



AC 21-40(0)

APRIL 2005

MEASUREMENT OF AIRSPEED IN LIGHT AIRCRAFT — CERTIFICATION REQUIREMENTS

CONTENTS

1. References	1
2. Further Reading References	2
3. Purpose	2
4. Status of this Advisory Circular	2
5. Introduction	2
6. Airworthiness Standards	3
7. Calibration	4
8. Summary	10
Annex A Terms and Abbreviations	13
Annex B Pitot Sources and Pitot-Static Heads	14
Annex C Trailing-Bomb Pitot-Static Source	16
Annex D Trailing-Cone Static Source	17
Annex E Dynamic Lag Balancing	22

1. REFERENCES

- CASR Part 21 - Certification and Airworthiness Requirements for Aircraft and Parts.
- CASR Part 23 - Airworthiness Standards for Aeroplanes in the Normal, Utility, Acrobatic and Commuter Category.
- CASR Part 26 - Airworthiness Standards for Aircraft in the Primary Category or the Intermediate Category.
- CASR Part 27 - Airworthiness Standards for Rotorcraft in the Normal Category.
- CASA AC 21-35(0) – Calibration – Inspection and Test Equipment.
- FAA AC 23-8B – Flight Test Guide for Certification of Part 23 Airplanes.
- JAA Publication - JAR-23 AMC & I - Flight Test Guide for Certification of JAR-23 Aeroplanes (JAR-23 FTG).
- FAA AC 27-1B – Certification of Normal Category Rotorcraft.

Advisory Circulars are intended to provide advice and guidance to illustrate a means, but not necessarily the only means, of complying with the Regulations, or to explain certain regulatory requirements by providing informative, interpretative and explanatory material.

Where an AC is referred to in a 'Note' below the regulation, the AC remains as guidance material.

ACs should always be read in conjunction with the referenced regulations

2. FURTHER READING REFERENCES

- NASA Reference Publication 1046, 'Measurement of Aircraft Speed and Altitude' by W.Gracey, May 1980. (Also expanded into book format under the same title and published by John Wiley & Sons in 1981.)
- NACA Technical Note 616, 'The Measurement of Air Speed of Airplanes' by F.L.Thompson, October 1937.
- NACA Report Number 919, 'Accuracy of Airspeed Measurements and Flight Calibration Procedures' by W.B.Huston, May 1946.
- NACA Report 1364, 'Measurement of Static Pressure on Aircraft' by W.Gracey, December 1956.
- NASA Technical Note D-7217, 'Subsonic Wind Tunnel Tests of a Trailing-Cone Device for Calibrating Aircraft Static Pressure Systems' by F.L.Jordan and V.S.Ritchie, May 1973.

3. PURPOSE

3.1 This Advisory Circular (AC) provides guidance on methods, not necessarily the only methods, of satisfying the requirements of Civil Aviation Safety Regulations (CASR) 1998 Part 21 subparts B, F and G and of CASR 1998 Parts 23, 26 and 27 for the development, calibration, control and operation of instruments and flight test systems used to measure the airspeed of an aircraft.

3.2 This AC provides information to assist;

- (a) people responsible for the design, construction, calibration and operation of airspeed measurement systems used during flight testing of aircraft certificated or manufactured under CASR 1998 Part 21; and
- (b) applicants for Type Certificates or Supplemental Type Certificates under CASR 1998 Part 21.

3.3 Terms and abbreviations used in this AC are defined at Annex A.

4. STATUS OF THIS ADVISORY CIRCULAR

This is the first issue of Advisory Circular 21-40 and will remain current until it is cancelled, suspended, amended or superseded.

5. INTRODUCTION

5.1 Accurate, consistent and reliable measurement of airspeed, and its effective presentation on an airspeed indicator (ASI), is essential for the safe and efficient operation of an aircraft. Reliable airspeed information is required by the pilot to prevent inadvertent stall and loss of control at the low-speed edge of the aircraft's operating envelope or overspeed and possible structural damage at the high-speed edge. The calibration of airspeed measurement and indicating systems is an important step in the overall aircraft design, flight test and certification processes.

5.2 Modern airspeed systems and instruments, including ASIs and Machmeters, continue to derive and display airspeed as a function of total and static air pressures.¹ The principles involved, and the errors inherent, in this form of airspeed measurement are available in the literature. The aim of this Advisory Circular is not to present a complete treatise on these subjects but to provide reference to important information that can be found in other documents. This AC is focussed toward flight testing of aircraft at the lighter-weight and lower-speed ends of the scale, principally those in the primary, normal, utility or acrobatic categories, and the information provided is intended as guidance for designers or builders of these machines.

5.3 This AC refers to those sections of the airworthiness standards that define airspeed measurement and calibration requirements. It then provides some detail on methods of calibration of airspeed measurement systems and advice on how to apply those methods. The literature on the subject is extensive and the references should be consulted if the reader needs a more complete understanding. FAA AC 23-8B or the JAR-23 FTG² provide regulatory information. The best references for theoretical and technical advice are probably NASA Reference Publication 1046, 'Measurement of Aircraft Speed and Altitude' by W.Gracey and NACA Report Number 919, 'Accuracy of Airspeed Measurements and Flight Calibration Procedures' by W.B.Huston.

