.

ad 1) The pre-travel is the distance which is covered by the machine between the moment of real contact between probe and object and the moment of reading of the scales. This means that the pre-travel is a function of the probing direction. A major constituent of pre-travel is stylus bending. The magnitude of bending depends on the minimum force necessary to get a reading of the scales of the machine. So the measuring force varies with the angle between the normal vector of the object surface and the probing direction and with the probing direction in relation to the probe itself. The latter is related to the mechanical construction of the probe system. The effect of a direction-dependent measuring force is called lobing, an effect that is present in three directions. In publications most times only the lobing effect of a probe in a horizontal plane is presented.

But it must be emphasized that the lobing effect is present for every plane in space. An example of this measured lobing of a kinematic defined reference position of a probe is presented in figure 5 [1]. Pre-travel will increase with both stylus length and probe trigger force [12, 21].

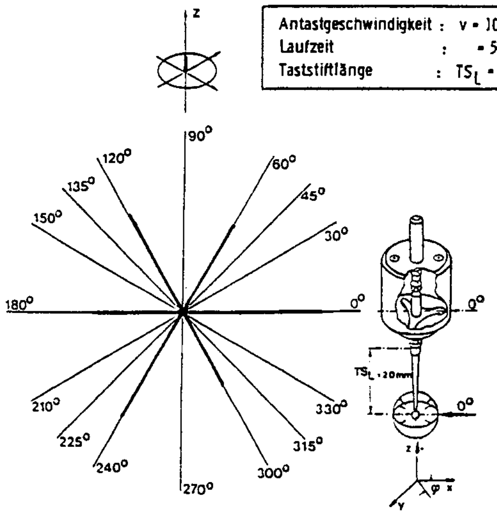


Figure 5 : Pre-travel as function of the angle. This figure shows the relation between the seating elements and the pre-travel [1].

ad 2) Pre-travel variation is the difference between the maximum observed pre-travel and the minimum observed one, regardless the probing direction of the observed maximum or minimum pre-travel. In literature and practice, e.g. with software correction, pre-travel variation is usually defined in one plane. The pre-travel variation is an indication for the variation in probing force and consequently for the deformation of the object surface, the stylus tip, the stylus and inner components of the probe. Pre-travel is a direct consequence of the mechanical construction.

ad 3) The repeatability is the ability of a probe system to give, under defined conditions of use, closely similar responses for repeated measurements of the same object. Repeatability of a system is in fact the only error source which is really random [12]. The reason is that a lot of physical and mechanical causes can have their influence on the repeatability of a probe system, but it is impossible to quantify the contributions of each cause to the total error. Possible influences on repeatability are e.g. roughness of the contact surfaces, adhesion between contact surfaces, contamination or differences in friction between the surface of the object and the stylus tip when the surface is not touched perpendicular.

An important source for repeatability errors is the performance of the mechanical construction of the probe. Most touch trigger probes show at certain probing directions some instability at the moment of probing. The already in chapter 2 described touch trigger probe has three of these points of instability. This is also shown in figure 6 [17], in which is shown the deviation of the measurements as function of the probing direction in the horizontal plane.

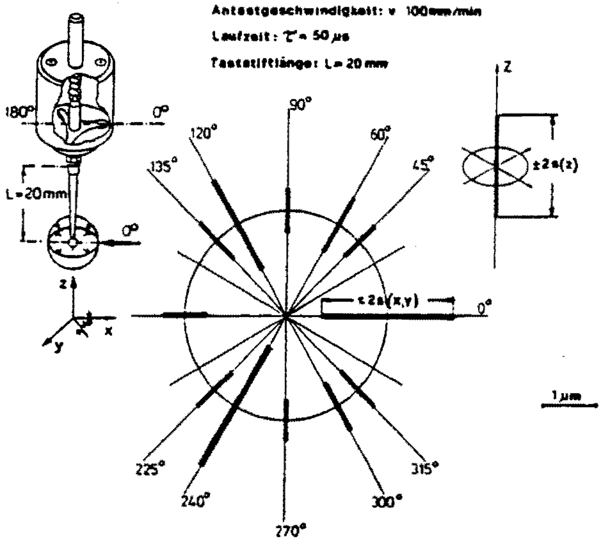


Figure 6 : The deviation of the measurements as function of the probing direction in the horizontal plane.

It can be seen that for the directions 0°, 120° and 240° the repeatability is worse in comparison with other directions. The mentioned instability is due to the mechanically not defined rotation axis around which the stylus carrier can rotate when touching a surface.

ad 4) A linearity error quantifies the position error of the sensing means. This error is only relevant when the probe system is an analogue one. Measuring errors can be introduced due to scale errors or due to a limited resolution of the used measuring means of the probe.

ad 5) Clearance in a probe system can manifest itself as real clearance or as hysteresis. When real clearance is present in a construction this is due to a worse construction. Real clearance must be avoided at all times. Hysteresis is due to friction between components due to a reverse of motion. A probe with large hysteresis does not necessarily have a poor resolution but it can be an indication of the quality of the probe.

With above described systematic and random errors and probe characteristics every probe design can be judged.

# 4. Construction principles of touch trigger probes

## 4.1. Introduction

In this chapter first an overview of existing principles of construction of touch trigger probes and related construction principles will be presented. This overview is mainly based on a bibliographical study of patents. This overview is, because of the main goal of the project, limited to touch trigger probes.

In a touch trigger probe three different functions can be distinguished :

1) sensing;
2) seating;
3) overtravel.

ad 1) The probe must have a means to detect a movement of the stylus tip or to detect a contact between the stylus tip and a surface of an object.

ad 2) Each probe must have a certain reference position to which the actual position of the stylus tip can be related. For the touch trigger probe this reference position is defined by a seating construction on which the stylus carrier is resting.

ad 3) Each mechanical probe system must have a capability for overtravel. The reason is that a machine needs a discrete time interval (displacement) to come to a stop after contacting an object. During this slowing down period the probe must allow some deflection of the stylus without being damaged or damaging the machine or object to be measured.

In most probe systems above mentioned functions cannot be distinguished separately. In most cases at least two, and sometimes the three mentioned functions, are integrated in one mechanism. In the next paragraph, above mentioned functions will be distinguished en described.

The order of most described probe systems is based on the year of publication of the accompanying patent. This gives some understanding of the developments of touch trigger probe systems.

## 4.2. Description of probe systems and related inventions

### 4.2.1. Renishaw TP2 probe system (≃ 1972)

The construction principle of this probe is already described in the example of touch trigger probes (see figure 2).

In this probe the sensing function is direct related to the seating function. The three seat constructions are electrically wired in series, and a constant current source is connected. A measurement is taken when the stylus is deflected, resulting in a change of resistance in the electric circuit because one cylindrical rod of the stylus carrier is lifted out of its rest position. After deflection the stylus carrier has to reseat in the three seating constructions. This cause an error because of the presence of friction and some electrical effects in the seating construction. Consequently the stylus tip has an other position as it had before the measurement, i.e. the actual reference position is different from the previous reference position.

This proves one of the most important disadvantages of kinematic constructions. On macro scale these kind of constructions look like ideal, but on micro scale these constructions are responsible for position errors, due to a number of effects.

### 4.2.2. Zeiss ST and RST touch trigger probe system (1977)

The seating construction of the stylus carrier (patent DE 27 12 181 A1) consists of two separated classical seat constructions (5a, 7a). The latter exists of three balls which are uniformly distributed over a circumference, and which have confronting seats which are preferably different of design, so a kinematically defined position is guaranteed. The stylus carrier (3b) rests, by means of a seat construction, on an intermediate ring (8) (see figure 7). The stylus carrier is urged into its position by uniformly distributed magnets (10).

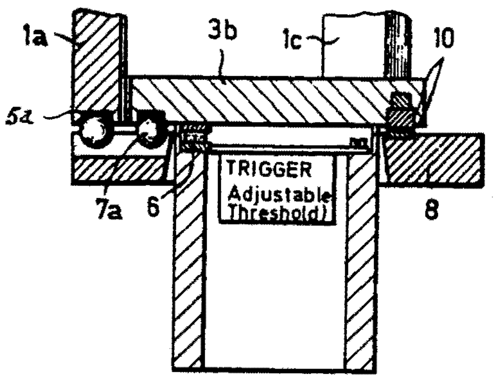


Figure 7 : Seat construction. The intermediate ring is represented by number 8, the magnets by number 10.

