U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

AD-A036 095

AGARD FLIGHT TEST INSTRUMENTATION SERIES

VOLUME 8. LINEAR AND ANGULAR POSITION MEASUREMENT OF AIRCRAFT COMPONENTS

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT, PARIS, FRANCE

JANUARY 1977

(16) - Design and Application of Resolvers, Bulletin IRDA-9 American Electronics Inc., Fullerton, California.

(17) - Two-Speed Autosyn Synchros, Publication W 26, Elliott Brothers Ltd., London SE 13.

(18) - Kearfott Brushless Synchros, Kearfott Products Division, Little Falls, N.J., 1968.

(19) - Kollsman Synchrotels, Publ. N.90-500-2-61, Kollsman Instr. Corp., New York, 1961.

(20) - Arinc Reports 407 and 407-1, Synchro System Manual, Aeronautical Radio, Inc., 1700 K.St., N.W. Washington 6 DC, 1964.

(21) - Synchro Conversion Handbook, ILC Data Device Corporation, Airport International Plaza, Bohemia, Long Island, New York, 1974.

(22) E.E. Herceg - Handbook of Measurement and Control, HB-72 Schaevitz Engineering, Pennsauken, N.J., July 1972.

(23) - AC Inductive Pick-offs, Publ. No. 753/3, Sperry Gyroscope Comp. Ltd., Middlesex, England.

(24) - DC/DC LVDT Displacement Sensor, Product Information Sheet No. 1304, Penny and Giles Ltd., Mudeford, Christchurch, Hants, England, 1971.

(25) A. Pool, D. Bosman (editors) - Basic Principles of Flight Test Instrumentation Engineering, AGARDograph No.160, Vol.1.

AD-A 026 835

AGARD-AG-160-VOL. 8

AGARDograph No.160

AGARD Flight Test Instrumentation Series
Volume 8
on
Linear and Angular Position Measurement of Aircraft Components

by

J.C.van der Linden and H.A.Mensink

AGARD-AG-160
Volume 8

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARDograph No.160 Vol.8

LINEAR AND ANGULAR POSITION MEASUREMENT OF AIRCRAFT COMPONENTS

by

J.C.van der Linden and H.A.Mensink

Volume 8

of the

AGARD FLIGHT TEST INSTRUMENTATION SERIES

Edited by

K.C.Sanderson and A.Pool

This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.

THE MISSION OF AGARD

The mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Exchanging of scientific and technical information;
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Program and the Aerospace Applications Studies Program. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

Published January 1977

ISBN 92-835-1236-8

Printed by Technical Editing and Reproduction Ltd
Harford House, 7 9 Charlotte St, London, W1P 1HD

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AG-160 Volume 8	ISBN 92-835-1236-8	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title LINEAR AND ANGULAR POSITION MEASUREMENT OF AIRCRAFT COMPONENTS

7. Presented at

8. Author(s)	9. Date
J.C.van der Linden and H.A.Mensink	January 1977

10. Author's Address	11. Pages
National Aerospace Laboratory (NLR) Amsterdam, The Netherlands	46

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Flight tests	Control surfaces	Sensitivity
Position indicators	Measuring instruments	Indicating instruments
Aircraft equipment	Frequency response	

14. Abstract

This AGARDograph is the 8th of the AGARD Flight Test Instrumentation Series and concentrates on the flight test instrumentation for determining the position of movable aircraft components such as:

- rudder, elevator and aileron surfaces,
- wing flaps, trim tabs, speed brakes, spoilers,
- power-control levers,
- elements of nosewheel-steering systems and of landing gear mechanisms, etc.

The sensitivity and frequency responses of the various systems used for making these measurements are discussed in the following groups with examples:–

- potentiometers,
- synchros,
- inductive systems,
- digital systems.

This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.

PREFACE

Soon after its foundation in 1952, the Advisory Group for Aeronautical Research and Development recognized the need for a comprehensive publication on flight test techniques and the associated instrumentation. Under the direction of the AGARD Flight Test Panel (now the Flight Mechanics Panel), a Flight Test Manual was published in the years 1954 to 1956. The Manual was divided into four volumes: I. Performance, II. Stability and Control, III. Instrumentation Catalog, and IV. Instrumentation Systems.

Since then flight test instrumentation has developed rapidly in a broad field of sophisticated techniques. In view of this development the Flight Test Instrumentation Committee of the Flight Mechanics Panel was asked in 1968 to update Volumes III and IV of the Flight Test Manual. Upon the advice of the Committee, the Panel decided that Volume III would not be continued and that Volume IV would be replaced by a series of separately published monographs on selected subjects of flight test instrumentation: the AGARD Flight Test Instrumentation Series. The first volume of the Series gives a general introduction to the basic principles of flight test instrumentation engineering and is composed from contributions by several specialized authors. Each of the other volumes provides a more detailed treatise by a specialist on a selected instrumentation subject. Mr W.D.Mace and Mr A.Pool were willing to accept the responsibility of editing the Series, and Prof. D.Bosman assisted them in editing the introductory volume. In 1975 Mr K.C.Sanderson succeeded Mr Mace as an editor. AGARD was fortunate in finding competent editors and authors willing to contribute their knowledge and to spend considerable time in the preparation of this Series.

It is hoped that this Series will satisfy the existing need for specialized documentation in the field of flight test instrumentation and as such may promote a better understanding between the flight test engineer and the instrumentation and data processing specialists. Such understanding is essential for the efficient design and execution of flight test programs.

The efforts of the Flight Test Instrumentation Committee members and the assistance of the Flight Mechanics Panel in the preparation of this Series are greatly appreciated. In particular, thanks are due to Professor T. Van Oosterom who until 1976 was Chairman of the Flight Test Instrumentation Committee and held this position during the preparation of this Volume.

N.O.MATTHEWS
Member of the Flight Mechanics Panel
Chairman of the Flight Test
Instrumentation Committee.

CONTENTS

LINEAR AND ANGULAR POSITION MEASUREMENT OF AIRCRAFT COMPONENTS

by

J.C. van der Linden and H.A. Mensink
National Aerospace Laboratory (NLR)
Amsterdam
The Netherlands

1.0 INTRODUCTION

This volume concentrates on flight test instrumentation for determining the position of movable aircraft components such as:

rudder, elevator and aileron surfaces,
wing flaps, trim tabs, speed brakes, spoilers,
power-control levers,
elements of hydraulic systems and airconditioning systems,
elements of nosewheel-steering systems and of landing gear mechanisms,
etc.

The application of position measuring devices in transducers, where the integration of the position measuring device with the other parts of the transducer is usually done by the instrument manufacturer, is not a primary subject of this volume. Many of the details about the position measuring devices discussed here apply, however, to cases where they form an integral part of a transducer.

The discussion in this volume has been limited to measurements of the relative positions of two aircraft components. Measurements of deformations inside the construction of a component, such as strain measurements, are not included. They have been discussed in Volume 7 of the AGARD Flight Test Instrumentation Series (Ref.(1)). Also excluded are measurements of displacements with respect to space, such as displacements obtained by integrating velocity or double-integrating acceleration as for instance is performed by inertial navigation systems.

The measuring ranges of the instruments discussed in this volume vary from less than 1 mm to several hundreds of mm for linear displacements and from less than 1 degree to several times 360 degrees for angular displacements. The required frequency response is generally from zero to a few Hz; frequencies of up to 30 Hz can occasionally occur. Many systems exist for the measurement of such displacements. In this volume only those regularly used during flight testing are discussed. These can be classified in the following groups:

- potentiometers,
- synchros,
- inductive systems,
- digital systems.

A uniform classification system for position-measuring systems does not exist and there is a large measure of confusion concerning terminology. In the literature a subdivision of potentiometers into resistive, capacitive and inductive potentiometers is often used. This is not common usage, and in this volume the term "potentiometer" is reserved for resistive devices. Another example to illustrate how methods of classification differ applies to AC synchro systems, which are often considered to be special inductive systems. In this paper they are treated separately, because there are some aspects that apply only to the special characteristics inherent to these systems. Inductive systems are not always regarded as a main group, but often as a subgroup of reluctive systems. Sometimes inductive and reluctive systems are considered as separate groups. As the number of inductive and reluctive systems available for the measurements discussed in this volume is very limited, and the principles and characteristics differ only slightly, they are treated in this paper as one group.

In some cases it was difficult to determine in what group a specific system could best be classified. In such cases rather arbitrary decisions were made. The "induction potentiometer" is described neither in Chapter 3.0, potentiometers, nor in Chapter 5.0, inductive systems, but in Chapter 4.0, synchros, because it is a device that is similar to most members of that group in appearance and characteristics. The device is treated under its second, less used, name "linear synchro".

It must be stressed that only those measuring systems are discussed that are frequently used for position measurement during flight tests and that have proven their usefulness in practice. Some systems that were frequently used in the past but have currently lost their importance, are briefly mentioned, especially when an interesting principle formed the basis for such systems. Examples are the synchrotel system and the magnesyn system. Systems frequently used for displacement measurements and treated as such in many handbooks on this subject can have certain disadvantages when used as position transducers for flight test work. Such systems, that are only very rarely used for the types of measurements discussed in this volume, have not been treated here. Examples of such systems are capacitive systems, optical systems, photo-electrical systems, and piezo-electric systems.

General considerations concerning the above-mentioned types of transducers are given in Refs (B1) to (B6) and (2).

Signal conditioning equipment, used in combination with transducers for flight tests will be extensively treated in a later volume of the Flight Test Instrumentation Series. Only some aspects on signal conditioning for transducers, used for position measurement are briefly considered in this volume.

2.0 CONSIDERATIONS AFFECTING THE CHOICE OF A SYSTEM

The choice of a transducer and the associated linkage and signal conditioning systems for each particular application depends on many things, the most important of which will be briefly discussed in this chapter.

Availability. On-the-shelf availability can be a major consideration for choosing a specific type of transducer, especially (but not exclusively) for measurements with a short lead time. In addition to the availability of a transducer with suitable characteristics and dimensions, the availability of suitable linkages or signal conditioning equipment must be considered. Several types of transducers are manufactured with suitable linkages attached, which reduces the in-house development and installation time. For many of the applications considered here, several types of transducers could be used with equal success. In such cases the availability may be the decisive factor.

Experience. In newly developed systems there is always a chance of unexpected trouble. The experience of the team which designs, installs and maintains the system with a particular type of installation may be one of the main factors contributing to success. On the other hand, a watchful eye must be kept upon new developments, and for every application it must be considered whether or not other (newer) systems will better meet the requirements. Conservatism can result in failure to use more suitable systems. It is the authors' opinion that conservatism is one of the main reasons that variable differential transformers are not used more extensively nowadays.

Accuracy. The static accuracy required for the type of measurements discussed here is in general not very high, i.e. in the range of 1 % of full scale. In exceptional cases, however, higher accuracies may be required. An example is the very accurate measurement of control surface deflections (0.3 % of full deflection) required for the method described in Ref.(3).

Measuring range. The measuring range can vary considerably for different applications, from less than 1 mm to several hundreds of mm for linear displacements and from less than 1 degree to several times 360° for angular displacements. For measuring very small and very large displacements there are in principle two possibilities: either a linkage is inserted to increase or reduce the original displacement to a value which is measurable with the required accuracy by normal transducers, or a special transducer is used which can measure the original displacement directly.

Linearity or conformity. In most applications, transducers with a linear relationship between the position of the sensing shaft and the output can be chosen and a non-linear relationship is necessary only for special purposes. For non-linear transducers, the notion of conformity is generally used. The term conformity is principally used for potentiometers, because potentiometers are best suited for realising non-linear functions. Therefore, terms like linearity, conformity, etc. are described in detail in

Chapter 3.0 on potentiometers.

Dynamic response. For most of the measurements considered here the dynamic response required will be only a few Hz. Only in those cases where the dynamic characteristics of systems must be investigated will a higher frequency range be required, in general not higher than about 30 Hz.

Environmental conditions. The effects of temperature, pressure, humidity, electro-magnetic fields, vibration and shock on the transducers will in many cases be important considerations when choosing a transducer. In special cases other effects can be important, such as radiation, corrosive environments, etc. Several measures can be taken by the manufacturer of position transducers to make his product better resistant to the above mentioned conditions.

In several Military Specifications about potentiometers and synchros, detailed requirements about environmental conditions are given (Refs (4), (5) and (6)). It must not be thought, however, that a transducer meeting all requirements of a Military Specification will provide an optimum solution under all circumstances. It is, for instance, almost impossible to meet in an optimal way requirements for extreme humidity and simultaneously for extremely low torque; high humidity resistance is usually obtained by very good sealing of the shaft, which cannot be realized in a low torque transducer. A similar conflict arises when the requirements for a potentiometer include long life and high vibration resistance. The first requirement can only be met by choosing the wiper pressure as low as possible, whereas the second requirement demands a high wiper pressure.

Type of output required. The choice of the transducer may to some extent depend on whether the information must be displayed on a pointer instrument or recorded on film or magnetic tape and, in the latter case, whether digital or analog recording is required. The ready availability of many accurate types of signal conditioning equipment has in recent years reduced the importance of this aspect for the choice of transducers.

Reliability. Reliability is a very important consideration in the choice of the transducer and the associated measuring equipment. There are two aspects:

a the measuring system must under no circumstances (in normal operation or after break-down) reduce the reliability of the normal operation of the aircraft.

b the reliability of the measuring equipment itself must be such that loss or deterioration of information is very improbable. This means that transducers with a relatively short service life (such as some types of potentiometers when used under adverse conditions) should only be used when the measurements are of short duration or when suitable maintenance and replacement is an integral part of the test procedure.

Cost. All aspects mentioned above affect the cost of the installation in some way or other. Though in some cases cost may not be the primary factor, it will play an important part in the choice of the system.

3.0 POTENTIOMETERS

3.1 Principle of potentiometers

In the potentiometer, a sliding contact (wiper) moves over a resistance element, the beginning and end of which are usually connected to a voltage source, which can be either DC or AC. The wiper is mechanically attached to the input shaft or rod and is usually electrically insulated from it. The output of the potentiometer depends on the position of the input shaft or rod.

3.2 Types of potentiometers

Concerning the movement of the wiper in angular position potentiometers, two types can be distinguished, viz.:

- the single turn potentiometer, in which the wiper movement is a rotation. Shaft rotation ranges up to 355° can be realized with this type.

- the multi-turn potentiometer, in which the wiper movement is a combination of rotation and translation. The wiper is driven along a helix by means of a lead screw. Shaft rotation ranges up to about 60 x 360° can be realised with this type.

The movement of the wiper in linear position potentiometers generally is a simple translation. The different types of wiper movement are shown in Fig. 3.2-1.

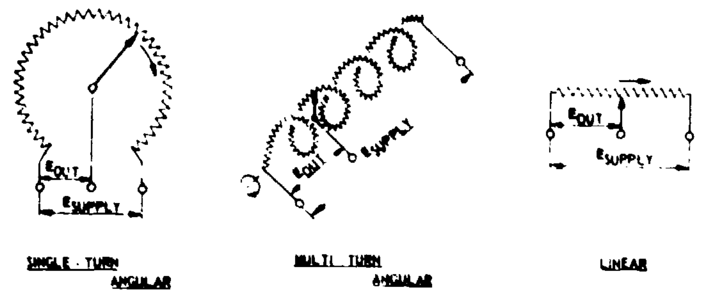


Fig. 3.2-1 Wiper movement in angular and linear position potentiometers

Concerning the material of the resistance element in potentiometers, two types of potentiometers can be distinguished, viz. the wire potentiometer and the film potentiometer.

Both types of elements can be applied in angular as well as in linear potentiometers, and in single-turn as well as in multi-turn potentiometers.

General considerations on potentiometers are given in Refs (7), (8) and (9).

3.2.1 Wire potentiometers

A simple form of wire potentiometer is the "slide wire" potentiometer, in which the wiper moves along a single wire. The wire is installed in the form of a straight line in the case of linear position transducers, in the form of a circle-arc in the case of single-turn angular position transducers, or in the form of a number of turns in the case of multi-turn angular position transducers. Although slide wire potentiometers have the attractive property of almost infinite resolution, they are seldom used in position transducers for flight test purposes as they have the disadvantage of short life time, caused by the need to use very thin wire in order to get a useful resistance value.

The most widely used wire potentiometer nowadays is the wire-wound potentiometer (see Fig. 3.2-2), in which the resistance element consists of an insulated resistance wire of a special metal alloy, wound around a core. The insulation of the wire is removed where the wiper moves over the element.

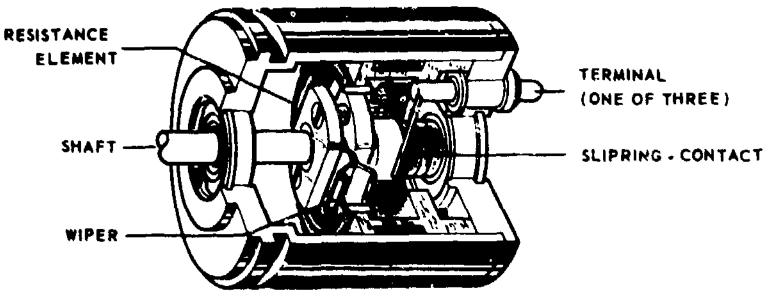


Fig. 3.2-2 Construction of a single turn wire-wound potentiometer.

3.2.2 Film potentiometers

In film potentiometers, the resistance element consists of a thin foil of metal, carbon, or conductive plastic, over which the wiper can move.

Metal film potentiometers are seldom used for flight test purposes, because life expectancy and reliability are limited. This is caused by the fact that, because of the low specific resistivity of metals, the foil must be extremely thin to obtain useful resistance values.

Carbon and conductive plastic film potentiometers are being used more and more often for flight test purposes. Due to the high resistivity, the resistance material of these potentiometers can be much thicker than in metal film potentiometers, resulting in longer life expectancy and better reliability.

3.2.3 Characteristics of potentiometers

In principle, a potentiometer for position measurement can be used as a variable resistor or as a voltage divider (see Fig. 3.2-3). Application as a voltage divider must be preferred for the following reasons:

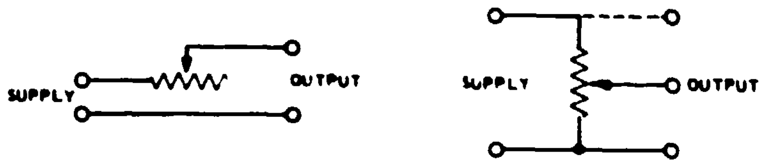


Fig. 3.2-3 Potentiometer, used as a variable resistor (a) and as a voltage divider (b).

- In many cases the wiper-to-element resistance cannot be neglected with respect to the potentiometer resistance and will, moreover, often vary considerably. Measuring the resistance between the wiper and one of the end terminals will not provide a good measure for the shaft position, as the unknown resistance affects the result. If the potentiometer is used as a voltage divider in properly designed (high impedance) measuring circuits, this generally unknow resistance has a negligible effect on the accuracy of the measurement.
- In many cases only very small currents can be drawn over the wiper, especially with film potentiometers. This requirement can more easily be met when the potentiometer is used as a voltage divider instead of a variable resistor.
- In non-linear film potentiometers the resistance output curve can differ seriously from the voltage output curve because of the two-dimensional configuration of the element (Ref. (8)). Manufacturers' specifications always assume application as voltage dividers in such cases.
- The resistance of a potentiometer can vary seriously with varying temperature or humidity. When the potentiometer is used as a variable resistor, this temperature effect will directly influence the measurement. When the potentiometer is used as a voltage divider, (with a sufficiently high load resistance) the temperature effect on the output voltage will be negligible.