In the stylus carrier, which is the moving part of the probe, the sensing means (6) are positioned (e.g. piezo-electric elements). The intermediate ring is positioned to the probe head, fixed to the machine by means of a second seat construction.

The intermediate ring is urged into its position by means of a tension spring (not shown) which is attached to the machine (1a). A displacement of the stylus carrier in vertical direction is possible because it can glide along three slideways (1c). The slideways do not define the rest position because this is defined by the intermediate ring.

The probing force can be adjusted by selecting a suitable threshold level of the signal, in relation to the characteristic of the sensing elements. So the magnitude of the generated signal is used to adjust the trigger force. When the measurement signal does not exceed the threshold level, the signal is ignored. When the signal does exceed the threshold level it must prolong for a certain period of time to prevent false triggering in case the sensing element is adjusted too sensitive.

A disadvantage of this probe system is its relative big mass. This makes it unsuitable for fast measurement operations.

### 4.2.3. Tesa probe system (1988)

The seating construction shown in figure 8 (patent EP 0 307 782 B1) is probably developed to sidestep the invention described in section 4.2.1.

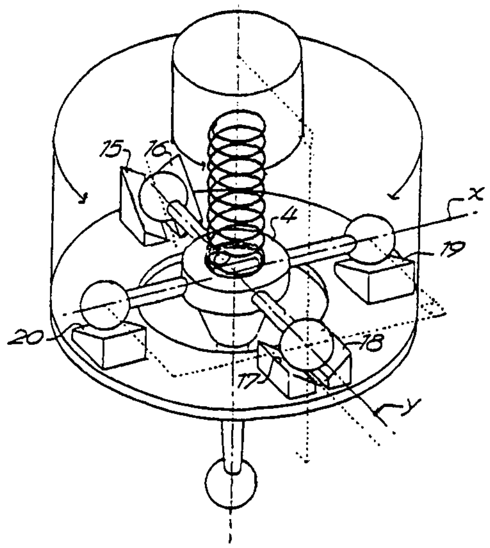


Figure 8 : An alternative kinematic defined seating construction.

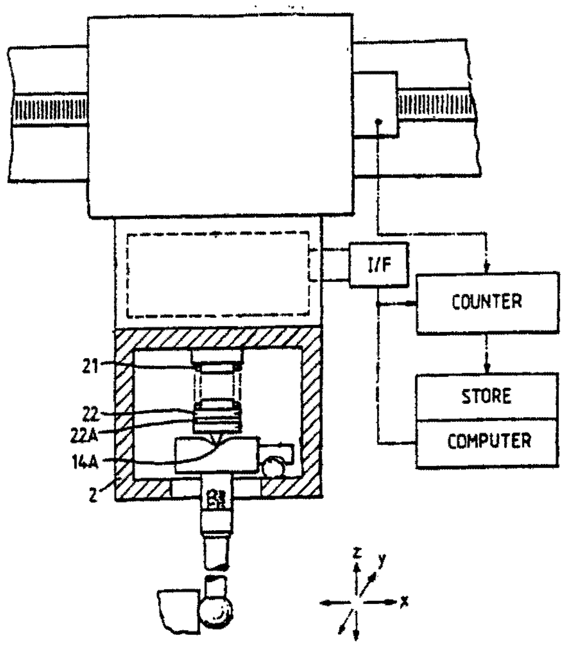
This seating construction is kinematically defined by its four at 90° intervals spaced rods terminated by balls, connected with the stylus carrier (4) and the special, confronting seat elements with a wedge form (15 - 20). The reference position is defined by a spring which acts on the stylus carrier to ensure a preload.

A typical disadvantage of this construction is the possible unambiguous defining of the reference position. If the weight of the stylus carrier and the preload is not big enough to overcome the frictional forces at the seats, the stylus carrier will not be reseated in the reference or zero position. An additional disadvantage of this type of constructions is the introduction of a non-uniform distributed probing force. This means the magnitude of the probing force is a function of the probing direction.

### 4.2.4. Renishaw TP12 probe system (1987)

This probe construction (patent EP 0 242 710) is also an extension of the classical touch trigger probe. The kinematic seat mechanism comprises three pairs of balls and three cylindrical rods, equally spaced around the axis of the stylus. The rods extends radially from the stylus holder and rest, when no external forces act on the stylus, on the pairs of balls. The stylus carrier is urged into its rest position by a spring (21). The construction allows overtravel. The pairs of balls are electrically insulated from the probe housing and electrically wired in series, so making an electrical switch, operated by the stylus. Between the spring and the stylus carrier a piezo-electric sensor (22A) is mounted (see figure 9). The flat circular piezo-electric sensor is sandwiched between an annular pressure pad with a collar (22B) for mounting the spring and a central pressure pad (see figure 10). This setup improves the effectiveness of the piezo-electric sensor. The bottom part of the sandwich element (22C) has a conical end, supporting the sensor in a corresponding recess at the centre of the stylus carrier.

The piezo-electric sensor makes the probe less sensitive to pre-travel variations because the sensing element operates probing-direction independent. This is easy to understand because the sensing function is in fact not based on the seat construction. The classical seat construction operates as a back-up system when the piezo-electric sensor fails to generate a signal, and it allows overtravel to prevent any damage. The piezo-electric sensor is extremely sensitive to shocks or accelerations. This includes a disadvantage because the probe can't be used on machines with high accelerations because the probe will generate false triggers. Even the probe can't be used at very low probing speeds, because the piezo-electric sensor will not generate a signal.



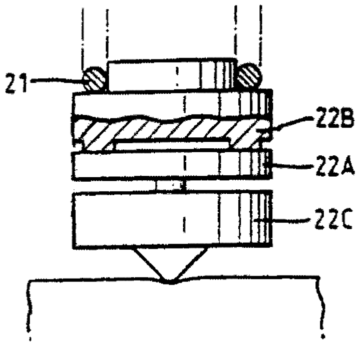


Figure 9 : Set-up of the Renishaw TP12 probe system.

Figure 10 : Sandwiched piezo-electric sensor.

### 4.2.5. Renishaw TP7 probe system (1989)

The kinematically defined seat construction used in this probe system (patent US 4,813,151) shows some similarity with the already described Zeiss ST and RST probe system.

This probe system is an extension of the (classical) touch trigger probe with three cylindrical rods and three pairs of confronting balls.

The stylus carrier is supported in a rest position on an intermediate member by means of three seat constructions, each consisting of a pair of balls (30) and a cylindrical rod (26), radially spaced at 120° intervals.

The stylus carrier is urged into its rest position by a tension spring which is connected to the intermediate member (see figure 10).

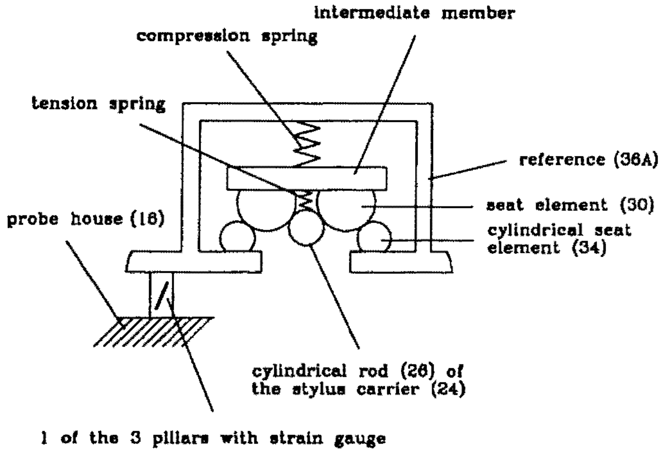


Figure 10 : Side-view of the basic principle of the Renishaw TP7 probe system. This shows 1/3 of the total seat construction.

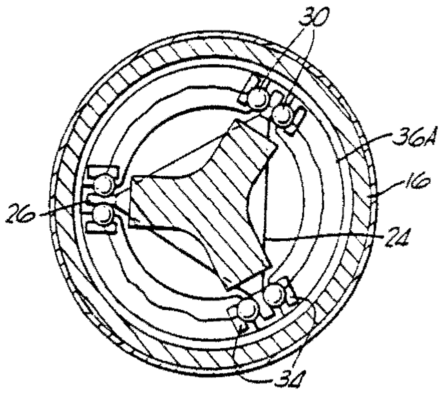


Figure 11 : Top view of the seating construction of the TP7 probe system.