Resolution with respect to potentiometer transducers can be defined as the smallest displacement of the input shaft that still produces a change in output.

When the wiper of a wire-wound potentiometer is moved continuously, the resistance between the wiper and one of the ends of the potentiometer changes in steps (Fig. 3.2-4). The voltage at the output of a potentiometer will also change in steps, which are, however, not completely equal. Their exact shape depends on the type of power source and on the geometry of the wiper. The resolution of such a potentiometer is, therefore, limited. It can be shown that the resolution of an ideal potentiometer is better than that given by the following formulae:

$$\text{Resolution (in \%)} = 0.5 \times \frac{\text{voltage per turn of wire}}{\text{supply voltage}} \times 100\ \% \quad \text{or}$$

$$\text{Resolution (in \%)} = 0.5 \times \frac{100}{\text{number of turns of wire}}\ \%.$$

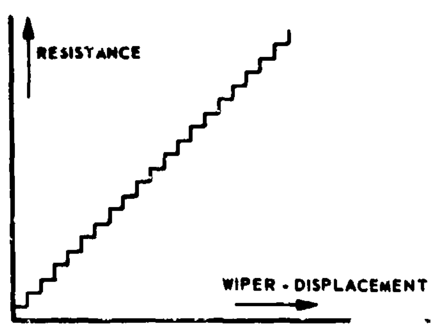


Fig. 3.2-4 Resistance as function of wiper displacement in wire-wound potentiometers

Due to irregularities in the windings and in the wiper-to-wire contact, the accuracy of the measurements with wire-wound potentiometers will often be slightly worse than this resolution.

To obtain a high resolution in a given case size, very fine wire has to be chosen. The wire diameter is, however, limited by a number of factors, so that in practice it is not possible to wind more than about 40 turns per mm without sacrificing reliability and life expectancy. Very high resolutions in wire-wound potentiometers can be obtained with large diameter cases and high element resistances. The maximum achievable resolution for wire-wound position transducers as a function of the case diameter is approximately as follows:

$$\text{resolution} = \frac{3 \text{ to } 6}{100\ D} \text{ degrees (D in mm).}$$

The maximum achievable resolution for wire-wound linear position transducers is about 0.02 mm.

Film potentiometers have an almost infinite resolution, depending only on the granularity of the material used. A resolution of about 4×10^{-3} mm of wiper displacement can be obtained with these devices.

Linearity and conformity are important factors in connection with the accuracy of potentiometers. These terms can be defined as follows:

Linearity is the maximum deviation of a calibration curve from a specified straight line, generally expressed in percent of the full measuring range.

Conformity is the maximum deviation of a calibration curve from a specified non-linear curve, generally expressed in percent of the full measuring range.

Several different types of linearity are used, especially for potentiometers. These will be discussed below. In an ideal potentiometer with perfect linearity, the curve of voltage output (or resistance output) plotted against shaft position would be a straight line, which, as is indicated in Fig. 3.2-5, passes through the points:

0 % voltage (or resistance) - 0 % position (A)
and 100 % voltage (or resistance) - 100 % position (B).

The so defined straight line is called the "line of absolute linearity". In practice, however, perfect linearity does not exist, and there will always be deviations from the ideal straight line. The maximum deviation of voltage-output (or resistance output) from the absolute linearity line is the "absolute linearity", generally expressed in percent of the total applied voltage and sometimes in percent of the total resistance.

In a non-linear potentiometer, the curve of voltage output (or resistance output) plotted against shaft position would be a curved line, ideally passing through the points:

0 % voltage (or resistance) - 0 % position (A)
and 100 % voltage (or resistance) - 100 % position (B).

The so defined curve (see Fig. 3.2-6) is called the "line of absolute conformity". In practice, perfect conformity does not exist, and there will always be deviations from the ideal curve. The maximum deviation of voltage output (or resistance output) from the absolute conformity line is the "absolute conformity", generally expressed as percent of the applied total voltage and sometimes as percent of total resistance.

Most potentiometers have some "end resistance", that is, resistance between the wiper and an end terminal or tap, when the wiper is positioned at the corresponding terminal or tap. This resistance is not only caused by the contact resistance between wiper and element but also by the resistance between terminals and element. Especially for film potentiometers, this resistance can have an appreciable value.

The "end resistance" in potentiometers is one of the reasons why the actual output line often does not pass through the points:

0 % voltage (or resistance) - 0 % position
and 100 % voltage (or resistance) - 100 % position.

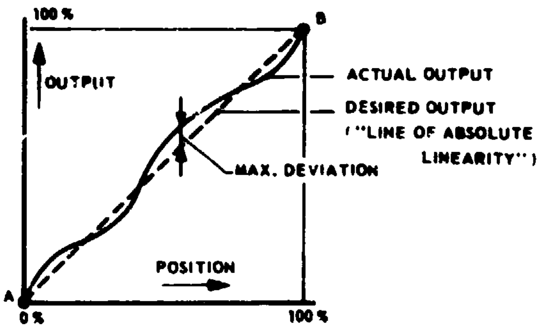


Fig. 3.2-5 Absolute linearity in a linear potentiometer

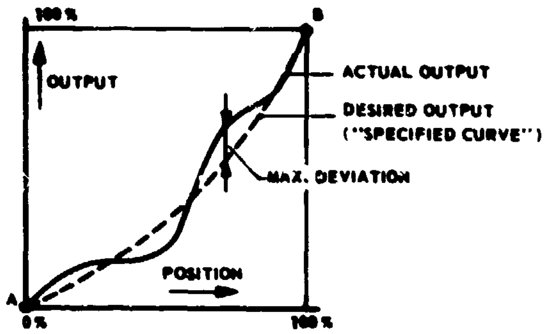


Fig. 3.2-6 Absolute conformity in a non-linear potentiometer

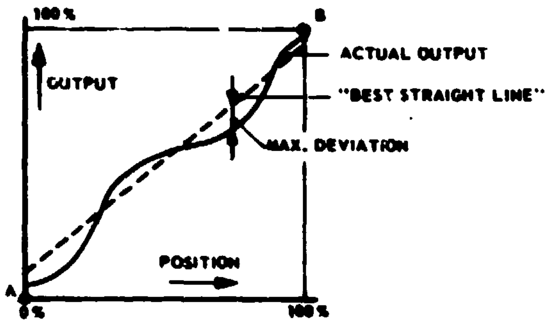


Fig. 3.2-7 Independent linearity in a linear potentiometer

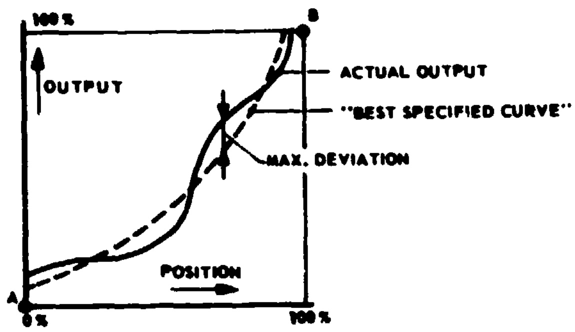


Fig. 3.2-8 Independent conformity in a non-linear potentiometer

This is shown in Figs 3.2-7 and 3.2-8 for linear and non-linear potentiometers. For this reason it has become common usage, especially in manufacturers' specifications of potentiometers, to specify the independent linearity for linear potentiometers and independent conformity for non-linear potentiometers. These terms are defined as follows:

Independent linearity is defined as the maximum deviation of the actual measured output with respect to a straight line, drawn in such a way that the sum of squares of the deviations is minimised. This line is called the "best straight line" or the "independent linearity line". Deviations with respect to this line are known as independent linearity errors.

Independent conformity is defined as the maximum deviation of the actual measured output with respect to the "best specified function curve", drawn in such a way that the sum of squares of the deviations is minimised. This line is called the "independent conformity curve". Deviations with respect to this curve are known as independent conformity errors.

Angular position potentiometers with large case diameters generally have a better linearity than the small-size types. Obtainable linearities with wire-wound angular position potentiometers are:

- about 1 % for potentiometers with case diameters smaller than 15 mm
- about 0.02 % for potentiometers with case diameters from 15 - 50 mm
- about 0.002% for potentiometers with case diameters from 50 - 250 mm.

Case diameters larger than 50 mm are, however, seldom used for flight test purposes due to space limitations.

The obtainable linearity with film-type angular position potentiometers can be 0.07 %.

The linearity for wire-wound and film potentiometers in linear displacement transducers is between 0.05 and 0.1 % of the full stroke.

Specific non-linear relationship between operating shaft and output can be realised by the manufacturers of potentiometers in different ways, for instance:

- by shunting parts of the potentiometer by fixed resistors, mounted inside the transducer case
- by varying the wire spacing, wire diameter, or core dimensions of a wire-wound potentiometer
- by varying the shape of the resistance element of a film potentiometer by local changes in film width and/or thickness.

The characteristics of film potentiometers are slightly different from those of wire-wound potentiometers because of the two-dimensional configuration of the element (see Ref. (8)). It appears, for instance, that in the case of a non-linear film potentiometer, the curve for resistance versus shaft position can differ significantly from the curve for voltage versus shaft position, whereas these curves always have the same form for wire potentiometers. In general, this effect will not limit the possible applications of film potentiometers, but it is all the more a reason potentiometers should be used as voltage dividers rather than as variable resistors.

Non-linear relationships between displacement and transducer output can also be realised by operating a linear transducer via a non-linear linkage or by shunting parts of the potentiometer by fixed resistors outside the case.

Non-linear potentiometers are seldom used for the position measurement considered in this volume. In a few cases, however, the application of non-linear potentiometers can be used as a means to cancel out non-linearities caused by mechanical linkages, etc.

A special type of non-linear potentiometer is the sine-cosine potentiometer (Refs (H1), (B5) and (7)). Four insulated brushes, located accurately at the corners of a square, move in a circle across a flat surface of a resistance element (see Fig. 3.2-9), which can be either of the film type or of the wire type. The voltage differences between diametrically opposed brushes are proportional to the sine and cosine of the angle of rotation. In position transducers for flight test purposes, these potentiometers are seldom used.

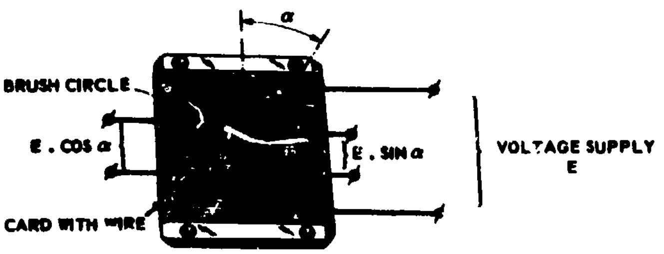


Fig. 3.2-9 Principle of sine-cosine potentiometer

Taps in potentiometers are fixed electrical connections that can be used:

- as a voltage reference. If such a tap is used as "centre tap", zero output is obtained at the centre position of the wiper (see Fig. 3.2-10)
- when the measurement range only corresponds to a part of a 360° turn. Potentiometers with multiple taps are very useful for obtaining a quick solution in such cases.
- to shunt parts of the potentiometer in order to influence the relationship between wiper position and output. This possibility is seldom used in flight test position measurements because in such cases non-linear potentiometers can provide much better accuracies.

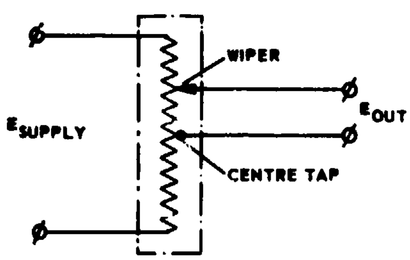


Fig. 3.2-10 Potentiometer with centre tap

For wire-wound potentiometers, a tap within the measuring range has consequences if one or more windings are shorted by the tap, viz.:

- decrease of local resolution (larger dead zone)
- increase of linearity errors.

In the ideal case, which cannot easily be realised, a tap is made on one single winding and the above mentioned disadvantages do not exist. For film potentiometers, two types of taps can be distinguished:

- the "zero width taps". Such taps give negligible dead zones. However, only very small currents (a few mA) may be drawn over them, because the resistance between each tap and the element is relatively high (a few tens of ohms).
- the "zero resistance taps" or "current taps", which have a resistance of only a few ohms and are capable of carrying currents up to about 50 mA. The width of such a tap is generally not negligible (minimum about 0.5 mm) and introduces a dead zone.

Resistance values for normal types of potentiometers for flight test purposes are from a few hundreds to a few thousands of ohms. Special types can have lower or higher values.

Maximum allowable power ratings for normal types of potentiometers for flight test purposes are from 0.5 W to 5 W. Special types can have higher ratings.

Sizes of potentiometers. In many specifications or dimensions of potentiometers, the notation "size number" is used. This size number represents the maximum outside diameter in tenths of inches. Fractions of tenths of inches are rounded to the next higher tenth. For instance, a potentiometer with a diameter of 1.08 inch is designated as an 11-size potentiometer. Most commonly used sizes for potentiometers for flight test work are sizes 8 and 11.

The temperature range within which potentiometers may be used is from -60° C to +100° C for relatively common types and -60° C to +250° C for special types. The latter may for instance be required when flight tests at high Mach numbers have to be performed.

It must be kept in mind that in some cases the temperature rise caused by the electrical power dissipation in the potentiometer cannot be neglected. This is especially true for low-resistance potentiometers that will be chosen, for instance, when direct indicating instruments have to be connected. In most manufacturers' specifications, the temperature limitations are expressed in two values:

- a value of the temperature rise occurring at the maximum allowable power rating
- a maximum value of the environmental temperature in which the potentiometer is used.

It must be kept in mind that the actual limiting factor is the temperature of the potentiometer element, which is subject to the sum of these two. In cases where there is appreciable power dissipation, it is safer not to use the potentiometer at environmental temperatures higher than the specified maximum environmental temperature minus the temperature rise due to power dissipation.

Loading error with respect to potentiometers is the effect that results because the output of a potentiometer depends on the current that is drawn through the wiper. In Fig. 3.2-11 a potentiometer with a resistance R_p has a supply voltage E and is loaded by a resistance R_L.

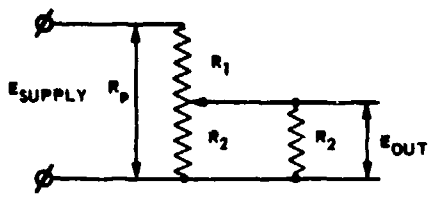


Fig. 3.2-11 Potentiometer with load resistor

The wiper divides the potentiometer in R_1 and R_2. The current through R_1 will divide at the wiper into a part passing through R_L and a part passing through R_2. Thus, the current in R_2 is smaller than the current in R_1, and the voltage E_{out} will become lower by the presence of the load resistance R_L. Fig. 3.2-12 shows the effect of loading on the output of a linear potentiometer. The error is zero at both ends of the travel and maximum about 2/3 from the zero voltage end.

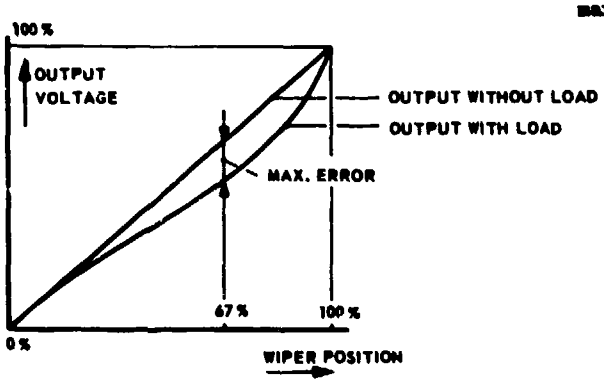


Fig. 3.2-12 Loading effect for a linear potentiometer

The magnitude of the error and the location of the maximum depend on the resistance ratio, i.e., the ratio of the load resistance to the element resistance (Ref. (9)).

The maximum error is approximately:

$$\text{Maximum error} = \frac{15}{\text{resistance ratio}} \%$$

For instance, for a potentiometer of 1 KΩ and a load resistance of 20 KΩ, the maximum error amounts to $\frac{15}{20}\% = 0.75\%$. The load effect can be minimised by choosing a high load resistance ratio. To achieve this, it will sometimes be necessary to use an amplifier between the potentiometer output and the load. Compensation of the load effect can be achieved by applying a non-linear potentiometer and matching both non-linearities. This is, however, a very expensive method, usable only when the potentiometer is always loaded in the same way.

For flight test purposes, linear potentiometers with a load resistance as high as possible are usually chosen so that the effect is negligible; the residual influence can be cancelled out by overall calibration of the measuring system.

Noise from a potentiometer is defined as the fluctuating distortion of output that is not present at the input as voltage fluctuation or shaft movement fluctuation. Noise acts as an additional voltage source in the measuring circuit combined with a varying resistance in series with the potentiometer output lead.

Some sources of noise are:

a) varying resistance between wiper and element, especially during movement of the wiper
b) contact of the wiper with more than one winding of a wire potentiometer
c) presence of dirt and corrosion on wire and wiper
d) vibration of the wiper and "chatter" when the wiper moves quickly across the wire element
e) galvanic and chemical action between wiper and element.

Noise is most commonly expressed in ohms and is then called Equivalent Noise Resistance (ENR).

In Ref.(5) the following method for measuring this ENR in wire potentiometers is described. The potentiometer shall be connected to a constant current source of 1 mA and to a high impedance oscilloscope as shown in Fig. 3.2-13. During the test, the shaft shall be rotated in both directions at an angular rate of 4 revolutions per minute. The equivalent resistance shall be calculated using the following formula:

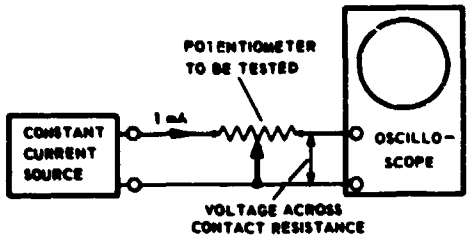


Fig. 3.2-13 ENR test for rotary wire potentiometers

$$\text{noise} = \frac{E_{pn}}{0.001} \text{ ohms, where } E_{pn} = \text{measured peak voltage in volts.}$$

Before the measurement takes place, the potentiometer shaft shall be rotated 10 cycles. In most specifications, a maximum of 25-100 ohms is given as the allowable value for the ENR so measured.

For conductive film potentiometers, the ENR, when measured as described above, will generally show a large DC component (sometimes called DC offset). This is due to the rather high contact resistance between wiper and film (often about 2 % of the total resistance). When the noise of film potentiometers is measured, the steady component is generally blocked by connecting a 0.1 µF capacitor in series with the oscilloscope input.

Low noise can be obtained if the manufacturer takes steps to provide it, such as proper design of contact arms, carefully calculated contact pressure, clean assembly conditions, etc. Noise can generally be minimized by avoiding high wiper currents, i.e., by applying high resistance loads. The effect of noise on the measuring circuit can be kept to a low level by applying filters.