The intermediate member (see figure 11) rest with its three pairs of balls on three pairs of radially oriented cylindrical rods (34), which rest on an annular roller plate (36A). The intermediate member is urged into its rest position by a compression spring. The annular roller plate is connected to the probe house (16) by at least three pillars, spaced at regular intervals. On each pillar (44) one strain gauge (46) is attached, with its longitudinal axis inclined at a certain angle to the axis of the pillar (see figure 12). The pillars form a region of relative weakness in the load path between the stylus and the probe body so that they form areas of greatest strain in that load path when a force is applied to the stylus.

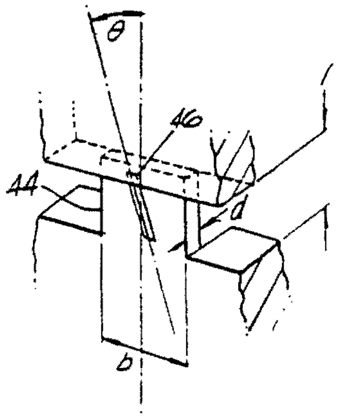


Figure 12 : One pillar of the probe system which is very sensitive to tension variations.

An advantage of this system is that the sensing function has been shifted from the seating mechanism to a real detection system. This gives the possibility to make the probe system more sensitive and this solution makes the probe less sensitive to direction-dependent pre-travel. Of course there is still a pre-travel, but due to the high sensitivity this is relative small. A disadvantage is that the reference position is based on two kinematically defined seat mechanisms, which can be subject of a lot of adverse influences like friction and contamination.

### 4.2.6. Measuring of reseating errors (1989)

In a probe which uses a kinematic defined reference position for the stylus carrier there is always the problem of accurate reseating of the stylus carrier. This is due to the presence of friction between the confronting seat elements. So the reseat position after deflection of the stylus may be different from prior position. Consequently the position of the stylus tip can vary after each displacement of the stylus, which is particularly apparent when a long stylus is used. A spring, which urges the stylus carrier in its reference position, cannot completely prevent reseat errors without unacceptable high spring forces (patent EP 0 423 307).

Therefore the invention has been done to measure the forces acting on the supporting seat elements. With these information the current position of the stylus carrier can be derived and thus the position of the stylus tip can be calculated.

Figure 13 shows how the measurement of forces acting on the seating elements can be performed.

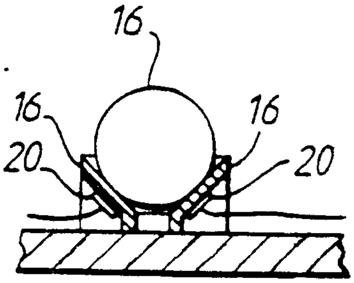


Figure 13 : Setup for measuring seating forces.

Mentioned figure 13 shows one of the three seat constructions, constraining a cylindrical rod (16) and a hollow wedge-shaped seating element which is attached to the probe housing. In each hollow wedge-shaped seating element two strain gauges (20) are suitably positioned to measure strain in the wedge structure. Each position of the cylindrical rod is related to a certain strain distribution, so with the known spring force which urges the stylus carrier into its reference position and the weight of the stylus carrier the position of the stylus tip can be derived.

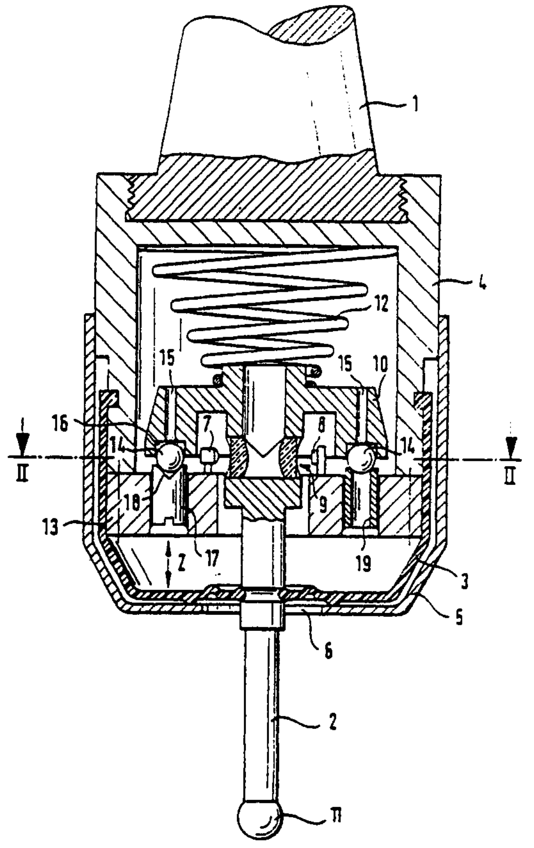
An advantage of this invention is that the position of the stylus carrier and thus the stylus tip is better known and consequently the accuracy of the probe measurements has been improved. A disadvantages is that the strain distributions also depends on the construction of the probe in use and the speed and acceleration of the probe at the moment of object contact (e.g. a star stylus with five styli has an other weight and mass moment of inertia than an ordinary one-stylus probe).

### 4.2.7. Heidenhain probe system (1988)

The Heidenhain probe system (patents DE 3 640 160 A1 and US 4,763,421) is a typical probe for machine tools. Therefore it is heavily protected from contamination and solidly constructed.

The probe (see figure 14) consists of a stylus carrier and a seating carrier (13) which is finally connected to the machine. The stylus carrier is equipped with 16 seat elements, e.g. balls (see figure 15), which are fixed to the carrier with resin cement. The reference or seating carrier, on which the stylus carrier is resting, is equipped with 16 cylinders, in each a conical shape (17) has been applied. A mechanical advantage of this construction is the relative high stiffness. An important drawback from the geometrical point of view is that the construction is not kinematically defined.

To ensure a defined seating a special assembly procedure must be performed. The cylinders (see figure 16) have eccentrically orientated conical shapes, so when the balls are positioned in between the stylus carrier (10) and the probe house (13), the cylinders (17) can rotate to make a circular contact between each ball (14) and cylinder (17) possible. Each cylinder can be adjusted in vertical direction. This process can be precipitated by a vibration device. The orientation of the balls will be fixed by resin cement which will be hardened after adjusting.



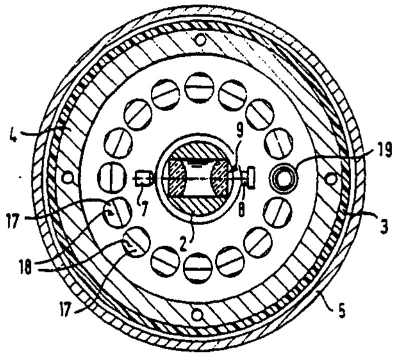


Figure 14 : Setup Heidenhain probe system.

Figure 15 : Construction of the seating elements and the position of the detector number 8.

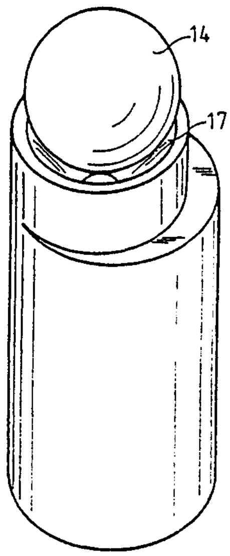


Figure 16 : Seat element with eccentrically orientated conical shape.

When all the seating elements contribute to the support the liquid resin cement is hardened and the cylinders are fixed.

A movement of the stylus is detected by an optoelectronic method. A light beam is emitted by a light diode to the position sensitive detector (PSD) (8, figure 16). The light beam shines through a set of diverging lenses, mounted in the stylus, resulting in an other position of the beam on the detector when the stylus is deflected.

### 4.2.8. Butler probe system (1988)

This construction (patent EP 0 423 209) is based on a three-point support, consisting of three small balls (50) and a big, central one (43) which is carrying the stylus (see figure 17). The stylus thus pivots about a point which is the centre of curvature of the part-spherical surface. The constraining means (20) may be a resilient, flexible element. On the stylus carrier is mounted a mirror (42) which reflects light from the source back to the sensing means.

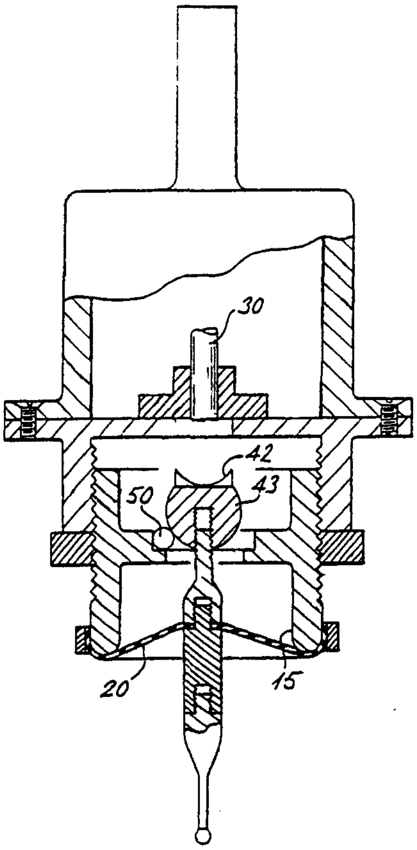


Figure 17 : Seating construction existing of a central big ball and three equispaced small ones.

The light can be emitted by a fibre optic (30) extending from a radiator of light. The change in the amount of reflected light or the change in position of the reflected beam resulting in significant movement of the stylus can be used to measure or observe stylus deflection [2, 3].

An advantage of this kind of construction is that action of this probe is not influenced by a requested accurate re-seating, because its position can be measured. A further advantage is that the sensing action is not affected by the direction of stylus deflection and that introduced pre-travel is circle symmetric in the horizontal plane.
The impossibility for direct probing along the vertical axis as well as the sliding friction between the three small balls and the big central one of the stylus carrier is a disadvantage. The latter will cause wear on the contact surfaces and stick-slip effects.

### 4.2.9. Zeiss probe system (1990)

The seat construction of this probe system (patents US 4,942,671 and US 5,018,280) has a special form. The stylus carrier (5) consists of a isosceles-triangular pyramid (a pyramid which has two sides that are the same length), rising from an equilateral-triangle base (a base that has sides that are all the same length) and truncated at a smaller equilateral triangular section which is parallel to the base (see figure 18).

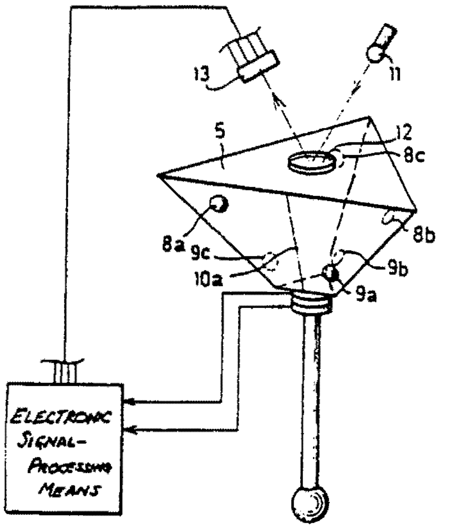


Figure 18 : The pyramid-alike probe carrier of the Zeiss probe system.

The kinematic seating is realized by six seating points (8, 9), which can exist of six balls or rods. Due to the special form of the construction, it is self-centering within a very large region, what is assured by a spring which is urging on the stylus carrier.
The detection of the deflection of the stylus (see figure 18) is done by means of a light emitting diode (11), a mirror (12) and a position sensitive detector (13).

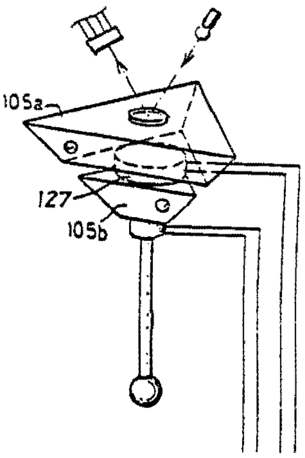


Figure 19 : Reseating mechanism with an oscillator to improve the reseating capability of the system.

To improve the reseating qualities of the described probe a vibrator is used to overcome probe-seating friction (see figure 19). To realize this a piezo-electric oscillator (127) can be used which vibrates the stylus carrier (105a, 105b) after each probe-object contact for a predetermined period of time. The frequency of the oscillations must be at least in the vicinity of the eigenfrequency of the probe carrier. Sometimes the oscillation function can be combined with the sensing function, when the sensing function is a piezo-electric element too. This method results in a reseating improvement of 0,4 $\mu$m without oscillator to 0,2 $\mu$m with oscillator.

An alternative of the seat construction is shown in figure 21. Here the reference position of the seat construction is not based on material points but on an air gap. Not known is the stability of this seating construction.

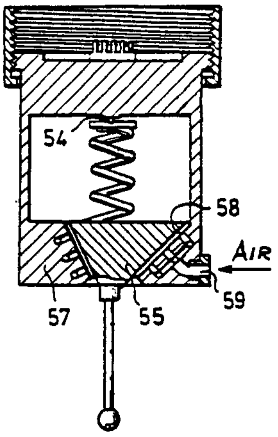


Figure 20 : Air-based seat construction.

### 4.2.10. Double kinematically defined probe system (1991)

To overcome traditional problems of kinematically defined seat mechanisms a new construction has been developed by the manufacturer Renishaw Inc..

The two main problems with seat mechanisms are :

1) the variation in pre-travel;
2) hysteresis caused by friction between the seating elements.

The first problem can be solved to make the seat mechanisms more direction independent in relation to the pre-travel. The second problem can be solved if the seat function is disconnected from the preload which is necessary to keep kinematic support elements seated on each other.

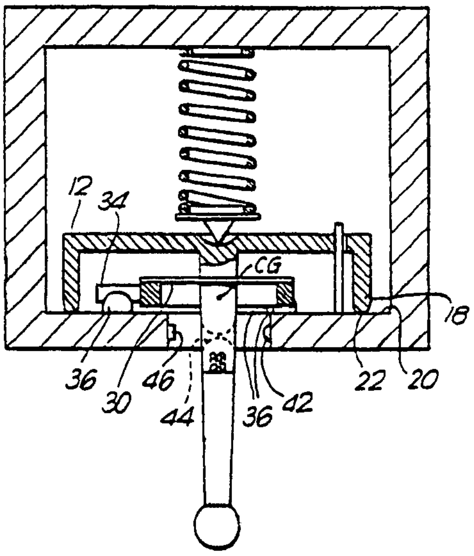


Figure 21 : Double kinematically defined probe system.

To avoid above described problems, a new probe system (see figure 21) has been developed (patent EP 0 445 945 A1). This system consists of a stylus holder (12) which is cup-shaped, having a depending skirt (18) (see figure 22). The annular bottom edge of the skirt (22) rests on a very flat internal surface of the probe housing (20). This ensures that the stylus holder is supported an a precise axial rest position. The stylus holder is urged into its position by a spring. The stylus holder is also located in a very precise lateral rest position. A diaphragm-like planar spring (30) is secured in its central position to the stylus holder and by a seat mechanism, consisting of three pairs of balls (36) and three cylindrical rods (34), all spaced at 120° intervals. With this construction the stylus holder is well-defined in a lateral position. The planar spring is stressed upward, the other spring downward, so those two springs realize a resulting small force downward. Consequently the friction between the probe housing surface and the surface of the skirt is very small.

The outside edge of the skirt functions as a rotation point when the stylus is deflected. This is because the initial deflection is accommodated only by tilting of the skirt on the probe house surface and not by movement of the kinematically mounted ring.

The force required to produce the deflection is the same for all horizontal directions. By this deflection it is possible that at least one of the cylindrical rods is lifted out of its seating with the associated balls. During the reseat operation the lateral rest position of the stylus holder is assured by the three seat constructions, consisting of three cylindrical rods and three pairs of balls. Friction in the seat elements may prevent exact lateral reseating, but the axial reseating is assured by the skirt, which is reseated by the normal spring. This flexibility is built-in by the planar spring. Deflections of the system are detected by an optical system (42, 44, 46).

### 4.2.11. Magnetically defined probe system (1989)

A completely other way of defining a stylus carrier is to define its position (see figure 22) with a magnetic field (patent DD 278 993 A5). The stylus carrier (18) is axial and lateral defined by permanent magnets (3, 4) which are connected to the probe housing (13). In the invention described in this patent the movements of the stylus in the horizontal plane are still realized mechanically, the displacement in the vertical direction is possible due to free movements in a magnetic field.

Advantages of this construction are the absence of friction, a low mass inertia and the possibility of correction for expansion of probe parts, due to change in temperature. Not known is the accuracy with which the system can position the stylus in radial and axial direction.

A disadvantage of this system is the lack of torsional stiffness, this means the use of star shaped styli is not possible because the position of the horizontal styli is not ambiguous defined.