4.0 SYNCHROS

4.1 Principle of synchros

A synchro is an electromagnetic device in which the angular position of a shaft determines a unique set of AC output voltages or, conversely, in which a shaft is moved to a certain angular position determined by a unique set of AC input voltages. The name "synchro" indicates that these units are mainly used to transmit a shaft rotation electrically from one place to another ("electrical axis"). In this application two in principle identical units are electrically interconnected; rotation of the shaft of one unit (the "transmitter") then results in a synchronous rotation of the shaft of the other unit (the "receiver"), at least at low speeds. For flight testing, synchro transmitters are often used without the receiver. The output voltages are then converted to DC or digital signals by signal conditioners. Such synchro-to-DC or synchro-to-digital converters can also be connected to an existing synchro chain.

The basic structure of the synchro consists of a stator and a rotor, both of which carry one or more coils.

The power to or from the rotor is generally supplied via slip rings. The normal power supply for synchros used for flight test applications is 26 V or 115 V with a frequency of 400 Hz.

Fig. 4.1-1 shows a typical synchro.

General considerations on synchros in position measuring systems are given in Refs (11) to (14).

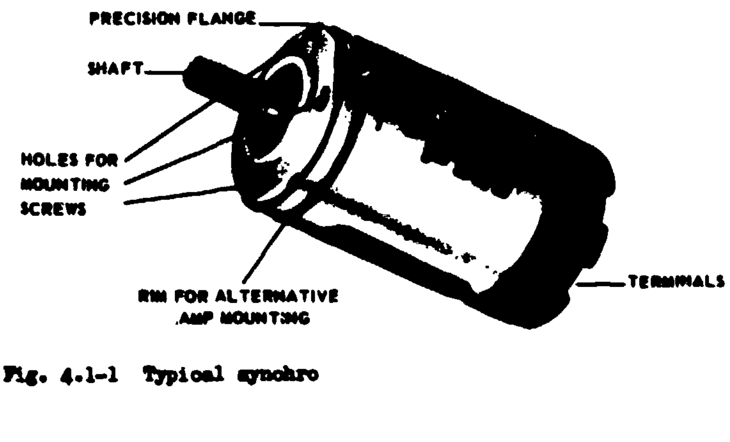


Fig. 4.1-1 Typical synchro

4.2 Types of synchros

Synchros can be classified in three main groups:

- torque elements
- control elements
- resolver elements.

Within these basic groups there are additional differences, depending on the individual functions in angle-transmission systems.

Elements in the above mentioned groups are:

transmitters

receivers

differentials

control transformers.

Before more details are given about the three main groups (Sections 4.2.2 to 4.2.4), Section 4.2.1 gives definitions of the most important elements. There are special types and forms of synchro elements to meet particular requirements. These will be treated in Section 4.2.5. In Section 4.2.6 some attention is given to a number of special synchronous remote indicating systems. These systems are, however, based on principles differing somewhat from the normal synchro principle. In Section 4.2.7 a short description is given of a special DC synchronous system that was originally developed for direct-indicating purposes and is still occasionally used for flight test purposes.

4.2.1 Definitions of synchro elements

A torque transmitter is a synchro which transmits electrical information corresponding to the position of the rotor relative to the stator. This synchro is designed primarily for operation with receivers and torque differential transmitters. The unit can also be used with signal-conditioning circuits with relatively low input impedance.

A torque receiver is a synchro which converts the electrical information received from a torque transmitter into a torque applied to the rotor, thereby turning the rotor to a position relative to the stator corresponding to that of the torque transmitter rotor. This synchro is designed primarily for operation with torque transmitters and torque differential transmitters.

A torque differential transmitter is a synchro which when connected to an energised torque transmitter, transmits electrical information corresponding to the sum or difference (depending on the interconnecting wiring system) of the angular positions of the rotors of these two units relative to their respective stators. This synchro is designed primarily for operation between a torque transmitter and a torque receiver.

A torque differential receiver is a synchro in which the rotor is forced to assume a position with respect to the stator equal to the sum or difference (depending on the interconnecting wiring system) of the electrical angular information received by its stator from one transmitter and by its rotor from a second transmitter. This synchro is primarily designed for operation with two synchro torque transmitters.

A control transmitter is a synchro which transmits electrical information corresponding to the position of the rotor relative to the stator. This synchro is designed primarily for operation with control transformers and high input impedance signal-conditioning circuits.

A control transformer is a synchro which, when connected to an energised control transmitter, gives an output signal proportional to the sine of the difference of the angular positions of the rotors of the connected units relative to their respective stators (error voltage). This synchro is designed primarily for operation with control transmitters and control differential transmitters. The rotor output is generally connected to a servo system which turns the rotor until the rotor output is zero.

A control differential transmitter is a synchro which, when connected to an energised control transmitter, transmits electrical information corresponding to the sum or difference (depending on the interconnecting wiring system) of the angular positions of the rotors of these two units relative to their respective stators. This synchro is designed primarily for operation between a control transmitter and a control transformer.

A resolver transmitter is a synchro which has two perpendicular windings on the stator and generally two windings on the rotor. The resolver has its rotor mechanically positioned for transmitting electrical information, corresponding to the angular position of the rotor with respect to the stator. This synchro is designed primarily for use with resolver control transformers and resolver differential transmitters.

A resolver control transformer is a synchro which has two perpendicular windings on the stator and generally two windings on the rotor. This resolver transforms electrical angular information from the stator to a voltage proportional to the sine of the difference between the electrical input angle and the resolver control rotor angle. This synchro is designed primarily for use with resolver transmitters and resolver differential transformers.

A resolver differential is a synchro which has two perpendicular windings on both the rotor and the stator. This resolver has its rotor mechanically positioned for modifying electrical angular information received from a transmitter and re-transmitting the electrical information, corresponding to the sum or difference (depending on the interconnecting wiring system) of the electrical input angle and its rotor position angle. This synchro is designed primarily for use with resolver transmitters and resolver control transformers.

A transolver is a synchro which has a three-phase winding and two single-phase windings, either of which may be the rotor or the stator. It can be regarded as a combination of a synchro control transformer and a resolver. The unit can be used for a wide variety of applications. Transolvers form the bridge between the three-phase devices on one side and the resolvers on the other side.

More definitions on synchros are given in Ref. (15).

4.2.2 Torque synchros

Torque synchros are used for the transmission of angular position information and for the reproduction of this information by the position of the shaft of the receiver, which can, for instance, drive a pointer or a set of pointers in a direct-indicating instrument. Misalignment between the shafts of the transmitter and receiver synchros increases with the mechanical load on the receiver shaft, and for this reason these synchros give the highest accuracy when the receiver systems have small inertia and are well balanced. The system is not power-amplifying, and hence any mechanical load acting upon the receiver is fed back as a load for the transmitter. Both the transmitter and the receiver have a three-phase stator and a single-phase rotor winding.

The principle of the torque system is as follows: The rotors of both transmitter and receiver are energised from the AC supply (see Fig. 4.2-1) and produce an alternating flux in their corresponding stators. If the relative position of rotor to stator in the two synchros is different, the three voltages created in the two stators by the alternating flux differ, causing currents in the leads connecting them. Then torques are produced in both synchros, acting upon the rotors. These torques try to eliminate the difference in voltages, i.e., to align the two rotors. Generally, the transmitter rotor is fixed by its mechanical input and the receiver rotor is free to turn so that it aligns itself with the transmitter rotor. Thus, any movement of the transmitter rotor will be repeated "synchronously" by a corresponding movement of the receiver rotor.

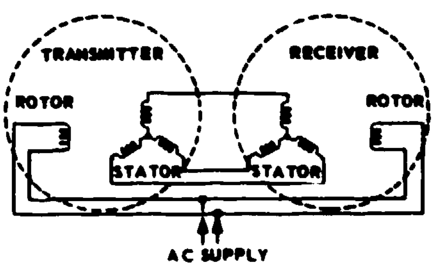


Fig. 4.2-1 Torque synchro AC-transmission system

When the rotors are aligned, the corresponding voltages of both stators are equal and no currents flow in the interconnecting leads. The voltages between the three stator lines are visualised as functions of the rotor angle of the aligned transmitter and receiver in Fig. 4.2-2. The voltages are given as a function of rotor position and not as a function of time. The three AC stator voltages are in time phase, whereas with respect to the rotor voltage they have a phase shift of 8 to 20 degrees (leading) for small synchros and of 2 to 8 degrees (leading) for large types.

The voltages between the three stator lines under static conditions are given as functions of the rotor angle by the following equations:

$$E_1 = E_m \sin \alpha$$
$$E_2 = E_m \sin (\alpha - 120^\circ)$$
$$E_3 = E_m \sin (\alpha - 240^\circ)$$

where:

E_m = max. induced r.m.s. line voltage

E_1, E_2 and E_3 = r.m.s. voltages between the three stator lines

α = rotor position in degrees.

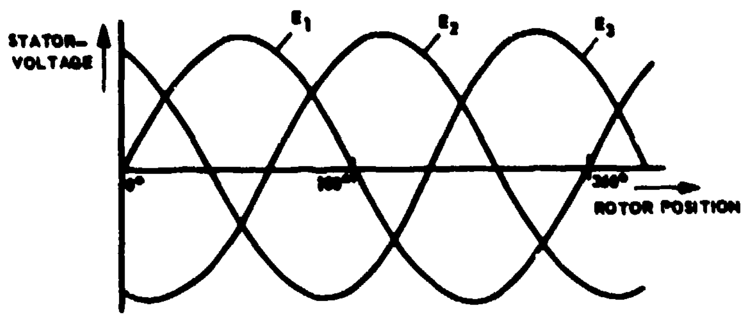


Fig. 4.2-2 Stator voltages as a function of rotor position

Fig. 4.2-2 and the above given formulae also hold for a single synchro transmitter, not connected with a receiver.

From the above equations the following relations can be derived:

$$\cot g\ \alpha = -\frac{1}{\sqrt{3}}\left(\frac{E_2}{E_1} + 1\right)$$

$$\cot g\ \alpha = \frac{1}{\sqrt{3}}\left(\frac{E_3}{E_1} + 1\right)$$

These show that the angle α is independent of the supply voltage E_m and is fully defined (within $\pm$ 360 degrees) by the ratios between the stator voltages. Changing the excitation voltage will influence the picture in Fig. 4.2-2 only with respect to the voltage amplitudes and not with respect to the ratio of the three voltages to each other.

For flight test purposes it is possible to connect two (or more) receivers in parallel to one transmitter but, in general, such additional receivers are liable to impair the accuracy of the system if no special precautions are taken. Misalignment due to excessive mechanical load on one receiver shaft is reflected back into the system and affects the accuracy of all other receivers. This mutual interference can be reduced by using receivers with higher stator impedances. The number of receivers that can be operated depends on the power rating of the transmitter.

If the difference or the sum of two angles must be measured, a torque differential transmitter can be inserted in the transmission chain. The differential torque transmitter has a three-phase rotor and stator. Its stator is connected to the stator of the transmitter and its rotor to the stator of the receiver (see Fig. 4.2-3). The angle of the output shaft of the receiver is the sum of the angles of the rotors of the transmitter and the differential transmitter. The difference instead of the sum of the two angles can be obtained by reversing any two interconnecting leads between the stators of transmitter and differential transmitter.

The principle of the torque differential receiver is allied to that of the torque differential transmitter. This device, when connected to two transmitters, will produce a shaft output angle which is the sum or the difference of the shaft angles of the two transmitters.

The transformation ratio of torque differentials is generally 1:1, but sometimes it is slightly more to compensate for the voltage drop in the system.

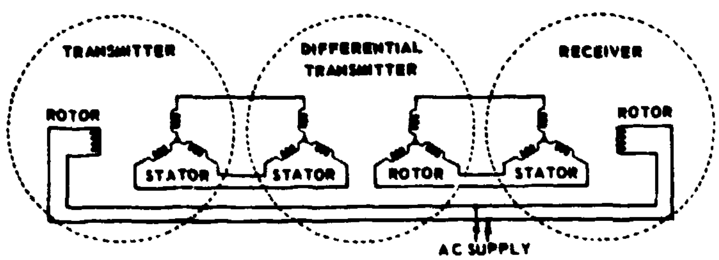


Fig. 4.2-3 Torque synchro-transmission system with insertion of a differential transmitter

4.2.3 <u>Control synchros</u>

Control synchros are employed in a data transmission system, in which a servo system is required to drive a mechanism which may have large inertia or requires a greater torque than can be provided by a torque element.

As in the case of torque transmission, the rotor of the control transmitter is energised from the AC supply (see

Fig. 4.2-4). The receiving synchro is called a control transformer, and the rotor is not energised but provides the input for an electronic amplifier. Both the transmitter and the transformer have a single-phase rotor and a three-phase stator.

When the rotor of the transmitter is energised, the three line voltages induced in the stator vary with the rotor position (see Fig. 4.2-2). These voltages, supplied to the stator of the control transformer, reproduce the direction of the alternating transmitter flux and, by transformer action, a voltage is generated in the rotor. This voltage is amplified and fed to a servo motor which drives the mechanism to be controlled (for instance, a pointer via a gear train) and also the rotor of the control transformer. The rotor is driven to a position at a right angle to the flux reproduced in the control transformer; then the rotor output voltage is zero. Any change in the position of the transmitter rotor alters the direction of the flux in the control transformer and a voltage is produced in the control transformer until the drive re-nulls the rotor. Ambiguity of zero position of the rotor is avoided by phase discrimination in the amplifier or the servo motor. Generally a two-phase induction motor is used, of which one phase is continuously energised, whereas the other phase is connected with the amplifier output. The output power of such a system depends only on the power output of the amplifier and servo motor. By means of such a servo system very small transmitters (small forces) can operate relatively heavy mechanisms.

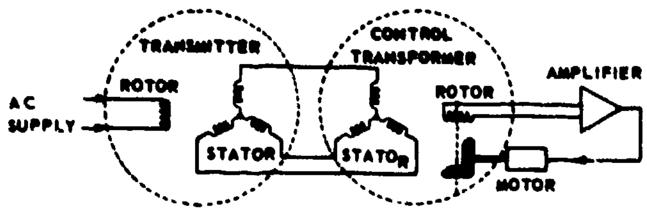


Fig. 4.2-4 Control synchro-transmission system

The output of a control transmitter can also be recorded by trace recorders or magnetic tape data recording systems by inserting a synchro converter as a signal-conditioning unit. Several types of such converters from synchro output to DC or digital are commercially available.

In a similar manner to that described for torque synchros, the sum or difference of two angles can be transmitted by using a control differential transmitter. This differential transmitter is then inserted between transmitter and transformer as shown in Fig. 4.2-5.

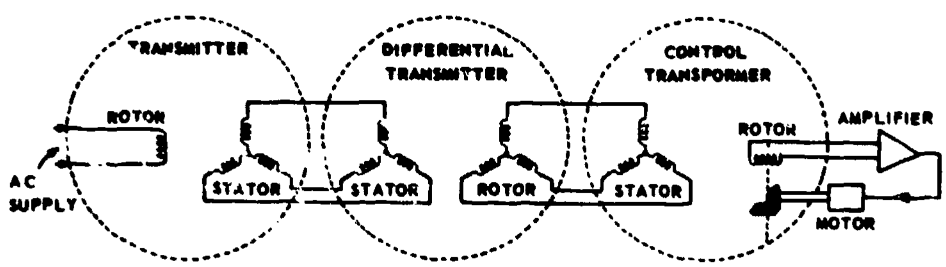


Fig. 4.2-5 Control synchro-transmission system with insertion of a differential transmitter

4.2.4 Resolvers

The classical function of a resolver, as the name implies, is to resolve a vector into its components, or, in other words, to convert voltages representing polar co-ordinates into voltages representing cartesian co-ordinates.

In general, the resolver consists of a rotor with two coils, wound in space quadrature, and a stator, also with two quadrature coils (see Figs 4.2-6 and 4.2-7). Energising one rotor coil with a voltage E induces a voltage in one stator winding; this voltage varies according to the sine of the rotor position angle α. The voltage induced in the other stator winding, which is in space quadrature with respect to the first, varies according to the cosine of the rotor position angle α. The two outputs are thus E sin α and E cos α (assuming a unity ratio between rotor and stator windings), which are the components of the input vector E. In this application the second rotor coil is short-circuited.

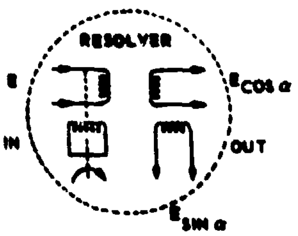


Fig. 4.2-6 Resolver as a converter from polar co-ordinates into cartesian co-ordinates

The vector resolution function is reversible, so that if voltages E_x and E_y, representing vector components, are applied to the inputs of the resolver (see Fig. 4.2-7), the corresponding polar co-ordinates (E, α) can be obtained. To realise this, one of the rotor windings is connected to an amplifier and a servo motor. This motor drives the rotor to the position where zero voltage appears across this winding. The other rotor winding is then in line with the flux axis; the induced voltage in this rotor winding is proportional to the amplitude of the alternating flux, i.e., proportional to

$$E_{out} = \sqrt{E_x^2 + E_y^2} .$$

This voltage represents the modulus of the polar vector. The shaft position represents the argument α of the polar vector,

$$\alpha = \text{arc tg}\,\frac{E_y}{E_x} .$$

Resolvers can also be used in control systems exactly like those described in Section 4.2.3. For such applications the units are referred to as:

- resolver transmitters,
- resolver differentials,
- resolver control transformers.

For more details on resolvers, see Refs (B5) and (16).

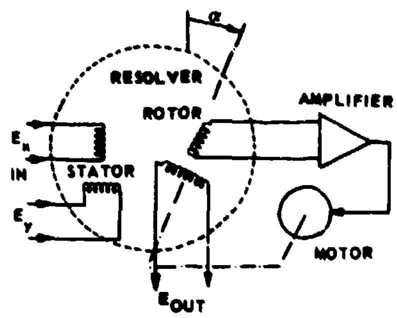


Fig. 4.2-7 Resolver as a converter from cartesian co-ordinates to polar co-ordinates

4.2.5 Special types and forms of synchro elements

To meet requirements for which normal synchro types cannot be used, special types and forms of synchro elements are available. Such special types are available for cases where an extremely high accuracy or an extremely high life expectancy is required, where the available volume dictates special dimensions, or where only a very low driving torque is available.

Mechanical multispeed synchros (Refs (B5) and (17))

To increase accuracy of a synchro measuring system, a coarse and fine indication system can be chosen. This implies that the transducer contains two synchros in one housing, one of which, the fine synchro, makes N revolutions for one revolution of the coarse synchro, where N is the ratio of the mechanical gearing between the two synchro shafts.

In general, the accuracy that can be obtained with such systems is about 3 minutes of arc, deteriorating, however, with wear.

Electrical multispeed synchros (Refs (B5) and (17))

This synchro type has also been developed to meet high accuracy requirements. It contains two separate sets of windings on the common cores of both rotor and stator. One set of windings (the "2-pole section") is arranged as in a normal synchro transmitter. It produces the normal output cycle of a synchro. The other set of windings (the "multi-pole section") is so arranged that the output voltages produce several synchro output cycles for one revolution. In Fig. 4.2-8 these outputs are shown for an eleven-to-one ratio between the synchro speeds.