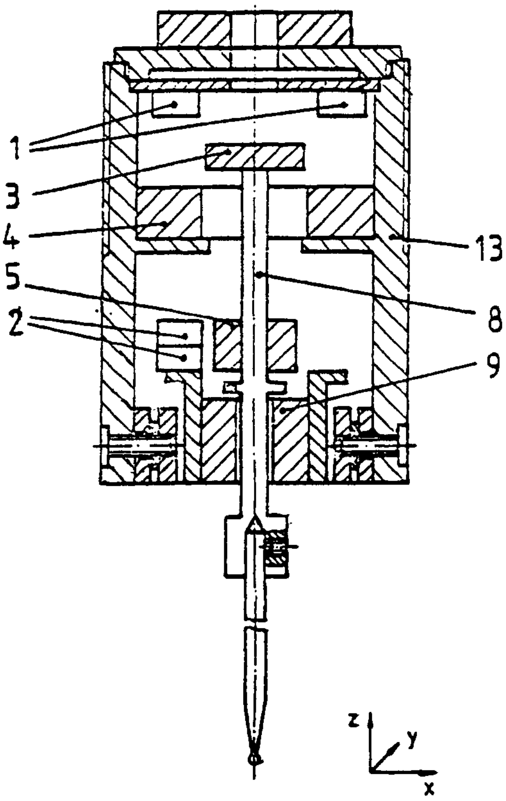


Figure 22 : Magnetically defined probe construction. Number 3 and 4 represents permanent magnets, number 1 and 2 are magnet field sensitive elements. Number 5 represents a annular shaped magnet.

### 4.2.12. Light as probing medium (1990)

One method to measure displacement of a stylus carrier is to use light as detection medium. One example is shown in figure 23 (patent EP 0 415 579 A1). An interferometer cube (100) is mounted on the stylus carrier (118). A laser beam (102) entering the interferometer is split by a beam splitter (104).

One part of the beam is reflected with an angle of 90° to a mirror mounted on the stylus carrier. The fraction of the beam which passes through the beam splitter without deviation, is reflected by a mirror and recombined with the deviated and reflected beam to form an output beam. This beam forms, after an other deflection by a mirror, an interference pattern at a detector.

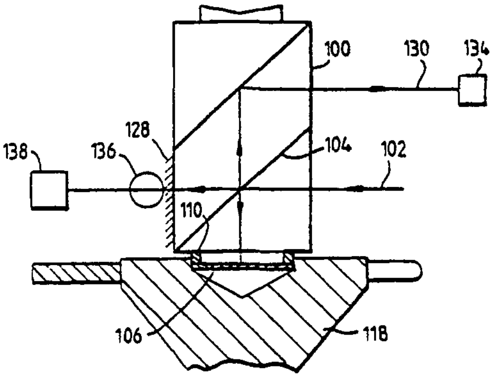


Figure 23 : Interferometer mounted on a stylus carrier and PSD, represented by number 138.

Vibration of the mirror mounted on the stylus carrier will cause a change in the path length of the laser beam which manifest itself as an shift in the interference pattern at the detector.

The fraction of the beam which passes through the beam splitter without deviation can be used as a reference axis, relative to which the position of the stylus carrier can be measured. The stylus carrier is kinematically seated. This principle is already described in an earlier section of this report.

The reference axis provides the possibility to measure the reseating of the stylus carrier after being deflected. This is performed with a transparent glass ball (136), positioned behind the semi-transparent mirror of the interferometer. The fraction of the beam entering the ball will be refracted by the ball according its point of entry. The refracted beam is incident upon a two-dimensional position sensitive detector (138). When after a deflection of the stylus the position of the beam on the position sensitive detector has changed, the re-seating was incorrect.

Also the stylus tip (426) of the probe (416) can be used as sensing element (see figure 24). This is achieved by providing an optical fibre (406) inside the stylus. The end of the fibre (D) is situated inside the (preferably centre of the) stylus tip, the latter must be spherical and manufactured of a translucent material. Light leaving the fibre is incident upon the interior surface of the sensing tip at an angle which is approximately perpendicular to the local surface. Consequently some light will be reflected back into the fibre. When the stylus tip contacts an object, the tip will deform so some light is not reflected back anymore into the fibre. Additionally the path length of some of the light reflected back into the fibre will change, due to deformation of the sensing tip. The change of state of the sensing tip may be detected either by observing the change in intensity or a change in path length.

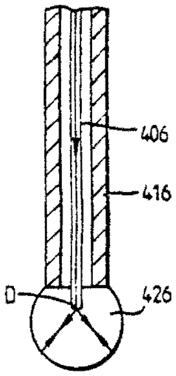


Figure 24 : Stylus tip as sensing element.

## 4.3 Review

A brief overview about the last 20 years of probe development have been given in last paragraph. Presented are important or remarkable principles as far as retrieved by patented information and publications by the Eindhoven University of Technology. From literature and patents it can be concluded that last 20 years a lot of work has been done to improve the accuracy of touch trigger probes. One important reason is that the field of applications is much bigger than for measuring probes, which are not discussed here.

From the presented overview it can be concluded that manufacturers had to cope with three main problems :

1) friction in the reseating construction(s);
2) increase of trigger-sensitivity without loss of utility as a results of false-triggering caused by accelerations;
3) decrease of trigger force deviation as function of the probing direction.

The popularity of touch trigger probes is due to their relatively simplicity of construction, their robustness, their ability of relatively fast probing in comparison to measuring probes and because they are relatively inexpensive.

The simplicity of the construction is due to the fact that touch trigger probes only has to observe *movement* of the stylus carrier or stylus. The *amount* of movement doesn't have to be observed. This implicates that, when the reference position is defined and this construction has a zero re-positioning error, only one sensor has to be used. Unfortunately the condition of a defined reference position with a (close to) zero re-positioning error can probably not completely be fulfilled. Examples of probes for which only a kinematically defined reference position of the stylus carrier was not sufficient, are presented in 4.2.6., 4.2.8., 4.2.9 and 4.2.12. In these designs the manufacturers decided to measure the re-position error or to reduce it with some extra equipment to overcome friction.

Several measurements have been done, e.g. described in [1, 2, 17, 18], to detect the repeatability of a probe system. In this repeatability error are included error sources of mechanical and electrical nature. In the part of the repeatability error due to mechanical imperfections probably a part is responsible for the re-positioning error. Also some experiments have been done to observe hysteresis. The results of both types of measurements indicates that the re-position error can be significant.
An explanation for the re-position error can probably found in (the fluctuations of) the friction coefficient between the separated contact surfaces, the standard deviation of the roughness peaks and the mean radius of those peaks. Further error sources can be probably found in the effects of current on the separated contact surfaces, when the construction of the reference position is also used as a electrical switch. A real random error source is the probable presence of contamination between the contact surfaces.

Some future research must be focused on above described aspect of the re-positioning error to obtain more fundamental knowledge about this surface-to-surface process. Based on this research a decision can be made about a possible application of components with separate contact-surfaces in reseating mechanisms, or an alternative construction to be developed.

Apart from the re-positioning error it can be noticed that manufacturers try to increase the sensitivity of their probe systems. This results in a decrease of the direction-dependent probing force which is, without any means, inherent to a kinematically defined reference position.

The raised sensitivity minimizes the deformation of the object, the stylus (tip) and the inner parts of the probing system before a trigger will occur. A negative effect of this raised sensitivity is sometimes the also increased sensitivity to the so-called " false triggering ", which means that the system observes some kind of vibration or acceleration and interprets this as a touch with an object.

" False triggering " can strongly limit the usefulness of the probe. False triggers usually stop the operation of the machine because apparently a workpiece edge has been detected. This is especially dangerous when the probe generates a false trigger just before a real trigger should have happen.

To overcome the problem of false triggering, two solutions have been applied upto now :

1) the mechanical solution : the preload has been increased upto the level the stylus carrier cannot make any movement caused by accelerations or vibrations except for a real touch of an object. The increased preload strongly influences the trigger sensitivity of the system and reduces the measuring accuracy of the probe system;
2) the software solution : the trigger signal will be tuned at a certain suitable threshold level. When a trigger occurs the duration of the generated signal will be observed and when the level of the signal exceeds the threshold level for a arbitrary time interval the trigger signal will be treated as a real trigger for the machine to make a read out of its scales. The justification of the threshold is a criterion for the trigger sensitivity and the " false trigger " problem.

It is clear that above described problem can be treated apart from measurement method. For touch trigger probes in principle two measurement methods can be distinguished :

1) measurements of movements of probe components;
2) measurements of stresses of probe components (see e.g. 4.2.4, 4.2.5, 4.2.9).

It must be clear that the second method in its fundamentals must be more accurate and sensitive than the first one. Always stress will occur first in components and this stress in a certain probe component will increase upto some movement will occur. This implicates that observations done by measuring stresses will occur earlier and in principle are more accurate because the chain between touch - stress - observation is shorter than the chain touch - movement - observation, so the number of error sources which can influence the measuring accuracy is, in theory, smaller. In practice of course everything depends on the practical realization of the probe system and the accuracy of the sensing means.

The third mentioned problem, the decrease of trigger force deviation as function of the probing direction has not yet been solved by the present probe systems. In fact this problem is tied up with the increase of sensitivity of probes.

The whole problem of touch trigger probes can be described as follows :
the increase if probe sensitivity decreases the sensitivity for trigger-force deviations as function of the probing direction, but increases the sensitivity to false triggering, which is combined with a not-controlled re-seating of the stylus carrier.

# 5. Dynamic probing

## 5.1. Introduction

In a measuring process a measuring point can be taken in two different ways :

1) semi-static probing, i.e. the probing speed is close to zero. This method is used by the vast majority of the analogue probe systems. These kind of probes make contact with an object after which the machine is regulated back until the three measuring systems are close to their reference points, under the condition that the probing force has the value which was chosen in advance. Now the scales of the probe and the machine are read and combined to a final coordinate.
2) dynamic probing, i.e. the probing speed must have a certain value to trigger the probe system. This is of course inherent to the method of generating a signal used by these kind of probes.
   Dynamic probing is also used by analogue probes when they are used in a special purpose, namely scanning. During scanning (digitizing) a surface of an object the relevant scale of the analogue probe is sampled every discrete displacement of the machine in the main direction of movement to obtain the wanted coordinates. The probing force of touch triggering probes which in most cases can be adjusted is only valid under very special probing conditions, so this force can be supposed to be variable within certain limits.

Because dynamic effect are in most cases much more important rather than static effects, the effects included in the semi-static probing process will not be taken into consideration.

Assuming the most simple touch trigger probe, a stylus carrier with three cylindrical rods resting on three pairs of balls, the probing process is as follows.

When the probe is accelerated by the machine to measure a point on an object the position in space of the probe tip can change due to mass moments of inertia of the stylus. These moments can be significant when styli with extensions are used. The effects of deformation will manifest themselves basically in deformations of the seat elements or their connection to the probe housing. When the stylus tip touches the object, the tip and the surface of the object will deform due to the impact force. Additionally the stylus will undergo, before triggering, a deformation due to the force of probing and the force of the spring which forces the stylus carrier into its seatings.

When the probe is going to trigger, this means going to rotate around two of its three seating elements, the seating forces get another distribution, causing a bigger deformation of two of the seating elements and a lesser deformation of the third one, resulting in a change of the kinematically defined reference position before triggering will occur.
When triggering has occurred it is not clear if the carrier could reseat when the stylus tip was already free from the object surface or if it was still in contact. The latter causing a forced reseating, which is not necessarily the kinematically defined one, due to friction in the seating elements.

Of course above described phenomena can differ in importance in relation to the total unaccuracy of the probe system. But it must be clear that unaccuracy of the probe system can be introduced by errors of probe components within the submicron field. A few examples will illustrate this statement.

Example 1
Assume a probe system with three seating elements, each consisting of a pair of balls and a cylindrical rod, the latter connected to the stylus carrier. For simplicity reasons this can be modeled as shown in figure 25. When a maximum reseating error (which is measured at the stylus tip, perpendicular on the axis of the stylus) is allowed of 0.5 $\mu$m, represented as " x " in the figure, it can be calculated that, with a stylus length of 40 mm, the resulting maximum vertical error $\Delta h$ in reseating is 0.1 $\mu$m. This implies that the seating construction must comply with the strictest requirements in relation to the surface roughness, the accuracy of shape of the components (here the balls and the rods), the accuracy in orientation of the essential components and the rigidity of the connection of the seating components with the probe housing.

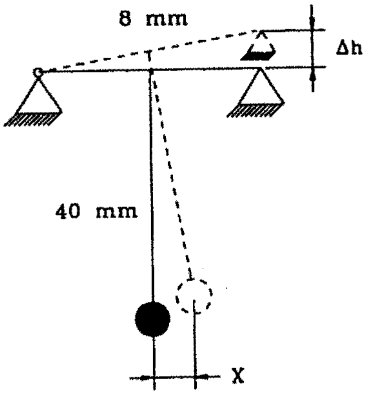


Figure 25 : Simple model of a triggering probe.

Probably more important, from this example it can be concluded that the sensing means, which has to detect a deflection of the stylus, must be very sensitive. To be able to measure very accurate, for example to detect a deflection of 0.2 $\mu$m, the sensing means must be able to detect movements of the stylus carrier of approximately 0.04 $\mu$m (using the dimensions of the components mentioned in figure 25). Hereby it is assumed that the movement at the stylus tip is linearly transferred to the stylus carrier at which the deflection is observed.

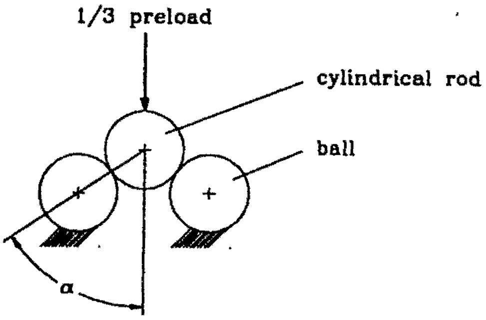


Figure 26 : Seating construction and the definition of the orientation of the components.

Example 2

Probing will cause, as already described above, another distribution of the seating forces. The effect on the reference position is, in a simplified model, calculated. Taken into consideration is the static load on two balls as function of their orientation to the cylindric rod of the stylus carrier (see figure 26) when the spring load, which urges the carrier into the seats, is 1 Newton. The radii of the ball and the rod are postulated. For this situation the approach of the two bodies (ball and rod) is calculated for three different material combinations (see figure 27). The approach is defined as the sum of the deformations of both confronting bodies on a line through both central axes, perpendicular on their common surfaces, i.e. their common Hertzes-flattening of their surfaces.

Assuming that the force acting on the stylus and acceleration forces will cause an increasing preload of 3 Newton on the stylus carrier, the resulting approach is showed in figure 28. The relevant formulas used to calculate the curves are [20] :

$$\delta = \varkappa_{\omega} \cdot \sqrt{\frac{9 \cdot F^2}{E_r^2 \cdot r}} \qquad [m] \qquad (5.1)$$

$$\frac{1}{E_r} = \frac{1}{2E_{r_1}} + \frac{1}{2E_{r_2}} \qquad [N/m^2] \qquad (5.2)$$

$$\frac{1}{E_{r_i}} = \frac{m_i^2}{m_i^2 - 1} \cdot E_i \quad , i = 1, 2 \qquad [N/m^2] \qquad (5.3)$$

$$m_i = \frac{1}{\nu_i} \quad , i = 1, 2 \qquad [-] \qquad (5.4)$$

In this formula is :

$\delta$ : approach of two contact surfaces [m];
$\varkappa_{\omega}$ : $0{,}630 \cdot \omega^{-9/44}$;
$\omega$ : curvature ratio [-], $\omega = \frac{R}{r} \geq 1$;
$F$ : normal contact force [N];
$E_r$ : reduced elasticity modulus [N/m$^2$];
$\nu$ : Poisson's ratio [-].