Accuracies of up to 10 seconds of arc can be obtained with this system. A disadvantage is that generally slightly larger housings are required.

Brushless synchros (Refs (14) and (18))

A weakness in the design of standard synchros is the brush-slipring interface, necessary for the electric rotor connections. Especially the life expectancy is limited by this component, because it is liable to mechanical wear and deteriorating electrical contact. When long life expectancy is required, brushless synchros may solve this problem.

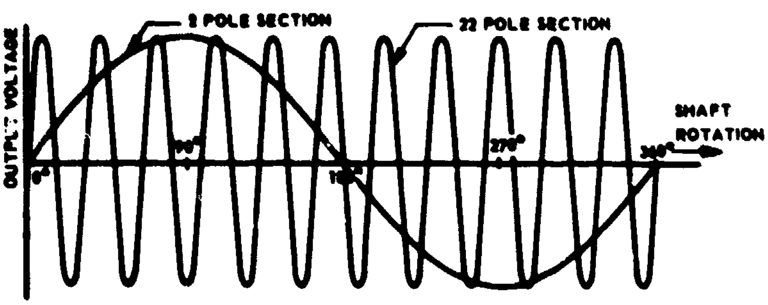


Fig. 4.2-8 Output voltages for one revolution of the shaft of an electrical eleven-speed synchro (only one phase of each output is shown)

Two types of brushless synchros are described below, viz.:

- the electromagnetic type
- the hairspring type.

Another, very special brushless synchro, the so-called "synchrotel", will be described in Section 4.2.6.

Electromagnetic-type brushless synchros

This synchro uses a rotary transformer as a means of voltage or current transfer to the rotor. This method allows continuous rotation of the synchro even at relatively high speeds. The transformer has some effect on performance characteristics, such as impedance level, phase shift, and influence of temperature, so that they are generally not directly interchangeable with normal types of synchros.

Hairspring-type brushless synchros

If a synchro is required to operate within a limited angular displacement range, the connections to the rotor winding can be made through flexible leads or hairsprings. The unit is normally supplied with mechanical stops to prevent damage to the hairsprings due to excessive shaft rotation. Generally, the total movement is about 360°; however, movements of 600° are possible in special types.

The advantage of a hairspring synchro over an electromagnetic brushless synchro is that electrical parameters are not influenced. These synchros can, therefore, generally be interchanged with normal synchros.

Linear synchros (Refs (B1), (11) and (14))

This type of synchro, sometimes known as induction potentiometer (Refs (B1) and (11)) or linear transformer (Ref. (14)), may be considered as a special kind of resolver. It consists of a single-phase stator and a single-phase rotor. The rotor usually carries the excitation winding, the stator the output winding. The stator output voltage must be measured by a phase-sensitive circuit because for one half of the measuring range the output voltage is (approximately) in phase with the supply voltage, and for the other half it is (approximately) 180° out of phase with it.

The principal difference between a linear synchro and a resolver is that the output of the former changes linearly with the input shaft angle and that the latter changes linearly with the sine of that angle. This linearity is achieved by a non-uniform distribution of windings and of the slots containing these windings.

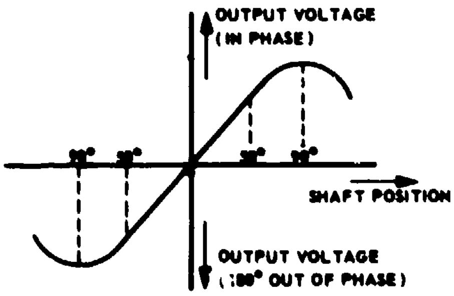


Fig. 4.2-9 Shaft rotation versus output voltage for a linear synchro

The rotation is usually limited to the range of about -50° to +50°. Beyond this range the plot of output voltage against rotor position tends toward a sinusoid (see Fig. 4.2-9).

Obtainable accuracies are on the order of 0.1 %.

Pancake synchros, slab synchros (Refs (B5) and (17))

As the names imply, these synchros have a much smaller length-to-diameter ratio than standard synchros. They are primarily intended for use in gyroscopes for gimbal-position transmitting and are often supplied as separate stators and rotors which can be mounted on existing shafts.

This special form may sometimes be attractive when the space available for the transducer is limited.

Transolvers (Refs (10) and (14))

The transolver is a special type of resolver. As shown in Fig. 4.2-10 it is essentially a normal synchro control transformer with a second rotor winding wound in space quadrature to the main winding.

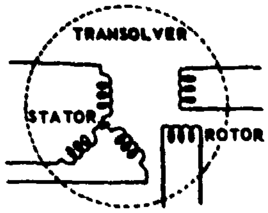


Fig. 4.2-10 Internal wiring diagram of a transolver

The transolver is used in systems where it is desirable to convert three-wire data to four-wire data.

4.2.6 Special AC synchronous systems

Synchrotel (Refs (B1) and (19))

The synchrotel (a manufacturer's trade mark) is a synchro that can function as a very-low-torque control transformer or as a transmitter.

Fig. 4.2-11 shows an exploded view of this device. A single-phase winding ("stationary rotor coil") surrounds the cylindrical core. The stator is of the conventional three-phase synchro type and also surrounds the core. The rotor consists of an oblique section of a hollow cylinder attached to one end of the rotor shaft. The oblique section rotates in the clearance between the core and the two coils. The rotor is made of aluminum and has a very small weight. As there are no brushes and no electrical reaction at the null, the positioning torque need only overcome the friction of the bearings.

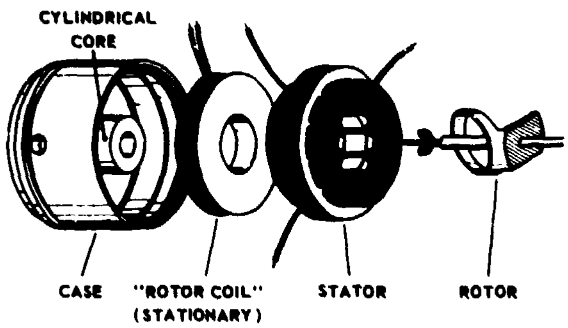


Fig. 4.2-11 Exploded view of a synchrotel

In operation as a control transformer, the stator windings are excited with alternating voltages, which produce a radial alternating flux. The portion of this flux that links the aluminum single-turn loop rotor, induces a current in this loop, which, in turn, produces an axial component of alternating flux in the cylindrical core. The flux in the core induces an alternating voltage in the stationary rotor winding with an amplitude that is a sinusoidal function of the relative positions of the rotor and of the stator radial flux.

The low-inertia, low-friction, movable element can be coupled to mechanisms which can only be lightly loaded, to convert rotary movement into an AC output signal with the relatively high degree of accuracy of about 1^{o}. The unit is used for the measurement of diaphragm and bellow-displacement in aircraft pressure transducers, altimeters, airspeed transducers, etc. In principle, it is possible to use the element in position transducers, especially when extremely small driving torque is available.

The synchrotel has lost its importance since simpler and more accurate low-torque transducers have become available.

Magnesyn (Ref. (B1))

This is a system with a three-phase stator and a permanent magnet rotor. In a direct-indicating system the transmitter and receiver are identical and are interconnected as shown in Fig. 4.2-12.

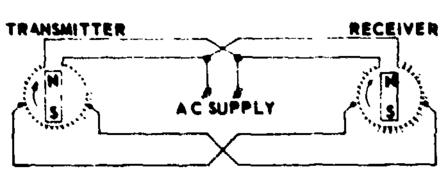


Fig. 4.2-12 Magnesyn system

The theory is somewhat involved. It is based on the principle that harmonic voltages are induced in a coil placed in a saturated field generated by a sinusoidal supply power. If the rotor of the receiver is not correctly aligned with that of the transmitter, harmonic currents will flow between the transmitter and the receiver that tend to bring the two rotors into correct alignment. When this takes place, the same even harmonic voltages will be induced in the transmitter and receiver stator coils, and the flow of harmonic current ceases. Due to the small value of the misalignment torque, jewelled pivots are used.

Owing to the very small reactive torque, magnesyns have in the past been used in airspeed, rate of climb, compass, altitude, and fuel flow instruments. The accuracy of the system is not very high ($\pm$0.5 degree). The use of this type of synchro as a position transducer for flight test purposes need not be considered further. The same arguments as those mentioned under synchrotels also apply to magnesyns. The availability of modern, more accurate low-torque transducers have degraded them to devices of practically no importance for flight test purposes.

4.2.7 Special DC synchronous system

Fig. 4.2-13 shows the basic DC synchronous system. The transducer contains a uniformly wound toroidal resistance with three equally spaced taps over which a brush assembly rotates. This brush assembly applies the DC voltage to the resistance at two diametrically opposed points. The indicator has three coils, connected in star and wound on a soft iron stator. These coils are connected to the taps of the transmitter. In the stator a permanent magnet, to which the indicator pointer is attached, can rotate freely. The rotation of the brush assembly changes the currents in the three coils and thereby the direction of the resultant magnetic field and that of the pointer. Apart from a slight cyclic error, there is synchronism between the brush rotation in the transducer and the pointer rotation, which is within wide limits independent of the magnitude of the DC power supply. More details on the system are given in Ref. (12).

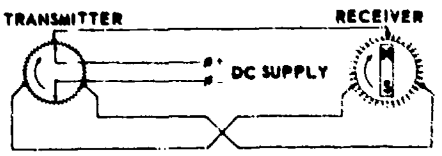


Fig. 4.2-13 Principle of the DC synchronous system

The system is intended exclusively for direct indication. A system already present in the aircraft as standard equipment for normal operation can be tapped without appreciably influencing the measuring accuracy, so that a second indicator can be connected for application in a photo-panel recorder for flight test purposes. The signal is not, however, directly usable in tape recording systems and can also not easily be converted into a suitable form for this purpose. For small parts of the measuring range of the transducer, the varying voltage between two taps or a tap and one of the brushes can sometimes be useful as a "poor man's solution" for certain measuring problems in which accuracy requirements are low. These voltages are, however, not single-valued for one complete revolution, so that the output is only usable if the measuring range of interest falls within a non-reversing part of a voltage versus position curve.

Further disadvantages are those considered in Chapter 8.0 about potentiometers, to which this system is somewhat related.

4.3 Characteristics of synchros

In this section a number of typical synchro characteristics connected with accuracy and suitability for application in position transducers for flight test purposes will be considered.

The resolution of synchros is infinite, i.e., even the smallest displacement of the operating shaft produces a measurable change in output.

Defining the zero-position is a necessity for all types of transducers for reasons of uniformity and interchangeability. For devices with end stops, one of the stops is generally chosen as the zero position. Because synchros, generally, are devices that can rotate over more than 360° and do not have any end stops, it is necessary to define the zero position in a different manner. The zero position, or electrical zero point, is defined differently for each synchro type. It is always a rotor position where a specified output winding gives a minimum voltage when the nominal power and frequency is supplied to a specified winding. The methods for determining these points are internationally normalized and specified, for instance, in Refs (4), (6), (15) and (20). Some manufacturers indicate the location of electrical zero by a mark on the shaft which must be aligned with an arrow stamped on the housing. This is only meant as a rough indication of electrical zero and is intended to aid in defining the right null when, as is generally the case, two minimum voltages appear at shaft positions 180 degrees apart (differing only slightly in amplitude).

The minimum output signal, called the null voltage, is always a quadrature voltage and is generally less than about 30 mV for types with an excitation voltage of 26 V and less than 100 mV for types with an excitation voltage of 115 V.

Before discussing the linearity error of a synchro, it is necessary to define the "electrical position" of the synchro rotor. The electrical position of the rotor relative to the stator is defined by a set of electrical output voltage ratios corresponding to the formulae for an ideal synchro of the type considered.

For normal synchros these formulae are given in Section 4.2.2, and for resolvers they are given in Section 4.2.4.

Synchro linearity is defined as the difference between the electrical position angle corresponding to the output voltage ratios and the actual rotor position angle. It is determined in a calibration process that starts at the electrical zero point and continues with steps of generally 5 degrees until a complete revolution is accomplished.

A typical electrical error curve is shown in Fig. 4.3-1. For normal control synchros the maximum linearity error is about 7 min. of arc. Special types can be more accurate (to about $\pm$ 3 minutes of arc).

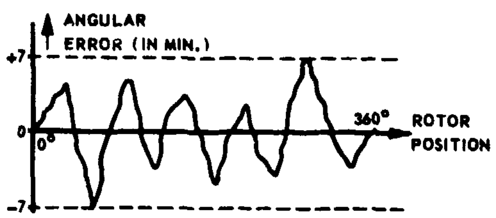


Fig. 4.3-1 Typical error curce for a control synchro transmitter

The accuracy depends on electrical error, mechanical perfection, and such characteristics as phase shift, transformation ratio, impedance, etc. The accuracy of a normal control synchro transmitter (when measured by an ideal measuring system) is of the order of 7 minutes of arc, which corresponds to 0.03 % of a full rotation. For special synchros, even higher accuracies are claimed. The overall accuracy of a synchro measurement also depends, however, on the other elements in the synchro chain.

The accuracy of a torque system with a direct indicating pointer instrument is generally not better than 1°. To achieve high accuracy in a torque system it is important to have a high torque gradient, that is, the torque per degree misalignment. The relationship between misalignment and torque is non-linear, but up to about 10 degrees misalignment it may be regarded as linear.

A synchro chain consisting of a control transmitter, a control transformer, a servo amplifier, and a servo motor can have an accuracy of 10 minutes of arc. With multispeed synchros, accuracies of about 20 seconds of arc can be obtained.

The accuracy of a synchro chain, containing a synchro-to-digital or a synchro-to-DC converter also depends on the characteristics of the chosen converter. Normal converters have accuracies of about $\pm$ 5 to $\pm$15 minutes of arc, when used for quasi-steady measurements at speeds up to some hundreds of degrees per second, whereas more sophisticated converters can have accuracies of $\pm$2 minutes of arc under these circumstances. For accurate measurements at higher shaft-rotation speeds, up to some thousands of degrees per second, special rate-compensated converters are available (Ref. (21)).

Resolvers are generally slightly more accurate than control synchros.

In many manufacturers' specifications, the term voltage gradient is used. This quantity can be defined as follows: The voltage gradient of a synchro is the output voltage per unit of angular displacement around the electrical zero position. It is expressed as: voltage gradient = volts at max. coupling multiplied by sin 1°.

A typical value of voltage gradient is: 0.2 volts/degree for synchros with an output voltage of 11.2 volts at max. coupling.

The power rating of normal types of synchros for flight test purposes (sizes 8 to 15) varies from 0.1 W to 1 W, depending on the size and function. Control elements and resolvers generally have lower ratings than torque elements of the same size.

The temperature range within which normal synchros may be used is from about -60° C to +100° C. At higher temperatures brushes often cause difficulties. Special types, for instance, the brushless types, can be used at higher temperatures up to about 300° C.

Changing the connections of three-wire synchro systems will result in a shift in the electrical zero or in a reversal of the shaft rotation of the receiving element.

Normally, synchro elements are connected in a standard way, for which purpose the terminals are marked with normalized indications (see Section 4.4). Especially with calibrated-scale indicators, it is essential that the manufacturer's instructions concerning the connecting method be followed strictly in order to ensure meaningful indications.

In a simple indicating system consisting of a torque transmitter (position transducer) and a torque receiver (direct-indicating pointer instrument), reversing the two rotor connections in either the transmitter or the receiver causes a shift in the indication of 180°. When the three stator connections are cyclically changed, a shift of 120° or 240° results; interchanging two of the three stator connections results in an opposite direction of the pointer rotation.

When changing two of the three stator connections in a circuit with a differential synchro, the sum instead of the difference of two angles will be measured, or vice versa.

4.4 Synchro coding

The following designations for the different synchro elements are internationally accepted (Ref. (6)).

Table 4.4-1

Standard designations of synchro elements

synchro element	designation
torque transmitter	TX
torque receiver	TR
torque receiver (also usable as torque transmitter)	TRX
torque differential transmitter	TD (or TDX)
(torque) differential receiver	DR
control transmitter	CX
control transformer	CT
control transformer (also usable as control transmitter)	CX/CT
control differential transmitter	CD (or CDX)
resolver synchro	RS
resolver transmittor	RX
resolver control transformer	RC
resolver differential	RD (or CDS)
transolver	TY (or CSD)

To further distinguish the synchro elements, a military standard code system (Refs (4) and (6)) is generally employed, which gives information about:

- size (for instance 11, 15, 18, etc.)
- function (for instance TRX, CT, RC, etc.)
- frequency (4 = 400 Hz; 5 = 50 Hz)
- design modification (represented by one letter a, b, c, etc.).

The size number represents the maximum outside diameter in tenths of inches. Fractions of tenths of inches are rounded to the next higher tenth. For instance, a synchro with a diameter of 1.08 inch is designated as an 11-size synchro. Most commonly used sizes for synchro elements used in flight-test work are size 8 and size 11. For example: the type number 11 TX 4b is given to an 11-size torque transmitter for 400 Hz use, which has been modified once since the original design.

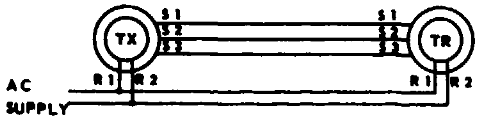


Fig. 4.4-1 Torque transmission system

Circuit-diagram symbols. In circuit diagrams a simpler symbol than those given hitherto is often used. The symbol is normalised and has two concentric circles, the inner representing the synchro rotor, the outer the synchro stator. The synchro function is indicated by the standard designation (given in Table 4.4-1) which is placed in the centre of these circles (see below). Normalised indications are R_1, R_2, R_3, R_4 for rotor connections and S_1, S_2, S_3, S_4 for stator connections. For elements with flying leads, wire identification is often realized by a normalised colour code, described in manufacturer's specifications (Ref.(10)).

The Figs 4.4-1 to 4.4-3 give examples of practical applications of this symbol system.

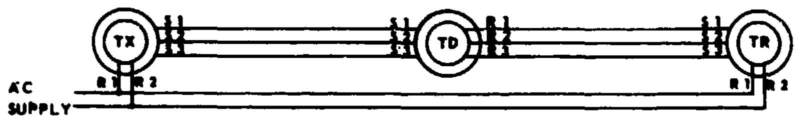


Fig. 4.4-2 Torque transmission system with differential transmitter

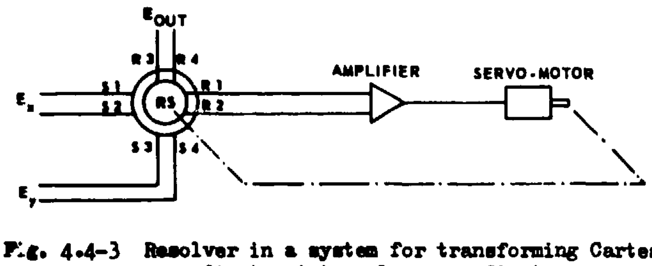


Fig. 4.4-3 Resolver in a system for transforming Cartesian co-ordinates into polar co-ordinates

5.0 INDUCTIVE SYSTEMS

5.1 Principle of inductive systems

Inductive systems for position measurement are essentially AC systems in which the measurand is converted into:

a) a change in the self-inductance of a single coil,

b) an AC voltage change by changing the reluctance path or the reluctivity between two or more coils, with AC excitation applied to the coil system.