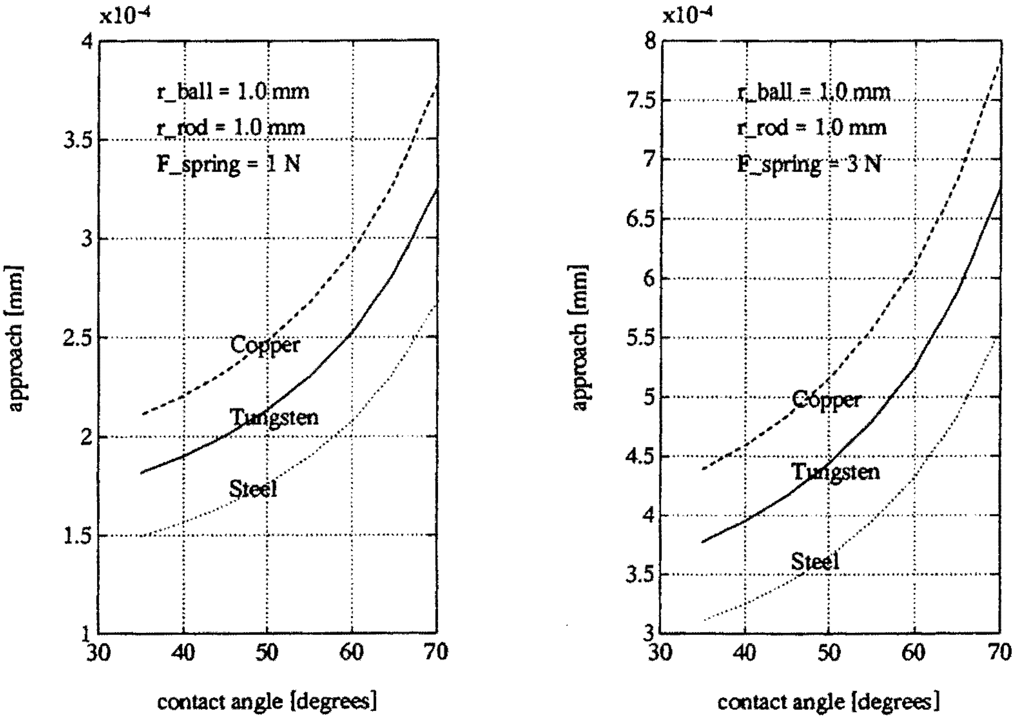


Figure 27 and 28 : Approach of the cylindrical rod to the ball as combinations with steel with a preload of 1 Newton and 3 Newton.

From this figure can be concluded that the approach between the rod-centre and the ball-centre is approximately 0.10-0.20 $\mu m$. Combined with the decreasing of approach of the unloaded seating element this will result in a maximum vertical error $\Delta h$ (see previous example) of about 0.10 $\mu m$, resulting in a reference-position error of 0.5 $\mu m$, calculating with a stylus length of 40 mm.

The approach due to the (dynamic) probing force between the ruby stylus tip (6 mm) and a steel polished surface is about 0.25 $\mu m$, assuming the maximum force is 1 Newton, see figure 29 [15]. When a grinded surface is probed with the same force the approach can be up to 10 times bigger, i.e. 2.5 $\mu m$.

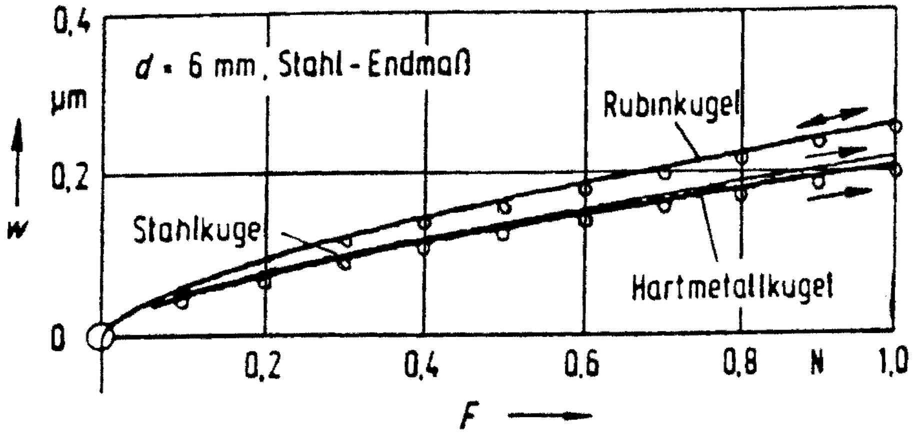


Figure 29 : Approach between a stylus tip and a polished endgauge of steel as function of the material of the stylus tip and the contact force.

## 5.2. Dynamic model

To get a better understanding of above described dynamic problems, which knowledge is indispensable for the development of a new probe type, dynamic analysis of the probing process must be performed. A proposal for a dynamic model of the probe is shown in figure 30.

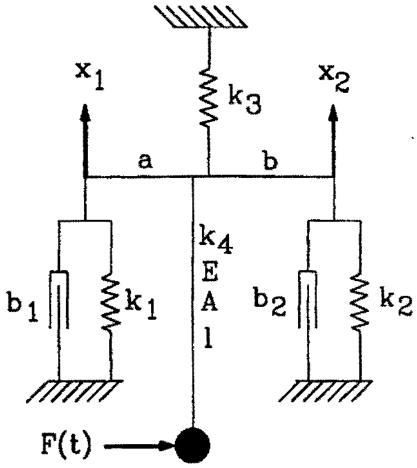


Figure 30 : Dynamic model of a touch trigger probe.

The parameters $b_1$ and $k_1$ represent the two seating elements which are more dynamically loaded when a triggering is going to occur. The parameters $b_2$ and $k_2$ represent the third seating element. These are the elements about which the stylus carrier is going to rotate after contacting the object. The parameter $k_3$ represents a preload which urges the stylus carrier into its seating elements. The parameters $k_4$, E and A represent respectively the stiffness of the stylus, the modulus of elasticity and the section of the stylus. The parameters $x_1$ and $x_2$ are the variables by which the movements of the stylus carrier is defined. The conditions are :

$x_1 > 0$ : $k_1 = 0$, $b_1 = 0$
$x_2 > 0$ : $k_2 = 0$, $b_2 = 0$

The probing force is represented by F(t). The probing force is a function of the time. As illustration is shown in figure 31 the maximum impact force as function of the probing speed and the radius of the stylus tip made of steel [9].

The attractiveness of this model is that the numerical results can be verified with, at the Laboratory of Precision Engineering available, equipment. Further nearly all the presented probes in previous sections can be modeled with above presented model.

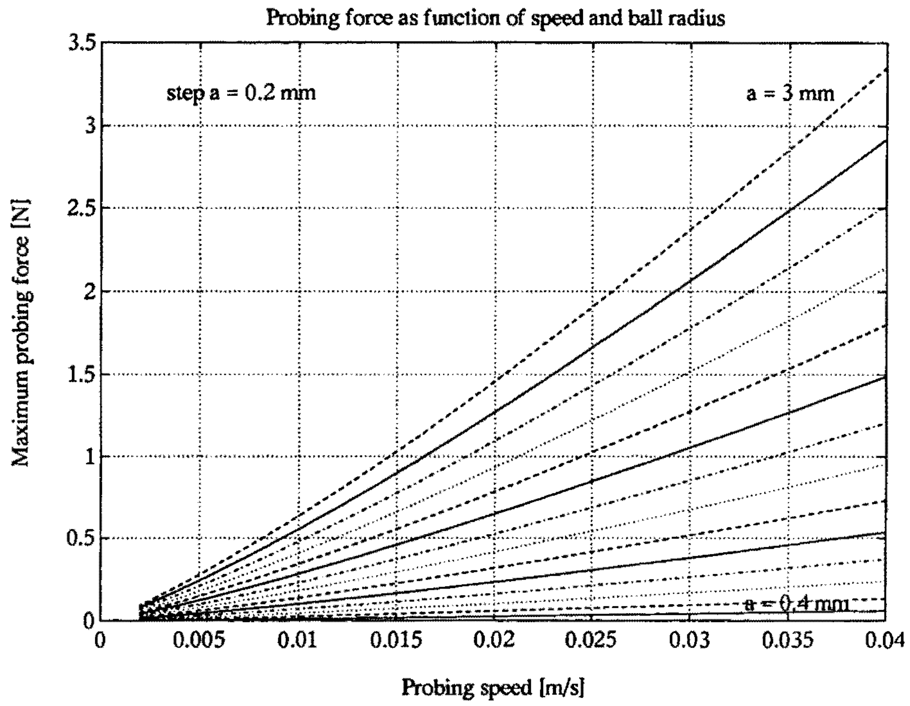


Figure 31 : Maximum probing force as function of the speed and the radius of the stylus tip. The stylus tip and the object surface are supposed to be made of steel. Not taken into account is the mass moment of inertia of the stylus.