Reluctivity can be defined as the measure of the ability of magnetic material to conduct magnetic flux. Reluctance in a magnetic circuit is comparable to resistance in an electric circuit.

Variable-reluctance systems are sometimes known under the name variable-permeance systems. Permeance is defined as the reciprocal of reluctance.

In some manuals only the systems indicated under a) are called inductive systems. Those indicated under b) are then called reluctive transducers. In most manufacturers' prospectuses, on the other hand, both groups are united under the title of inductive systems. This generic term was used in this chapter.

5.2 Types of inductive systems

There are several ways to change the inductance of a coil or to influence the voltage output of a system with two or more coils. The following types of inductive systems will be discussed:

a) linear variable differential transformers (LVDT's)

b) rotary variable differential transformers (RVDT's)

c) inductive systems with one coil

d) inductance bridges

e) systems with E-shaped pick-off cores

f) microsyns

Of these, the linear and rotary variable differential transformers (see Fig. 5.2-1) are the most widely used for flight test purposes. They will be discussed rather extensively in Sections 5.2.1 and 5.2.2. The others are less important and are discussed briefly in Sections 5.2.3 to 5.2.6.

Synchros are sometimes also classified as inductive systems. In this paper they are discussed separately because of their specific characteristics.

Induction potentiometers are described in Section 4.2.5 under the name "linear synchros". Electromagnetic and electrodynamic systems will not be described in this paper, because these self-generating devices are not suitable for static position measurement.

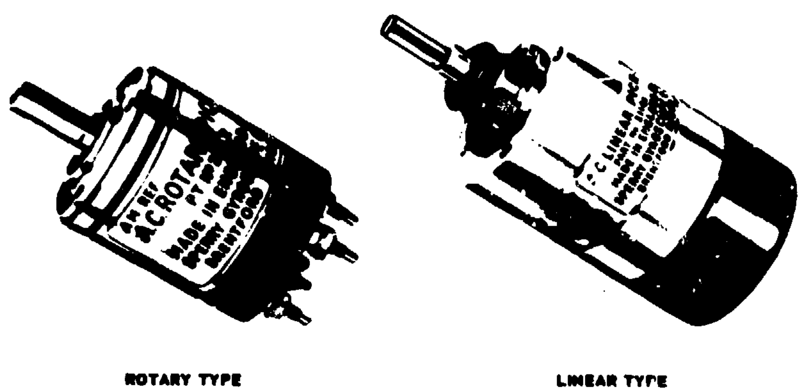


Fig. 5.2-1 Typical rotary and linear variable differential transformers

5.2.1 Linear variable differential transformer (LVDT)

The linear variable differential transformer consists of an AC excitated primary coil and two identical secondary coils on a non-contacting magnetic core as shown in the cutaway view of Fig. 5.2-2.

The two secondary coils are connected in series in such a way that when the core is in the centre between the two secondaries their voltage output is zero. In that situation the voltages induced in the two coils are equal and 180° out of phase. When the core is moved away from the centre position the mutual inductance of the primary coil with one secondary coil increases and with the other secondary coil decreases, due to the change in the reluctance paths. The induced voltages are no longer equal, and an output voltage appears. For displacements within the specified measuring range, this voltage is a linear function of the core position, as shown in Fig. 5.2-3.

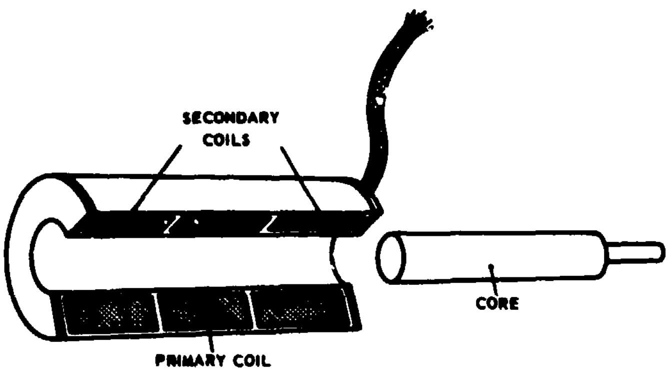


Fig. 5.2-2 Cutaway view of an LVDT

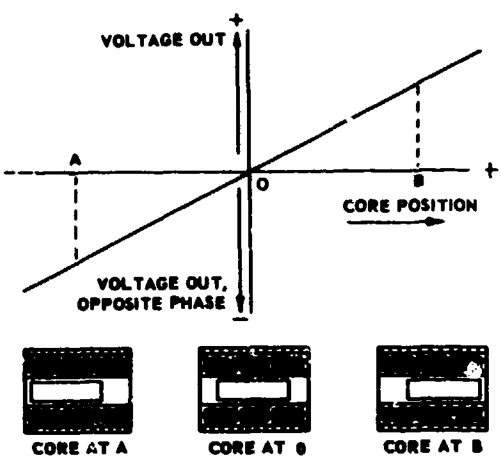


Fig. 5.2-3 Voltage output as function of core position for an LVDT

Concerning the manner in which the connections between both secondary coils are realised, there are three possibilities, as indicated in Fig. 5.2-4. In Fig. 5.2-4a the connection between the two secondaries is made within the transducer and only a two-wire output is available. This configuration is seldom applied, as it highly restricts the choice of further links in the measuring chain. The configuration in Fig. 5.2-4b makes it possible to use special measuring systems which are based on the measurement of the difference between the two coil voltages. Such systems have certain advantages in some cases. Fig. 5.2-4c gives the most universal configuration, where both secondary coils have two output connections. For normal use, the two secondary coils will be connected differentially, i.e., 180° out of phase with each other, as is done internally in situations a and b. Connecting both secondary coils in series (in phase) gives an extra possibility to test the transducer, as in this situation a constant output must be obtained over the whole measuring range, regardless of the core position. Fault location is made much easier by this feature.

Because there is no physical contact between the core and the coils, the LVDT is nearly frictionless. The only friction is caused by the fact that the core has to be

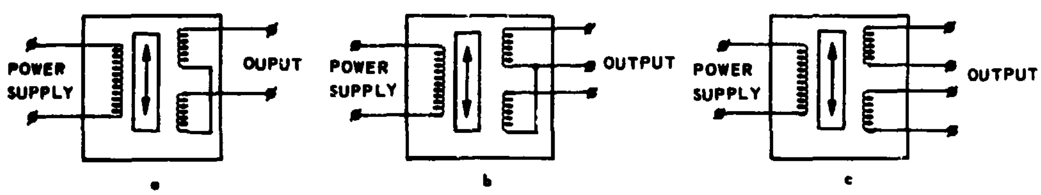


Fig. 5.2-4 Output configurations of variable differential transformer

guided within the coils by mechanical bearings. The life expectancy of this system is therefore very long. Other advantages of the system are infinite resolution and generally high sensitivity (high voltage output for relatively small displacements) and the fact that primary and secondary windings are fully isolated from each other, so that they can be grounded separately.

A recent development is the DC operated LVDT, in which an oscillator, generating a frequency of some kHz, is incorporated in the transducer case. Then generally a demodulator and a DC amplifier are also incorporated in the case, so that a real "DC in - DC out" sensor is obtained. Fig. 5.2-5 is a block diagram of such a device.

More details on linear variable differential transformers are given in Refs (22), (23) and (24).

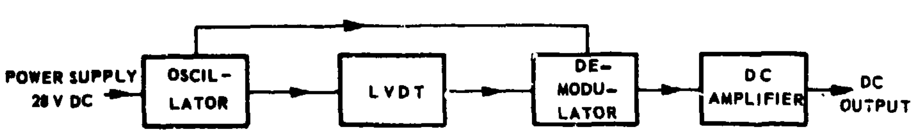


Fig. 5.2-5 Block diagram of a DC operated LVDT with DC output

5.2.2 Rotary variable differential transformer (RVDT)

The rotary variable differential transformer is in principle similar to the linear variable differential transformer; the mechanical arrangement of coils and core is, however, different, as shown in Fig. 5.2-6. This device is preferably used in cases where it is more convenient to have a rotating transducer to solve the measuring problem.

In an RVDT, the core is cardoid-shaped so as to get a linear output voltage for a wide range of angular displacements ($\pm 40^{o}$). Fig. 5.2-7 gives the output as a function of angular displacement. RVDT's are also available as "DC in - DC out" transducers.

More details on rotary variable differential transformers are given in Refs (22) and (23).

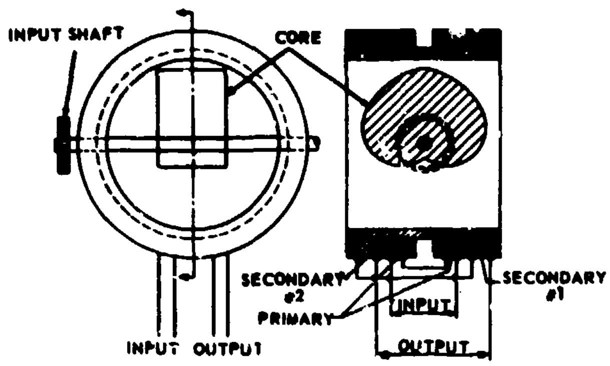


Fig. 5.2-6 Mechanical arrangement of coils and core in an RVDT

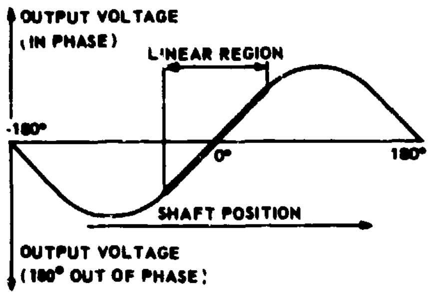


Fig. 5.2-7 Output voltage as a function of shaft rotation for an RVDT

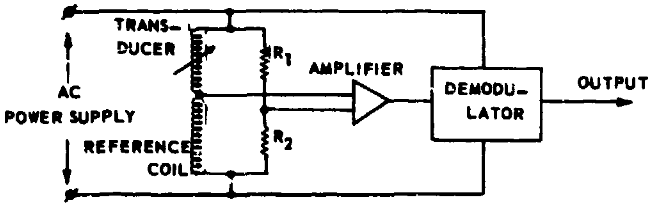


Fig. 5.2-8 Bridge circuit for AC transducers with one coil

5.2.3 Inductive systems with one coil

In transducers of this type, the measurand is converted into a change of the self-inductance of a single coil. This is usually effected by the displacement of a core which is free to move within a fixed coil. The coil can be used:

- in an impedance bridge
- in an LC-oscillator circuit.

When used in an impedance bridge, the inductance of the coil is compared with the inductance of a reference coil. Two resistors complete the bridge, which is excited with an alternating current (see Fig. 5.2-8). The output of the bridge is generally amplified and then demodulated in a phase sensitive circuit to obtain a DC output. The reference coil is usually mounted within the transducer case to reduce undesirable effects due to long connecting leads.

When used in an LC-oscillator, a capacitor is connected in parallel with the coil. A change in self-inductance then causes a change in the frequency of the output signal.

5.2.4 Inductance bridges

These are systems where the core can move within two fixed coils, so arranged that when the core position changes, the inductance of one coil increases, while the inductance of the other coil decreases. Such systems give twice the output of the system described in Section 5.2.3, which has one coil. The measuring circuit can be similar to that of Fig. 5.2-8, the second coil replacing the reference coil.

The principle can be used for linear displacements as well as for rotary position measurement. In the two cases the arrangement of the coils and the shape of the core differ (see Fig. 5.2-9).

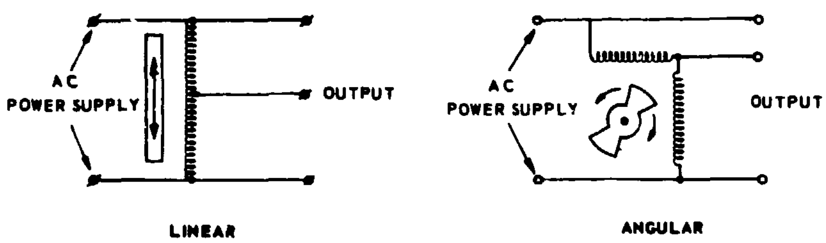


Fig. 5.2-9 Inductance bridge transducers for linear and angular position measurement

5.2.5 Systems with E-shaped cores

In Fig. 5.2-10, variable reluctance transducers are shown with an E-shaped laminated core with two identical secondary (series-connected) windings on the outer legs and one primary winding on the centre leg. When the centre leg is excited with an AC voltage, voltages are induced in the secondary windings that cancel out when the armature is in the centre position and that differ for other positions of the armature. The operation is similar to that of the LVDT, so for further consideration the reader is referred to Section 5.2.1.

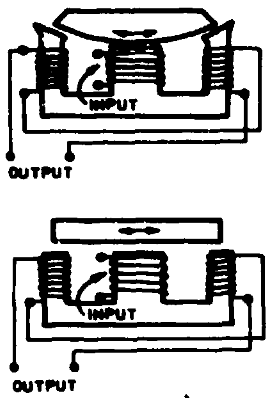


Fig. 5.2-10 Rotary and linear E-shaped transducers

In position transducers for flight test purposes, the E-shaped transducer is almost never used any more, because from the manufacturers' viewpoint it is a rather complicated device compared with other types of inductive systems, and its accuracy and linearity are generally inferior.

For more details, see Ref. (B1).

5.2.6 Microsyns

As shown in Fig. 5.2-11, the microsyn consists of a four-pole stator and a specially shaped rotor. Each of the microsyn poles is wound with two coils, a primary and a secondary coil. All primary coils are connected in series and connected to an AC supply voltage. The secondary coils are also connected in series and give an output voltage, the amplitude of which depends on the position of the core. The secondary windings are connected in such a way that in the neutral rotor position the output voltage is zero.

Microsyns are related to differential transformers and behave in a similar manner. In some manuals they are regarded as synchros. With other winding configurations, microsyns can also be used as torque generators; as such they are sometimes used in gyro systems or in force-balance servo systems.

For more details, see Refs (B1) and (B4).

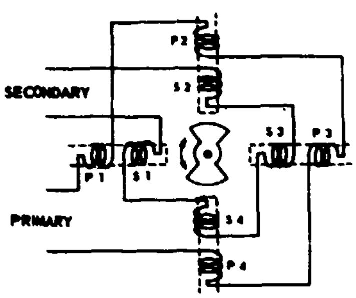


Fig. 5.2-11 Principle of the microsyn system

5.3 Characteristics of inductive systems

In this section typical characteristics of inductive systems, especially of variable differential transformers (LVDT's and RVDT's) will be considered, especially their accuracy and suitability for application as position transducers for flight test purposes. The discussion is mainly restricted to LVDT's and RVDT's, as these are the most important inductive systems. Most considerations also hold for other inductive systems. Special characteristics of the latter have already been considered in the general descriptions in Sections 5.2.3 to 5.2.6.

The resolution of all inductive systems is infinite, that is to say that even the smallest displacement of the operating shaft produces a measurable change in output.

The linearity of normal types LVDT's and RVDT's is about 0.5 % of the measuring range. Linearity can be improved if the transducer is used at less than its nominal range, because the linearity usually tends to deteriorate at the ends of the measuring range. Anomalies around the zero position of the core also often occur, because incomplete magnetic or electric balance often causes a residual quadrature voltage to remain. This quadrature voltage has, moreover, not always the same magnitude, but depends on, among other things, frequency and wave form. The effect of the quadrature voltage on the output curve is shown in Fig. 5.3-1. In most applications the magnitude of the null voltage, if it is constant, is not important, as it is generally smaller than 1 % of the total voltage output. In special applications it may be necessary to reduce the null voltage, which can be done by means of special circuits.

The frequency of the power supply is generally specified by the manufacturer and is in many cases 400 Hz, as this frequency is mostly directly available in the aircraft. The frequency has some influence on

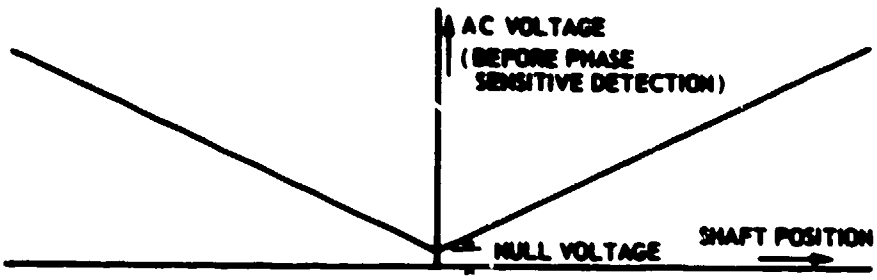


Fig. 5.3-1 Voltage output as a function of shaft position for a variable differential transformer

the sensitivity of the output signal, but this can generally be neglected for the variations of ± 5 % that can be expected in the frequency of the AC power supply of most aircraft. Sensitivity and efficiency generally increase at considerably higher frequencies, and for that reason the use of frequencies in the order of 1 to 5 kHz is sometimes preferred, although the application of a special oscillator is required then.

The sensitivity is in principle directly proportional to the voltage amplitude of the power supply. The output is therefore generally specified in terms of volts per cm displacement per volt input and ranges from a few mV/cm/V to a few V/cm/V. The maximum allowable value for the voltage amplitude of the power supply is determined by the maximum allowable power dissipation in the coils, magnetic saturation of the core, and insulation breakdown of the windings. The effect of the input voltage on the sensitivity can be cancelled in measuring circuits, based on the determination of the ratio between output voltage and input voltage. Systems based on the measurement of absolute voltages require a stabilised voltage supply if high accuracy is required. The excitation voltage is generally between a few volts and a few tens of volts. Types exist that can directly be supplied from the 400 Hz main power supply (26 V or 115 V) which is available in most aircraft.

The electrical load (input impedance) of the measuring circuit can affect the sensitivity. When high-impedance signal conditioning equipment is used, this effect will generally be negligible. Measuring systems with low input impedance, such as simple direct indicating instruments, can seriously decrease the sensitivity.

The phase angle of the output voltage with respect to the supply voltage can have appreciable values (some tens of degrees). This aspect must be seriously considered when choosing the measuring equipment. In applications where the core passes the centre position, complications can be expected because the sign of the phase angle changes. It is therefore often necessary to reduce the phase shift to less than a few degrees by means of a compensation circuit, that can generally be a simple capacitor across, or in series with, the output signal. The phase angle depends somewhat on the frequency of the excitation voltage, but this effect can generally be neglected for variations of the order of ± 5 %. The phase angle furthermore depends on the load impedance. This effect must be taken into account when dimensioning phase compensation circuits.

The temperature range within which normal types of variable differential transformers can be used is from -60° C to +100° C. Temperature has some effect on the sensitivity that cannot always be neglected. Special types can withstand temperatures up to +600° C without being damaged, although the accuracy can decrease to a few per cent of the measuring range. The so-called "DC in - DC out" types cannot withstand temperatures higher than about +100° C.

6.0 DIGITAL SYSTEMS

The following digital systems will be considered:

- shaft position encoders
- on/off switches.

The most commonly used type of <u>shaft position encoder</u> is the rotary encoder, the principle of which is shown in Fig. 6.0-1. It consists of a coded disc with a number of concentric tracks consisting of alternately conducting and insulating segments. The conducting areas are electrically connected to a collector ring, over which the voltage is supplied to all conducting segments. Fixed brushes are arranged opposite the tracks, so that a voltage output pattern is obtained that depends on the shaft position.

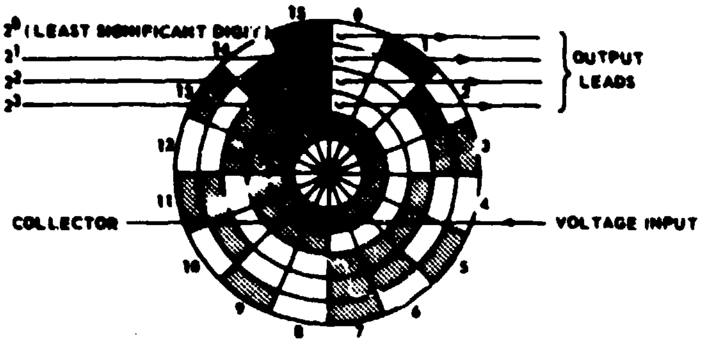


Fig. 6.0-1 Principle of a rotary type shaft position encoder

Fig. 6.0-2 Principle of a rectilinear type shaft position encoder

Besides this system with conducting and non-conducting areas, optical systems are available with clear and opaque segments, using light sources and photocells for detection. Other brushless systems make use of magnetic or capacitive sensing techniques. Disadvantages of the brush systems, such as excessive wear, unreliable functioning caused by dirty contacts, etc. are not present in these systems. In rectilinear position shaft encoders the same principle is applied (see Fig. 6.0-2).

The patterns used in the discs in Figs 6.0-1 and 6.0-2 give a binary coded output, in which each output lead represents a power of 2 (2^0; 2^1; 2^2; 2^3). The resolution is 1:16 or about 6 %. Higher resolution can be obtained by increasing the number of tracks. The patterns shown in Figs 6.0-1 and 6.0-2 have the disadvantage that at certain positions several bits have to change simultaneously. If, due to unsymmetric brush wear, a more significant bit changes slightly later than the other bits, large increasing errors can occur at these positions. Special code disks, in which only one bit changes at a time, have been developed to overcome this difficulty. Such systems require, however, more tracks to obtain the same resolution.

There are several reasons why shaft encoders are not widely used in flight testing, viz.:

- the case size for a given resolution is generally larger than for other types of position transducers
- the number of output wires that is needed is generally higher than with other types of transducers, because there is one wire for each ring
- shaft encoders are generally costly
- the output of analog position transducers can, if necessary, easily be transformed into a digital signal by means of electronic converters, that are often already present in the measuring system for conversion of other analog signals
- most types have a relatively low frequency response and are rather sensitive to vibration.

<u>On/off switches</u> can, in principle, be used to give single-bit digital information about the position of movable aircraft components. In practice this method is mainly used to signalise end positions and it is used almost exclusively if such a switch is already present for normal aircraft operation, as for instance to indicate the "up" and "down" positions of the undercarriage.

Taps in such existing systems can easily be made, and the signal, generally +28 V DC or 0 V DC, can directly be connected to an on/off channel of the recording system.

7.0 <u>INSTALLATION OF POSITION TRANSDUCERS</u>

7.1 <u>Introduction</u>

The installation of transducers in the aircraft can have a large influence on the overall cost, reliability, and accuracy of the total measuring system. In this chapter a number of aspects that must be taken into account during the design and installation will be discussed. The discussion will be focused on mechanical aspects; the electrical aspects (insulation, interference, grounding, etc.) have been considered in Volume 1 of this series (Ref. (25)) and will be major subjects in future volumes.

In many cases the transducer as obtained from the manufacturer is too fragile for direct installation in the aircraft. It then has to be "ruggedised" before it can be installed. This is discussed in Section 7.2.

The ruggedised transducer will then have to be connected to the mechanical parts the motion of which must be measured. In Section 7.3 the mechanical linkages that can be used for this connection are reviewed.

7.2 Transducer ruggedising

The shafts of most of the linear and angular position transducers can only stand very limited forces and moments. When this shaft is mounted directly to the part the motion of which must be measured, unacceptable forces and moments are likely to occur. Perfect alignment of the transducer shaft with the moving part will reduce some of these, though at a high installation cost. Nevertheless, if the moving part and the base to which the transducer is mounted move relative to each other (due to flight loads or vibration), large forces and moments on the transducer shaft will still occur. They will not only reduce the reliability of the transducer installation, but may also affect the transducer calibration. It is, therefore, better to connect the transducer shaft to a more rugged intermediate shaft, which is then connected to the part the movement of which must be measured. The intermediate shaft must then be designed so that it does not transmit unacceptable forces and moments to the transducer.

A basic example of such a ruggedised transducer is given in Fig. 7.2-1. The transducer and the intermediate shaft are mounted on a sturdy mounting frame, and coupled by a simple stiff coupling. The transducer and the intermediate shaft can be assembled on the frame in the workshop, where good alignment can be assured.

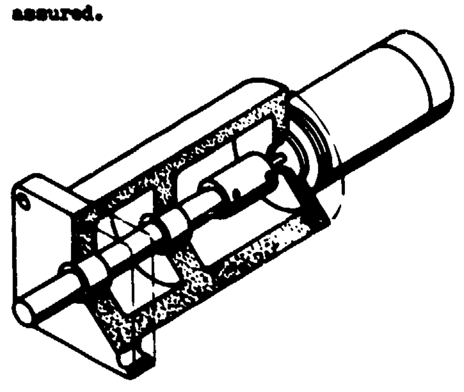


Fig. 7.2-1 Ruggedised position transducer

In some cases the environmental conditions - e.g. vibration level - as well as design and assembly procedures may still cause unacceptable load levels to be exerted by the intermediate shaft on the transducer shaft. It is then necessary to replace the stiff coupling by a flexible one. Examples of such couplings are shown in Fig. 7.2-2.

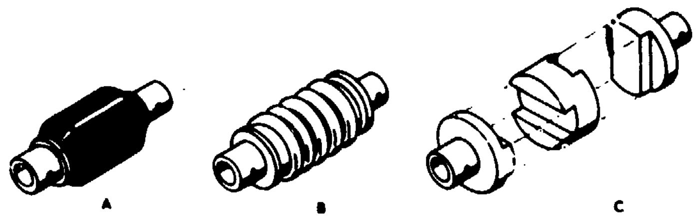


Fig. 7.2-2 Flexible shaft couplings
A Rubber coupling
B Steel bellows
C Oldham coupling

Type A is a rubber coupling. It is subject to torsion if large moments are to be transmitted, but is very suitable for the small moments generally required to move transducers. In some applications it has the advantage that it will damp out high-frequency vibrations. In the bellows coupling shown under B, no torsion will occur, and even in the case of relatively large axial movements of the intermediate shaft, it will exert only very small forces on the transducer shaft. Types A and B do not introduce backlash. The Oldham coupling shown under C is much smaller than the other two. Some play must exist between the parts of this coupling, which will result in some backlash.

The construction shown in Fig. 7.2-1 results in relatively long ruggedized transducers. For size 8 and 11 transducers, the overall length may well be more than twice that of the original transducer. If this is a problem, other designs can be used. Fig. 7.2-3 gives an example of a possible construction. The reduction of the length of the complete transducer is obtained by "folding back" the intermediate shaft around the shaft coupling. The intermediate shaft has become a bell-shaped part, supported by a single large-diameter slim-profile ball bearing. Due to its large diameter, this bearing can stand relatively large moments. In order to reduce such moments as far as possible, the input lever to the intermediate shaft is placed in the plane of the bearing.

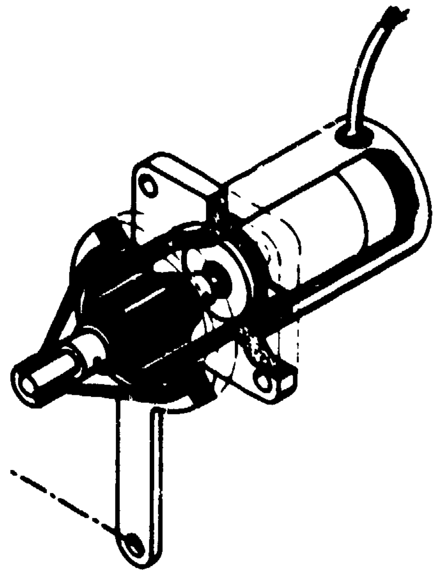


Fig. 7.2-3 Example of a construction to reduce the length of the transducer

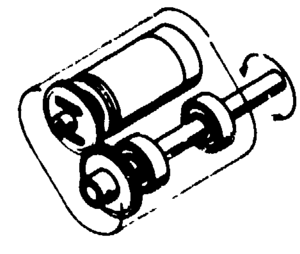


Fig. 7.2-4 Coupling of the intermediate shaft by gears

Fig. 7.2-4 shows another method for reducing the overall length of the transducer. There, the transducer and the intermediate shaft are coupled by gears. One of the gears must be of the split and internally spring loaded type to eliminate backlash. The spring must be strong enough to cope with sudden movements, which can be quite fast, as, for instance, in hydraulically operated control systems. In this type of coupling, a gear ratio can be introduced between the input shaft and the transducer shaft. The dimensions of this construction can be quite small.

Similar constructions can be made for linear transducers, but they generally become more complicated. Many linear differential transformers are already delivered with relatively strong input shafts and bearings, which can then be used without an intermediate shaft.

A limited range of ruggedised angular transducers is also commercially available, but for many applications they have to be specially designed and built.

When designing a transducer ruggedising system, the expected loads and displacements should be determined beforehand. A few details of the construction will be discussed here in some more detail:

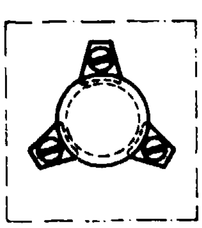
- the mounting frame
- the transducer mounting
- the intermediate shaft
- the housing.

The function of the mounting frame is to ensure that no unacceptable loads are transmitted to the transducer. Such loads can originate from three different causes:

- Axial and longitudinal forces and moments acting on the intermediate axis. The frame must be capable of absorbing these.
- Vibrations. Deformation of the frame under vibration must not introduce loads on the transducer shaft.
- Forces introduced through the mounting flange of the frame. These can be introduced either by deformations of the structure to which the flange is attached or by deformations of the flange when it is fastened to a non-flat surface. In general, the flange should be stiffer than the structure to which it is attached.

The best position for the mounting flange is as near as possible to the input side of the intermediate shaft and perpendicular to that shaft.

The method of mounting the transducer on the mounting frame can also affect the reliability and accuracy of the measuring system. Transducer manufacturers usually give detailed instructions about the preferred methods of mounting, and these should be adhered to as closely as possible. For synchros, the shape of the transducer and the methods of mounting were standardised long ago; more recently many potentiometers are built to the same standards. The preferred method of mounting such transducers is shown in Fig. 7.2-5.



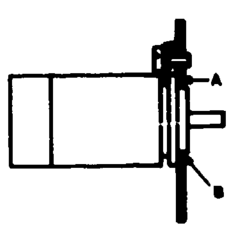


Fig. 7.2-5 Standard synchro rim mounting

The surfaces A and B of the transducer are made to close tolerances. Accurate and repeatable alignment can be achieved by carefully machining the hole and its surroundings on the mounting frame. The transducer is mounted by special clamps which are commercially available. An alternative method of mounting is shown in Fig. 7.2-6, where use is made of three holes that are available on the front of the transducer housing. This method is, however, not recommended if severe vibration occurs. Fig. 7.2-7 shows a method of mounting which is sometimes found in practice but is not recommended. The clamp can deform the housing and also present alignment problems.

The intermediate shaft should be designed in such a way that it will be strong enough to withstand forces and moments exerted on it by the aircraft structure and rigid enough not to transmit undue loadings to the transducer input shaft. For control position measurements and similar applications, a shaft diameter of 6 mm is generally sufficient. The shaft will in general be supported by two preloaded ball bearings. The distance between these bearings should be such that the bending moments on the inner bearing races are sufficiently low; 25 mm is generally sufficient. Installation can often be simpler if ball bearings with different diameters are used. The shaft and bearings can be held in place using collars and circlips. An example of an intermediate shaft design is given in Fig. 7.2-8.

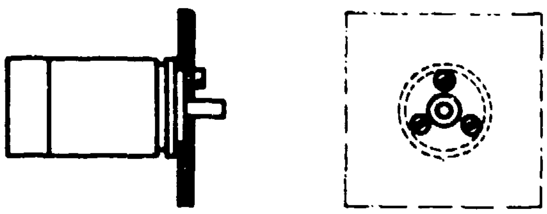


Fig. 7.2-6 Standard synchro screw mounting

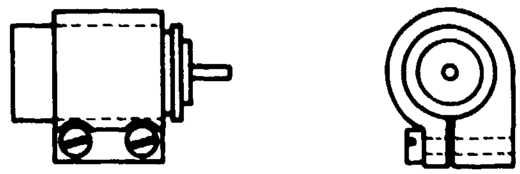


Fig. 7.2-7 Synchro clamp mounting

It is generally useful to enclose the construction by a dust cover, to make provisions for a safe connection for the electrical leads and a seal for the shaft end. Fig. 7.2-9 shows, as an example, the construction of a complete ruggedised transducer for measuring control surface positions.

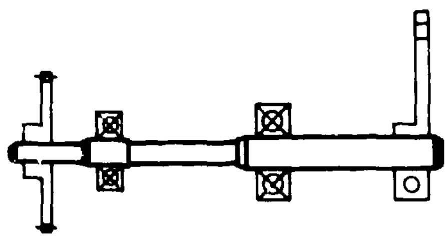


Fig. 7.2-8 Example of an intermediate shaft design

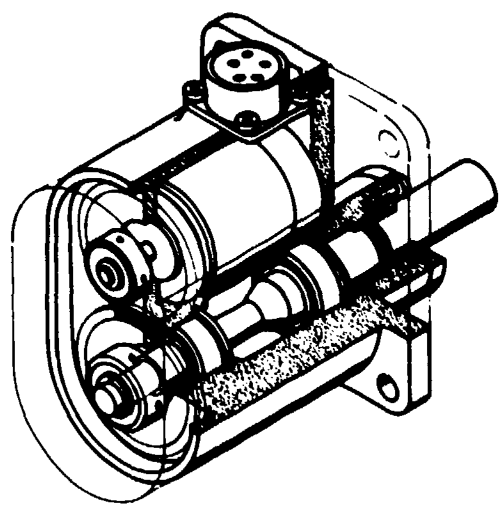


Fig. 7.2-9 Design example of a complete ruggedised angular position transducer

7.3 The coupling of the transducer to the moving part

7.3.1 General aspects

In general, it can be said that the (ruggedised) transducer should be mounted as closely as possible to the structural member the motion of which must be measured. This is, however, not possible in many cases. There may be no structural parts suitable for mounting the transducer, or the space near the moving part may be too small for mounting the transducer. In such cases the connection between the structural member the motion of which must be measured and the transducer must be made by transmission. This transmission must meet the following requirements:

- the transducer output must correspond to the position of the aircraft component exclusively; i.e. the base on which the transducer is mounted must not move with respect to the reference against which must be measured
- the effect of play and backlash should be small with respect to the required measuring accuracy
- in most cases the relationship between the position of the moving part should be as linear as possible; in special cases a specific non-linear relationship may be required, for instance if a high sensitivity (and accuracy) is required over only part of the total measuring range.

It must be realised that inadequacies of the transmission system can have a large effect on the overall measurement accuracy.

7.3.2 Direct coupling

Direct coupling between the transducer and the moving part is in general the best method if it can be realised. This can, however, be done only if a suitable base for mounting the transducer can be found near the moving part and if the relative motions in other directions than the measuring direction are small enough to ensure sufficient accuracy and reliability. For most control position measurements a flexible coupling will be required. Two examples are given in Figs 7.3-1 and 7.3-2. In Fig. 7.3-1 a commercially

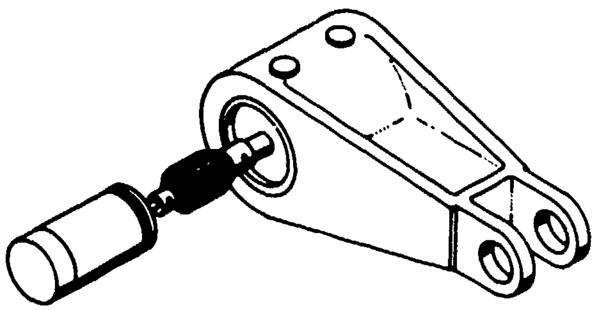


Fig. 7.3-1 Directly coupled transducer using a flexible coupling

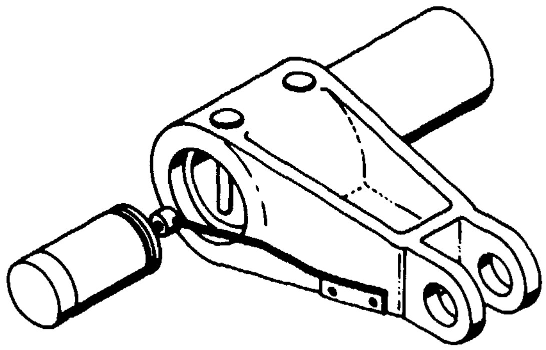


Fig. 7.3-2 Directly coupled transducer using a spring lever coupling

available flexible coupling has been used. In Fig. 7.3-2 a direct wire spring lever has been custom made. The wire spring must have bends to allow relative movements between the control surface shaft and the transducer and must be stiff enough to ensure good calibration adherence even during sudden control movements.

7.3.3 Lever coupling

For the measurement of the position of aircraft control surfaces and similar moving parts, the lever coupling (Fig. 7.3-3) is often the best solution. This construction can transmit the motion over relatively large distances and can accept rather large relative displacements between control shaft and transducer.

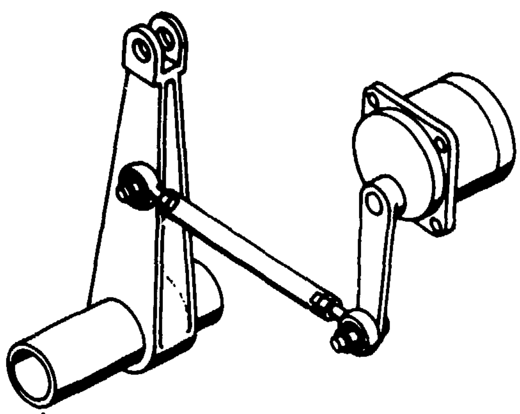


Fig. 7.3-3 Lever coupling

The accuracy of a lever coupling can be very high if the deformations of the lever parts under loading are kept small and if the levers are long enough to reduce the effect of bearing play to a negligible value. The linearity of the coupling will be high if the levers are parallel and of equal length. Fig. 7.3-4 shows what happens if the levers are not parallel. In this figure, the misalignment is the zero position of the output angle β at which the input angle α is zero (input lever perpendicular to the connecting rod). It is found that for a misalignment of 5 degrees the linearity error at $\alpha = 40$ degrees can be 5 degrees. For a misalignment error of 15 degrees, this becomes 15 degrees.

The effect of unequal lengths of the levers is shown in Fig. 7.3-5. This figure shows that even for a ratio $\frac{A}{B} = 1.2$, large differences occur between α and β.