Figure 29 is based on the next formula [9] :

$$F_{max} = E_r \cdot a^2 \cdot \frac{2}{3} \cdot \left[\frac{5}{2}\pi\right]^{3/5} \cdot (1 - \nu^2)^{-2/5} \cdot \left[\frac{v}{\sqrt{E/\varrho}}\right]^{6/5}, \text{[N]} \qquad (5.5)$$

In this formula is :

$F_{max}$ : maximum contact force [N];

$E_r$ : reduced elasticity modulus [N/m$^2$];

$a$ : radius of the ball [m];

$\nu$ : Poisson's ratio [-];

$v$ : speed of the ball [m/s];

$\varrho$ : density of the material of the ball.

# 6. Research to be done

## 6.1. Dynamic modeling of touch trigger probe and probing process

To study the influences of dynamic probing more in detail, the probe system described in chapter 5 can be modeled more in detail. This will give a better understanding of the process of probing, especially when probing with higher speeds than usual. With this model probably design rules for fast touch trigger probes can be defined.
The make a realistic general model it has to be figured out how the different probe components have to be modeled. This can be done partly analytical, partly experimental. To verify the whole model experiments must to be done to control the fitness of the model.

One experimental setup is nearly realized. This setup is based on an object reflective sensor (ORS) which is mounted behind the stylus by a construction which is fixed to the probe house (see figure 32). The sensor holder is made of aluminium to restrict the mass connected to the probe house. In this case the probe house is the reference of the sensor. The ORS consists of a diode and a detector, the latter is sensitive to the amount of light which is reflected by the stylus.

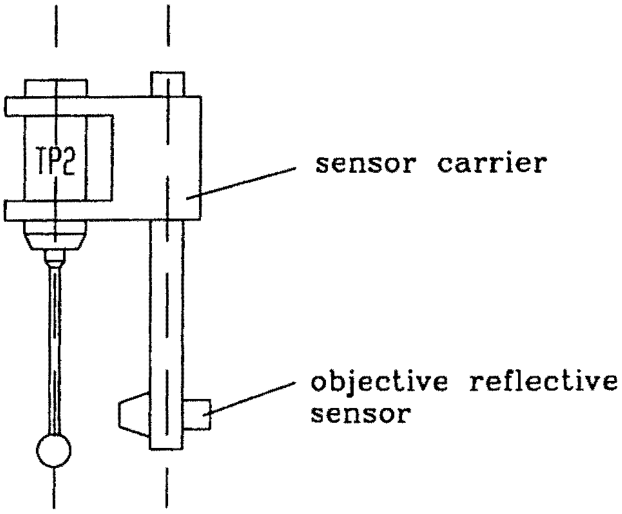


Figure 32 : Measurement setup for dynamic measurements.

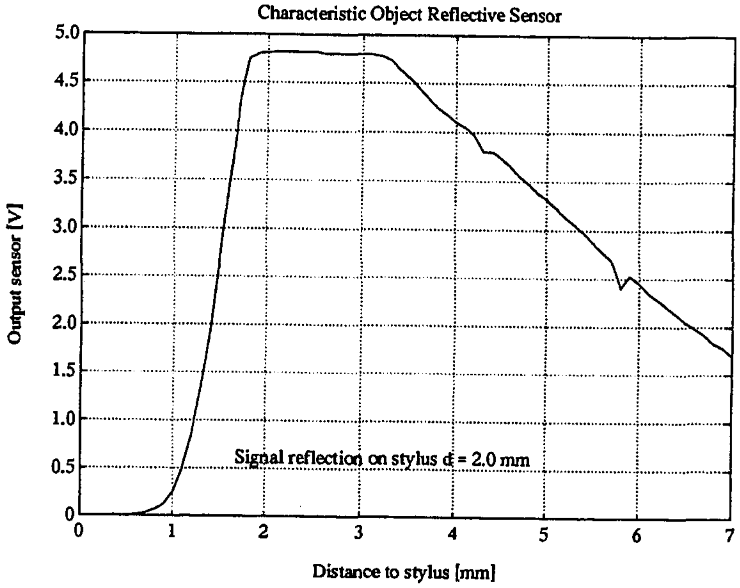


Figure 33 : Output characteristic of the object reflective sensor.

In figure 33 is shown the characteristics of the sensor. The output is realized on a polished stylus of steel with a diameter of 2,0 mm. With the sensor mounted behind the stylus on a distance of about 3-4 mm the relative displacements of the stylus can be observed during a probing action. The two dips in the curve are probably due to reading errors. The maximum frequency which can be measured is about 350 Hz.

To obtain more information about the probing process the probe will be used to touch a piezo-electric sensor to measure the probing force as a function of the time and the velocity of the probe.

The signals of the ORS, the piezo-electric sensor, the trigger signal of the probe and the processed signal are the input for a four-channel oscilloscope. With these signals the probing force, the pre-travel, the vibration of the stylus and the time delay probably can be measured or derived. In figure 34 two signals are displayed. Signal A is the trigger signal of the probe, signal B is the signal generated by the piezo-electric sensor. The difference in starting point of the slope is the pre-travel.

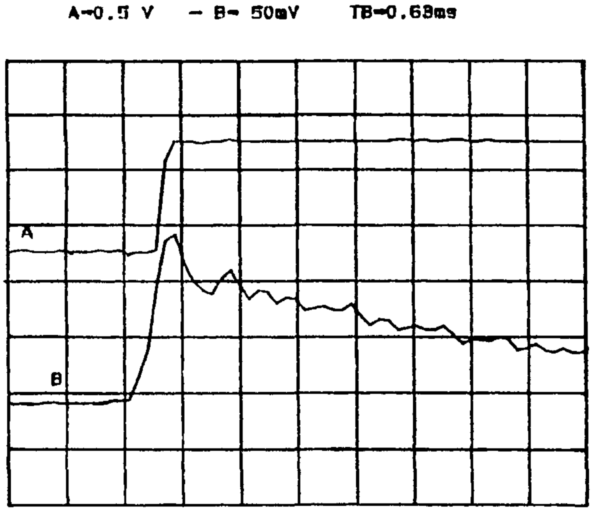


Figure 34 : Measured pre-travel of the probe by a probing speed of 50 mm/s.

## 6.2. Seating construction

As already shown in chapter 4 and 5 the kinematic defined seat construction has some disadvantages. As noted in paragraph 4.3 some research must be focused on the aspect of re-positioning of elements to obtain some more fundamental information about the surface-to-surface process. Therefore the whole whole probing process must be modeled to get more understanding of dynamic forces on probe components. Together with the already existing knowledge about surfaces and their geometric characterization, it is probably possible to decide the type of kinematic constructions with separated bearing constructions to define a reference position, is still useful for high precision and high speed probes. Included in this research will be the influences of current on the contact surfaces, because most of these constructions are also used as electrical security switch. If this study gives some reason to depart from this type of constructions efforts will be put in designing constructions based on (non-) kinematically defined stylus carriers without any friction. Probably it is better, and more accurate, to measure continuously the position of the stylus while the stylus carrier can move freely (no friction) in the probe house. This ensures that the position of stylus tip is always known. Solutions have to be found to solve problems like damping of the movements of the carrier and the required stiffness to realize a certain measuring force.

## 6.3. Analysis of temperature effects on the accuracy of probes

At the moment touch trigger probes are already in use on machine tools, but also on CMMs which are operating in unconditioned rooms. This means machine and probe are subject to influences of the environment. Especially when probes are used on machine tools the presence of heat sources will introduce measuring unaccuracy. This is probably significant because the variations in temperature in the machine are really big. Due to radiation, convection and conduction the probe will also absorb some heat. This will not cause only absolute geometric errors but also relative geometric ones, when the measuring process takes some time in which the temperature of the probe can change. To quantify the effects of heat on probe systems an analysis shall be done.

## 6.4 Software correction

If it seems impossible to avoid systematic errors, software shall be developed to improve, if possible, the probe behaviour.

Re-adjusted planning 12/92

| **period** | **subjects to be studied and actions** |
|---|---|
| | (kinematic) def. reference points and related problems |
| 01-93 | |
| 02-93 | report (2 weeks) |
| 03-93 | dynamic behaviour of probes, possible sensing methods, thermo-mechanical behaviour |
| 07-93 | holiday |
| 08-93 | dynamic behaviour of probes, possible sensing methods, thermo-mechanical behaviour |
| 10-93 | milestone report, combined with decision kin./non-kin. |
| 11-93 | development of possible concepts |
| 02-94 | realization concept |
| 07-94 | holiday |
| 08-94 | testing concept |
| 12-94 | report |
| 01-95 | adaptation concept |
| 03-95 | testing revised concept |
| 04-95 | writing thesis |
| 08-95 | |

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