The effects described above are sometimes used intentionally. In some applications, a higher sensitivity and accuracy is desired over part of the measuring range. From Fig. 7.3-4 it can be seen that the sensitivity at one end of the range shown is much higher than it would be if the levers were parallel; at about $\beta = 0$ the sensitivity is about equal to that of parallel levers and the sensitivity continues to decrease towards the opposite end of the measuring range.

Arrangements as described above can be used for the measurement of the position of lift dumpers and speed brakes, where the highest sensitivity is usually requested at the point where the surface begins to deflect. The arrangement of Fig. 7.3-5 with $A > B$ produces a high sensitivity at both ends of the measuring range and a lower sensitivity (though still higher than when the levers have equal length) in the middle of the range. In some applications, such as the measurement of control surface deflections, a high sensitivity in the middle of the measuring range is required, and the sensitivity near the ends of the range can be lower. A system of the type shown in Fig. 7.3-6 makes this possible.

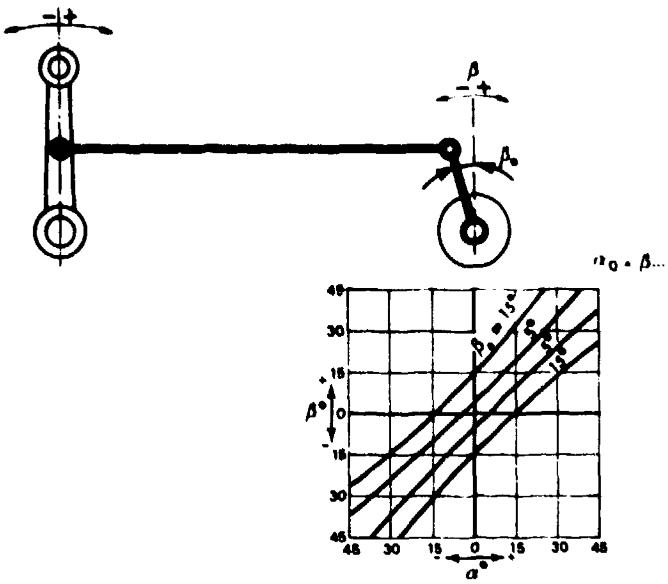


Fig. 7.3-4 Linearity errors due to non-parallel levers

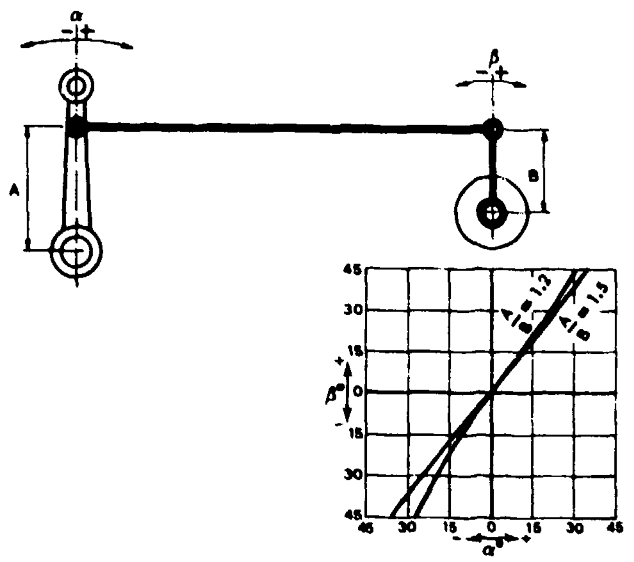


Fig. 7.3-5 Linearity errors due to difference in lever length

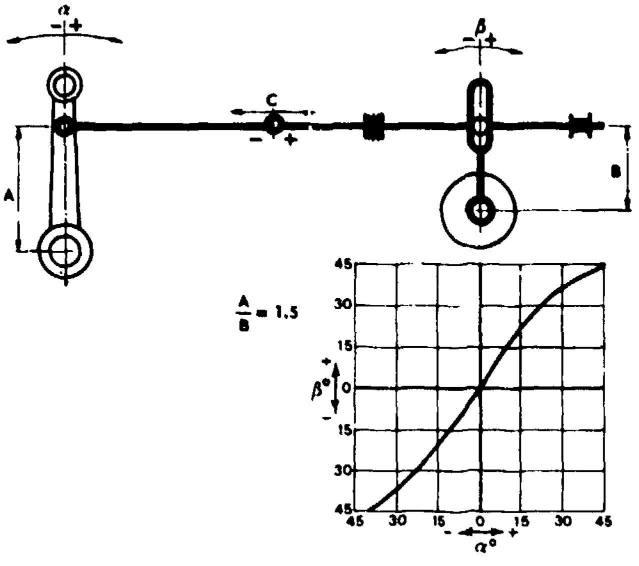


Fig. 7.3-6 Device for obtaining high sensitivity in the middle of the range and lower sensitivity at the range limits

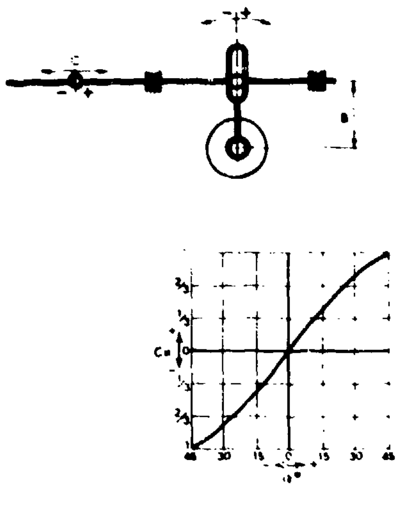


Fig. 7.3-7 Device for converting linear motion into angular motion

A similar mechanism can be used for converting linear into angular motion. The mechanism shown in Fig. 7.3-7 produces an angular deflection which is proportional to the linear displacement of the input shaft.

The mechanisms described above, which make it possible to obtain a higher sensitivity (and accuracy) over part of the measuring range, were very important in the past when accurate position transducers were not available. Now that very accurate transducers are easily obtainable, there is no need to use them. Especially the mechanisms shown in Figs 7.3-6 and 7.3-7, which are very expensive when they have to be built for high-accuracy applications, are used very rarely nowadays.

A few remarks can be made about the design of lever couplings. For optimum performance the joints should incorporate self-aligning ball bearings. An example of such a joint is shown in Fig. 7.3-8. Backlash is then reduced to a minimum and the joint can accept relatively large misalignments. Complete ball-bearing joints, which can be directly screwed on, are commercially available in a wide range of sizes and shapes. As shown in Fig. 7.3-8 the screw end which goes into the connecting rod between the two levers can be used for the adjustment of the rod length during installation.

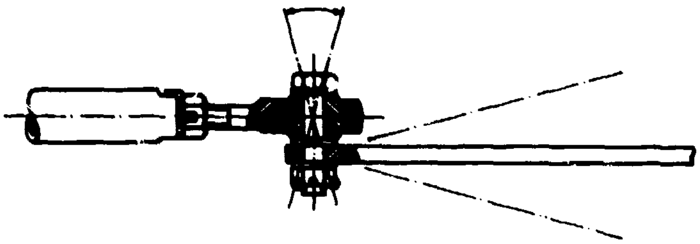


Fig. 7.3-8 Lever joint with self-aligning ball-bearing

For reasons of cost, nut-and-bolt joints are still extensively used, notwithstanding the following disadvantages:
- installation is more tricky because they are more sensitive to alignment errors
- because of the relatively high wear rate, maintenance will require more time
- backlash will be greater and may increase with time.

If used, such joints must be carefully designed. In the design shown in Fig. 7.3-9, the bolt can tilt in both holes. This not only causes a larger play than is necessary, but wear may increase this play considerably. A better solution is illustrated in Fig. 7.3-10, where the bolt is immobilised with respect to one of the parts of the joints.

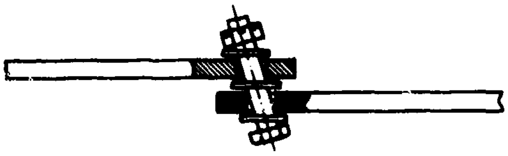


Fig. 7.3-9 Badly designed joint with bolt and nut

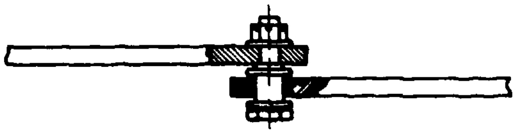


Fig. 7.3-10 Properly designed joint with bolt and nut

7.3.4 Cable coupling

Though lever coupling is used most for the types of measurement discussed in this volume, a few others are used in special cases. The most important of these are the cable couplings. Their main application is in cases where:
- very little space is available
- the angular movement extends over more than 90 degrees
- bends are necessary in the transmission between input axis and transducer
- a linear movement has to be transformed in a rotation.

Cable couplings are more vulnerable than lever couplings. Kinks or bends in the cable can have a large effect on the overall accuracy and can impede operation. Dirt can also have a detrimental effect. The overall accuracy is generally lower than for lever couplings.

A simple cable coupling is shown in Fig. 7.3-11. The cable is attached to the two pulleys. The spring keeps the cable under tension at all times. The disadvantage of this system is that the spring tension varies with the angular position. It can therefore only be used over a limited range. This is overcome in the closed-loop arrangement shown in Fig. 7.3-12. There, the spring has been inserted in the cable loop and the spring force is independent of the angular position. The range is limited only by the requirement that the spring must not touch the pulleys. If an external cable tensioner is used, as in Fig. 7.3-13, an even larger range can be obtained, which can extend to more than 360 degrees. As the cable must always be

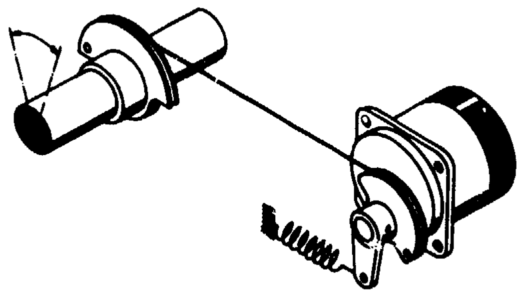


Fig. 7.3-11 Simple wire coupling with a single wire

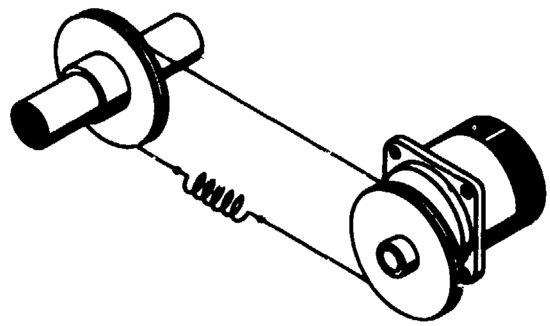


Fig. 7.3-12 Closed-loop cable coupling

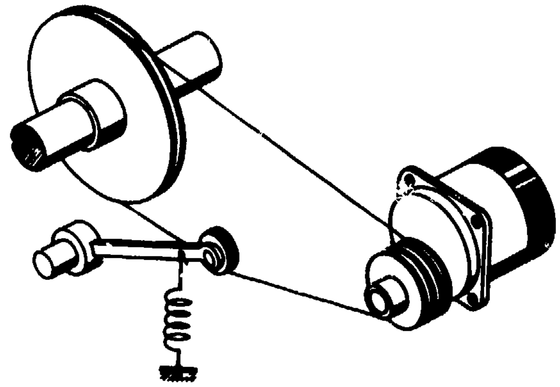


Fig. 7.3-13 Closed-loop cable coupling with external tensioning and a multi-groove pulley

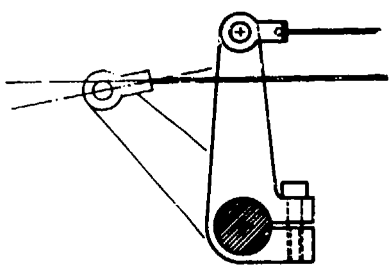


Fig. 7.3-14 Attachment of a cable to a lever

attached to a fixed point at both pulleys, the cable must make more than one turn about a pulley which turns over more than about 180 degrees. To prevent the cable loops from rubbing against each other and to guide them in exactly the same groove, multi-groove pulleys with a spiral groove are used in such cases. In Fig. 7.3-13 the range of the large wheel must be limited to about $\frac{1}{2}$ revolution, the range of the smaller two-groove wheel to about $1\frac{1}{2}$ revolutions.

The cable is made of stranded steel wires or nylon. The steel wire is not supple enough to follow the shape of smaller pulleys smoothly. Nylon is elastic and may change in length under stress. A compromise must be made for each application. In some designs attempts have been made to overcome the effect of the stiffness of steel cables by using levers connected by wire instead of the pulleys. It is found, however, that the cable bends due to hinge friction (see Fig. 7.3-14). Mainly for this reason cable-lever combinations are rarely used.

The direction of the cable can be changed between the input and output shaft by using idler pulleys at the bending points. If several such idlers are necessary, friction and spring effects in steel wires may have a too large effect on accuracy and the installation can also become rather clumsy. In such a case a Bowden cable (Fig. 7.3-15) may provide the best solution. Bowden cables are generally attached to levers. They should be loaded by a spring to take up any slack. The external hose of the cable must be supported at short intervals, especially at bends, because any movement of this hose will change the calibration of the overall system.

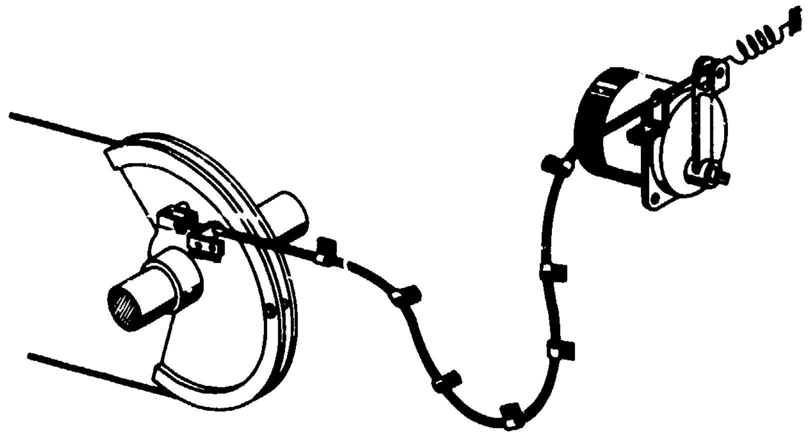


Fig. 7.3-15 Bowden cable coupling

7.3.5 Chain coupling

A chain coupling (Fig. 7.3-16) is sometimes used instead of a cable coupling if:
- the input and the transducer shafts are very close together
- the gear ratio is high
- the shafts have to make more turns.

Recently, new drive systems for instrumentation purposes have been introduced on the market. Two examples are shown in Figs 7.3-17 and 7.3-18. With respect to normal chain transmissions they have the advantage that they are less sensitive to dirt.

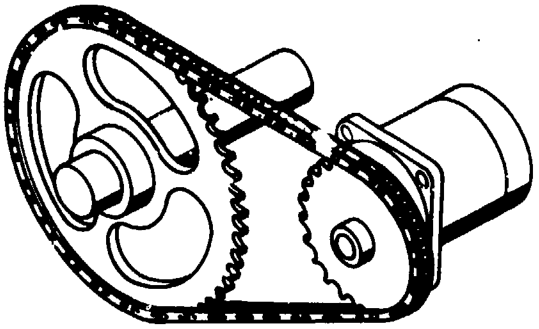


Fig. 7.3-16 Chain coupling

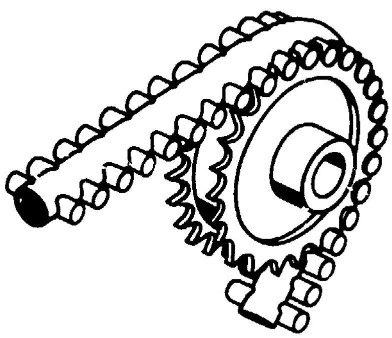


Fig. 7.3-17 Positive belt drive

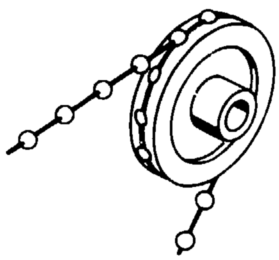


Fig. 7.3-18 Ball cord drive

7.3.6 Cam follower coupling

Especially when space is very limited, the cam follower coupling (Fig. 7.3-19) can have advantages. In a low vibration environment its accuracy is comparable to that of a lever coupling and superior to a cable coupling. It is very useful for non-linear transmissions.

The performance of this coupling depends to a large extent on the quality of the roller and the rocker. A ball bearing is often used for this purpose, the outer race of which rolls directly over the cam. As dirt can seriously impair the accuracy, the materials of the cam and the roller are often chosen so that they need not be lubricated.

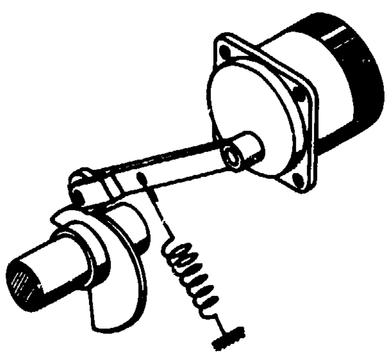


Fig. 7.3-19 Cam follower coupling

8.0 THE SELECTION OF A TRANSDUCER

In this chapter advice is given on how to select the most suitable type of transducer out of the many existing types for a given position measuring problem.

As already mentioned, it is in general possible to restrict the choice to one of the three following, most widely used, groups:
- potentiometers
- synchros
- inductive systems, and especially variable differential transformers.

In practice, it appears that the three groups are used in roughly equal proportions. Only in exceptional cases will other than the above mentioned groups have to be considered seriously.

The choice of the transducer is not only dependent on the special characteristics of each group, but is also closely determined by the characteristics of further links in the measuring chain, especially those of the interface between the transducer and the indication or recording equipment. Environmental conditions often also play an important part in determining the optimum choice.

In the following, for each of the three transducer groups attention will be paid to:

- aspects concerning physical environmental conditions
- aspects concerning interface equipment
- aspects concerning special characteristics of that group of transducers
- advantages and disadvantages, when comparing the transducers with transducers of both other groups.

Potentiometers. Of all transducers discussed in this volume, the potentiometer can most easily be adapted to many measuring systems without the need of complicated interface equipment for signal conditioning, as often required for synchros and variable differential transformers.

Concerning the interface equipment, the potentiometer should always be used in circuits that measure the resistance ratio rather than the absolute value of resistance, as only in the first-mentioned circuits the often highly fluctuating resistance between wiper and element can be cancelled out. This is especially important when film potentiometers are chosen, as these generally have a relatively high resistance between wiper and element.

Potentiometers can be applied in DC circuits as well as in AC circuits. High voltage outputs can easily be obtained. In applications where a relatively high output current is desired, as for instance in direct measuring instruments in photo-panels, potentiometers and especially the low-resistance wire potentiometers are a good choice.

Potentiometers can easily be integrated with other elements of computers and electromechanical control systems.

It is generally possible to connect more than one measuring system to one potentiometer. The effect of extra loading cannot always be neglected then, but can often be determined from a special calibration. When a second load is connected to an operational circuit in the aircraft, it is essential, however, that the performance of that circuit is not impaired. Furthermore, the possibility of introducing errors by feed back from additional measuring systems and errors from extra ground loops has to be scrutinised.

For low-accuracy applications (down to ± 1 % of full range), low-cost wire-wound potentiometers are available. In these cases the best choice with respect to life expectancy will be low-resistance types with large wire diameters. For higher accuracies more sophisticated potentiometers are available. Relatively common types have accuracies up to ± 0.1 %, whereas still higher accuracies (± 0.01 %) can be achieved by using potentiometers with large diameters or multi-turn potentiometers.

Wire-wound potentiometers have a finite resolution, depending on the number of windings. When a very high resolution is wanted, application of film-type potentiometers with practically infinite resolution must be considered.

High linearities can be achieved with both film-type and wire-wound resistances (± 0.02 %, resp. ± 0.07 %). If a non-linear relationship between position and output signal is required, this can more easily be achieved with film-type potentiometers than with wire-wound types. Conformities to ± 0.1 % can be obtained with both types.

Due to the wiper-to-element configuration, potentiometers are more subject to wear than synchros and variable differential transformers. For the same reason potentiometers have a lower signal-to-noise ratio than both other systems.

The life expectancy is proportional to the number of wiper operations and depends furthermore on wiper pressure, wire thickness, choice of material, and construction. High-precision single-turn potentiometers of both types (wire-wound or film) can have a life expectancy up to about 5×10^7 operations. Life expectancy of multi-turn potentiometers is lower. This is one of the reasons why these types are seldom used for position measurements during flight tests.

For quasi-static measurements the above-mentioned figure of 5×10^7 operations means an appreciable life expectancy. For dynamic measurements with high frequencies, however, it results in a short life, and for this reason the potentiometer is less attractive than synchros and variable differential transformers for those applications. It is true that dynamic position measurements above frequencies of a few Hz seldom occur, but often control surfaces, wing flaps, trim tabs, etc. are continuously subject to spurious high frequency vibrations, often around certain fixed positions. At the equivalent positions on the potentiometer, excessive wear can occur.

For measurements within temperature ranges up to about 100° C, relatively common types of potentiometers can be chosen. For temperatures to about 250° C, special types are available. When extremely high temperatures can be expected, as for instance when flight tests have to be executed at high Mach numbers, potentiometers can cause difficulties. For those applications, LVDT's are a better choice.

As a disadvantage, single-turn potentiometers can only be used for rotations of less than 360° (max. approximately 355°).

Synchros. The synchro system was originally intended for direct-indicating purposes. For this application simple indicators are available and as such the system has outstanding advantages over other systems. They are therefore extensively used in the circuits of the cockpit instruments in many aircraft types. For flight test applications, synchros have the disadvantage that rather complicated signal conditioning equipment has to be applied for the conversion of the electrical output into the DC or digital signals required by most flight test recording systems. That synchros are nevertheless extensively used in flight testing stems from two reasons:

- many of the signal conditioning circuits can be connected in parallel with a synchro indicator without degrading the normal operation of the original synchro chain. If the flight test system can be connected to an existing aircraft circuit in this way, it will not be necessary to install a separate transducer.
- especially when the signal conditioning system is already available for other purposes, synchro transmitters are also often preferred for specific flight test applications. Besides the technical characteristics, previous experience and the relatively low cost may contribute to this choice.

Important features of synchros are their high accuracy and reliability, infinite resolution and the absence of stops. The overall measurement accuracy is not only determined by the very high accuracy of the transmitter, but is also affected by the other circuit elements. A torque synchro chain has an accuracy of about 1 degree. A servo chain including a synchro control transmitter and a synchro control transformer can attain an accuracy of 10 minutes of arc or even better. Synchro-to-DC and synchro-to-digital converters are available with different accuracies.

Normal converters have accuracies in the order of ± 5 to ± 15 minutes of arc when used for quasi-steady measurements at speeds up to some hundreds of degrees per second, whereas more sophisticated converters can have accuracies of ± 2 minutes of arc under these circumstances. For accurate measurements at higher shaft-rotation speeds up to some thousands of degrees per second, special rate-compensated converters are available.

Normal power supply for synchros is 26 V or 115 V; 400 Hz, that can generally be obtained from the aircraft 115 V AC bus. Types working at higher frequencies (for instance 3000 Hz) are available and have certain advantages, especially with respect to the dimensions of transducers and the signal-conditioning components. For these types special power supply units are required.

Reliability and life expectancy of synchros are higher than can be obtained with potentiometers. A life expectancy of 5×10^8 operations can easily be obtained with normal types. For the highest reliability and life expectancy, the brushless types are recommended. Brushless synchros have almost the same reliability and life expectancy as variable differential transformers.

Linearity of normal synchros is generally better than ± 0.02 % of a full rotation; linearities better than ± 0.01 % are possible. Non-linear functions cannot simply be realized with synchros. In this respect potentiometers are more suitable. Of course, non-linearities can always be introduced by special mechanical linkages.

For measurements at temperatures up to about 100° C, relatively common types of synchros can be chosen. Brushes are a weak point in the synchro construction and especially at higher temperatures they cause many difficulties. Although with special types, for instance brushless synchros, measurements at higher temperatures (up to 300° C) can be executed, they are not recommended for use in this field. For measurements at high temperatures, variable differential transformers must be preferred to synchros.

Direct reading synchro indicators and synchro servo indicators generally have a low frequency response and cannot be used for accurate dynamic measurements above frequencies of a few Hz. The combination of synchro transducers and converters for recording purposes behaves better in this respect; however, in practice here also many difficulties are met when measurements above approximately 5 Hz have to be executed. There is not much literature available about this subject and manufacturers' specifications generally also give extremely brief information or none at all. In fact, accurate position measurements above a few Hz are seldom required, and the only requirement in this respect is that high frequency shaft vibration will not damage the transducer or degrade the measurement. Synchros can withstand vibration much better than potentiometers.

Variable differential transformers. Of all existing inductive systems for position measurement, only the linear variable differential transformer (LVDT) and the rotary variable differential transformer (RVDT) need to be considered seriously for flight test purposes, as these devices rise high above all other transducers of this group in meeting all kinds of general and specific requirements. As they require neither brushes nor wipers, their mechanical construction can be very simple. In general they are extremely rugged, are resistant to vibration and shock, and have a long life expectancy. In these respects they excell above potentiometers and can compete with brushless synchros.

Variable differential transformers have, like synchros and film-type potentiometers, the advantage above wire-wound potentiometers of having infinite resolution.

Variable differential transformers are essentially AC devices, using modulation frequencies from 50 Hz to a few kHz. The 400 Hz types have the advantage that the necessary power supply can be obtained from the aircraft AC main bus. Application at higher frequencies has certain advantages but requires a special oscillator.

Normally, the transducer contains a half bridge, and the other two arms necessary to complete the bridge are added externally. Cabling sometimes introduces capacitive unbalance which must be compensated for. This tends to make the signal conditioning more complicated and expensive.

Some of the above-mentioned difficulties with the signal conditioning equipment have been overcome in the "DC in - DC out" variable differential transformer, in which the modulator and demodulator circuits are fully integrated in the transducer case. In this type, most advantages of potentiometers are combined with the advantages of high reliability, resolution, and life expectancy.

For measurements at temperatures up to about 100° C, relatively normal types of variable differential transformers can be chosen, but special types are available for higher temperatures up to 600° C. In practice, the variable differential transformer is the only device that can successfully be used for position measurements where the transducer must withstand temperatures that occur during flights at high Mach numbers. Use of the "DC in - DC out" variable differential transformers is restricted to the temperature range of 100° C due to the limits prescribed by the built-in electronic components.

Concerning the dynamic response of variable differential transformers, there are no limitations except those due to the demodulation process. In general, frequencies up to about 1/10 of the carrier frequency can be measured. High-frequency transducer shaft vibrations will not seriously reduce the life expectancy or influence the measuring result if properly designed signal-conditioning is used.

For direct-indicating purposes, the variable differential transformers have the disadvantage that the relatively complicated signal conditioning remains necessary. For synchros and potentiometers simple indicators are available without the need of interface equipment for those applications.

Variable differential transformers cannot easily be integrated with other computer elements, etc. In this respect potentiometers and synchros must be preferred.

Advantages of variable differential transformers compared with potentiometers are finally:

- the low noise level
- the negligible actuation force
- the electrical separation between output signal and power supply.

Summary. The specific characteristics of the three main groups of position transducers for flight test purposes can be described as follows:

The potentiometer can be regarded as the device that is best suited for quasi-static applications. It has the advantages of low cost, high output signal, and of being the simplest to use. Disadvantages are the relatively low life expectancy, low reliability, and low resistance to shock and vibration and the relatively high noise level. Wire-wound potentiometers have the disadvantage of finite resolution.

The synchro is a device with excellent resolution, high accuracy (even for normal types), high reliability, and, especially in the case of brushless types, a long life expectancy. A disadvantage is the necessity for complicated and expensive signal conditioning for recording purposes.

The variable differential transformer is a device with excellent resolution, medium accuracy, and long life expectancy. Because of its robustness it can be used under extreme environmental conditions. A disadvantage is the necessity for relatively complicated signal conditioning, except for "DC in - DC out" types.

In special cases, systems other than the three mentioned above must be considered. This is for instance the case for applications in telemetry circuits, because variable self-inductance transducers can be easier adapted to an FM transmission system.

Another example is the application of the DC synchronous system for direct reading instruments.

9.0 CALIBRATION OF POSITION MEASURING EQUIPMENT

General considerations concerning the calibration of flight test measuring instruments or measuring chains are given in Volume 1 (Ref. (25)) of the AGARD Flight Test Instrumentation Series. From this it appears to be preferable to first calibrate each component of a measuring channel separately and then to combine the different component calibrations into an overall (end-to-end) calibration of the measuring channel. To be sure that all possible effects have been taken into account in such cases, the overall calibration is finally checked at a few points or a complete overall calibration is executed.

For position measuring channels it sometimes is not so easy to obtain an overall calibration by combining component calibrations. It may, for example, be difficult to separately calibrate the mechanical linkage between an aircraft control surface and the position transducer with sufficient accuracy. The combination of the control surface to be measured, the mechanical linkage, and the transducer can then be regarded as one component. The overall calibration can then be obtained by combining this calibration with the component calibrations of the signal conditioner, the recording channel, etc. If the mechanical linkage introduces a non-linearity, it may be necessary to take a relatively large number of calibration points. Especially in that case it may be better to execute an overall calibration of the total channel than to combine the component calibrations. Even when an overall calibration of the total channel is preferred, however, it is helpful to have component calibrations available for locating error sources if the total channel accuracy deteriorates after some time. Component calibrations can also be useful to check the accuracy, linearity, and play of mechanical linkages. This can be done by comparing the overall calibration of the combination of transducer and mechanical linkage with the calibration of the transducer alone. For this purpose both calibrations must preferably be executed in the laboratory.

In the following, consideration will be given to:

- calibration of position transducers with and without coupled mechanical linkages
- calibration of signal conditioning equipment for position measuring channels
- overall calibration of a complete position measuring channel.

The calibration of position transducers, which will generally be executed in the laboratory, is done by positioning the transducer shaft in a number of accurately known positions and measuring the electrical output at each position. The shaft position can be measured by means of an angular setting table, a linear displacement gauge of the dial-and-pointer type, a bubble inclinometer, a precision ruler, or a similar device that will mostly already be available for other purposes, for instance as a tool in the fine mechanical workshop. The electrical output measurement can be performed by standard laboratory instruments such as resistance ratiometers, precision voltmeters, precision synchro indicators, etc. Values for power supply, frequency, load impedance, etc. during the laboratory calibration must preferably be chosen in accordance with the values to be expected during the flight tests. Monitoring and recording of the excitation voltage during the calibration of position transducers is, in general, very useful.

In most cases the calibrations can be done under normal laboratory conditions. When extreme environmental conditions are expected, the calibrations will have to be done under simulated circumstances, for instance, in a high-temperature chamber.

Calibrations of the combination of the transducer, the mechanical linkage, and the control surface can be executed in a similar way. Such measurements must often be made on the aircraft itself. This should then be placed in a hangar so that the calibration is least influenced by other factors.

The calibration of signal conditioning equipment for position measurement is generally performed in the laboratory, but can in principle also be done after installation in the aircraft. The calibration is usually done by supplying a number of known input values (resistance ratio, voltage, synchro signal, etc.)

and measuring the output for each setting. To facilitate this work, often transducer simulators are used. These can vary from simple homemade devices to sophisticated special-purpose simulating equipment. For the calibration of synchro-signal conditioning equipment or synchro-input channels of recorders, computers, etc., special synchro simulators are available, containing high-accuracy precision synchros or multi-tap transformer circuits to meet very high accuracy requirements. Monitoring and recording of the excitation voltage during the calibration of signal conditioning equipment is, in general, very useful.

The overall calibration of a complete position measurement channel is executed after the installation of all components in the aircraft. It is performed by positioning the aircraft component in a number of known positions and recording or noting the output at the end of the measuring channel. Generally, the choice of the positions at which calibration points must be taken is self-evident, especially when there are special points such as end stops, centre positions, etc. in the movement range. The number of calibration points depends amongst other things on the desired accuracy and on the linearity of the measuring chain. The required number of calibration points in a non-linear channel, generally, is much larger than in a linear channel.

Devices that can serve as calibration standards are, for instance, inclinometers (especially bubble-inclinometers), precision rulers, displacement gauges of the "dial-and-pointer" type, etc. Often a certain measure of ingenuity and improvisation talent will be necessary to find the best solution for problems in this field.

For calibrations that cannot be realised with simple auxiliary devices and (or) that have to be performed frequently, it is often justified to develop special calibration tools. Obviously no general directives can be given for the manufacturing of such devices. They generally are homemade devices specially adapted to a certain measuring situation. An example of such a special calibration tool is an angular measuring mechanism used for the calibration of rudder control surfaces (see Fig. 9.0-1). It consists of two pairs of parallel arms; one pair is (by means of ball bearings) coupled at one end to a footplate and at the other end with a graduated dial plate; the other pair is coupled at one end to a footplate and at the other end to an adjustable, transparent, reference plate. Coupling and dimensions are such that two parallelograms are formed by which any angular rotation of the footplates with respect to each other is directly transmitted to the dial and reference plates. The indication is only dependent on the angle between the footplates and not on the distance between them. The footplates are provided with rubber suction cups by which one pair of arms can be attached to a convenient point on the rudder surface and the other pair of arms to the vertical stabiliser. With the aid of this tool, the position of the rudder with respect to the stabiliser can be read directly from the dial. The indication can be adjusted to zero for the centre position of the rudder. The determination of the rudder centre position must be done by other means that will not be described here. The tool can in principle also be applied for the calibration of elevator and aileron angles, but these calibrations can generally be executed better by using bubble-inclinometers.

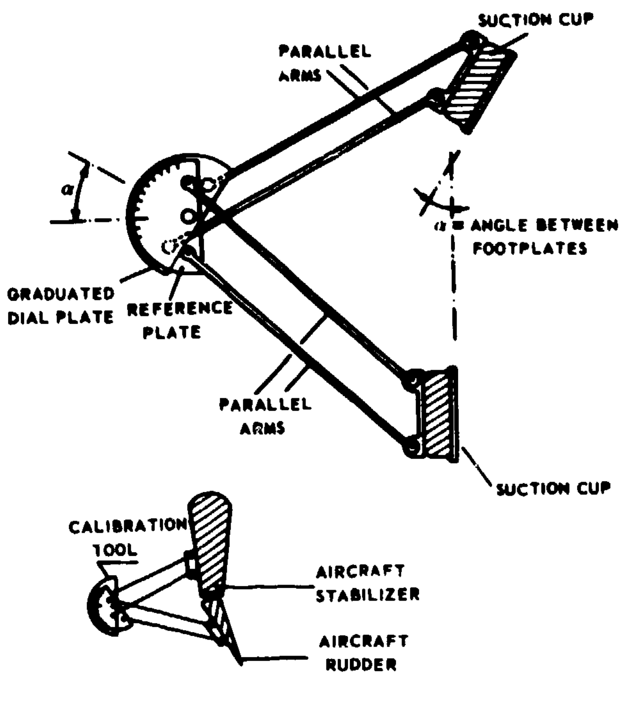


Fig. 9.0-1 Special tool for rudder calibration

10.0 [illegible]

Books

(B1) S.A. Davis, B.K. Ledgerwood — Electromechanical Components for Servomechanisms, McGraw-Hill Book Comp. Inc., New York, 1961.

(B2) P.H. Mansfield — Electrical Transducers for Industrial Measurement, London Butterworths, 1973.

(B3) E.O. Doebelin — Measurement Systems: Application and Design, McGraw-Hill Book Comp. Inc., New York, 1966.

(B4) H.N. Norton — Handbook of Transducers for Electronic Measuring Systems, Prentice Hall, Inc., Englewood Cliffs, N.J., 1969.

(B5) W.F. Walter — Servo Systems, Electronic Data Library, Vol. 2, Morgan-Grampian Books Ltd., Summit House, Globe Way, West Wickham, Kent, 1969.

(B6) Chr. Rohrbach — Handbuch für Elektrisches Messen Mechanischer Grössen, VDI-Verlag, Düsseldorf, 1967.

Reports and publications

(1) E. Kottkamp, H. Wilhelm, D. Kohl — Strain Gauge Measurements on Aircraft, AGARDograph No.160, Vol.7.

(2) T.J. Vandersluis, P.W. Batecon — Performance and Application Aspects of Linear Displacement Measuring Transducers, The Transducer 74 Conference, Seymour Hall, London W.1, Sept. 1974.

(3) R.J.A.W. Hosman — Advanced Flight Test Instrumentation: Design and Calibration, Memorandum M-222, Delft University of Technology, Oct. 1974.

(4) - — General Specifications for Synchros, Military Specifications, MIL-S-20708 C, Aug. 1969.

(5) - — General Specifications for Variable Resistors, Military Specifications, MIL-R-81106 A (AS), Oct. 1967.

(6) - — Military Specification for Electrical AC Resolvers, MIL-R-14346A (MU), Sept. 1967.

(7) R.L. Annesley — Potentiometers as Displacement Transducers, The Transducer 74 Conference, Seymour Hall, London W.1, Sept. 1974.

(8) H.H. [illegible] — Precision Film Potentiometers, IRE Wescon Convention Record, Computer Controls Ltd., London, 1960.

(9) - — Handbook of Litton Precision Potentiometers, Litton Precision Products Inc., New York, 1968.

(10) - — Servo Component Specifications, Catalog 26, Publication No. 70-11-30, Bendix Flight and Engine Instr. Div., South Montrose, Pa., 1970.

(11) - — Technical Information for the Engineer No.1, part III: Synchros for High Performance Servo Systems, Kearfott Div. of General Precision Aerospace, Little Falls, N.J., 1962.

(12) - — Muirhead Magslips and Synchros, Publication E-1000, Muirhead and Co Ltd., Beckenham, Kent, England, 1959.

(13) - — Servo Components, Publ. 753/1, Sperry Gyrosc. Comp. Ltd., Great West Road, Brentford, Middlesex, England.

(14) - — Clifton Precision Catalog No. 5/73 10M, Clifton Precision, Litton Systems Inc., Marple at Broadway, Clifton Heights, Pa. 19018, 1973.

(15) - — Aeronautical Recommended Practice ARP 461 A, Society of Automotive Engineers Inc., New York, 1959.