6. AIRWORTHINESS STANDARDS

6.1 The airworthiness standards that apply to primary, normal, utility and acrobatic category aircraft are defined in CASRs 23, 26 and 27. The standards called up in these regulations are FAR 23, JAR 23 and JAR-VLA for aeroplanes and FAR 27 for rotorcraft. In the case of primary category aircraft, CASR 21.017(6) also allows the use of such other airworthiness criteria that CASA considers appropriate to the specific design. There are two airspeed calibration requirements called for in these regulations:

- (a) calibration of the airspeed indication system that will be fitted as standard equipment to the production model of the aircraft³; and
- (b) calibration of the system or systems that will be used during certification flight testing.

6.2 Airspeed Indicating Systems

6.2.1 Section 1323 of the appropriate airworthiness standard details the requirements for a production airspeed indicating system. Section 23.1323 of either FAA AC 23-8B or the JAR-23 FTG expands on, and describes ways of meeting, these requirements. These ACs contain an explanation of the basic methods that can be used to calibrate a production airspeed system and a detailed illustration of each method is at the Appendix 9 of either document. (See also paragraphs 7.5.2 to 7.5.9 below.)

¹ The basic concepts derive from Bernoulli's principle ($Total\ Pressure = Static\ Pressure + Dynamic\ Pressure$) and can be found explained in several of the references. Normally, and in this AC, the terms *Total Pressure* and *Pitot Pressure* can be taken as interchangeable.

² Both the JAR-23 FTG and AC 23-8B provide the same, or very similar, information.

³ Colloquially known as the 'ship's' system.

6.3 Measurement of Stalling Speeds

6.3.1 Section 49 of each of the appropriate aeroplane airworthiness standards details the stalling speed requirements and Sections 23.49 of FAA AC 23-8B or the JAR-23 FTG expands on these requirements. For stalling speed measurement, these documents advise that the ‘production airspeed system is normally not sufficiently predictable or repeatable at high angles of attack to accurately measure the performance stall speed of an airplane’. This implies that an additional airspeed measuring system, one that is more suited to low speed and/or dynamic conditions, needs to be used during certification stall speed flight testing. Such a system will often feature a boom-mounted swivelling pitot head and a static source that is also outside the aircraft’s field of influence. Isolating the flight test static source from the aircraft is normally achieved by making the boom-mounted device a combined pitot / static head or by towing an independent static transducer behind the aircraft as part of a ‘trailing bomb’ or ‘trailing cone’ assembly. An alternative to mounting the pitot head on a boom is to incorporate it into the trailing bomb. Other methods may also be suitable.

6.4 Measurement at High Speed

6.4.1 Accurate calibration of the airspeed measurement systems for use during testing, and subsequent operations, at high airspeeds is required. Sections 251 (Vibration and Buffeting), 253 (High Speed Characteristics) and 629 (Flutter) of the airworthiness standards may be applicable and demand testing be carried out to V_D . Also, Section 335 requires design airspeeds to be developed in terms of equivalent airspeed (EAS). Compressibility effects may need to be taken into account.

6.5 Flight Test Instrumentation

6.5.1 CASR 21.039 requires that applicants for type certificates in the normal, utility and acrobatic categories submit a report to CASA. This report should detail calibration of instruments used for flight test purposes. CASR 21.024(b)(i) also requires such a report for primary category aircraft. More information on instrumentation calibration is published in CASA Advisory Circular 21-35(0) – Calibration – Inspection and Test Equipment.

7. CALIBRATION

7.1 There are essentially three airspeed system calibration requirements called for in the airworthiness standards or advocated by the advisory material:

- (a) The airspeed indicating instruments must be calibrated to indicate true airspeed at sea level in a standard atmosphere. (e.g. FAR/JAR 23.1323(a))
- (b) The airspeed system must be calibrated in flight to determine the system error. (e.g. FAR/JAR 23.1323(b), JAR-VLA 1323(a) & (b))
- (c) The performance stall speed test system utilised in a type certification program should be calibrated to a minimum speed at least as low as the predicted minimum stall speed on the test aeroplane. (e.g. FAA AC 23-8B / JAR-23 FTG Chapter 2, Section 23.49)

7.2 AC 21-35(0) provides information and advice on general calibration principles. A variety of methods, equipment and procedures are available for use in the calibration of airspeed instruments and systems. Sections 23.49.b, 23.1323 and Appendix 9 of either AC 23-8B or the JAR-23 FTG describe such methods suitable for use in the certification of small aircraft. These methods are outlined in the following paragraphs. Several are discussed in more detail in the annexes to this AC. Calibration of instrumentation should be carried out by suitably qualified persons using standardised test equipment in National Association of Testing Authorities (NATA) accredited laboratories.

7.3 Airspeed System Errors

7.3.1 There are various sources of error in an airspeed indicating system that is based on the measurement of pitot and static air pressures:

- (a) **Instrument Error.** Instrument errors result from imprecisions that are inherent in the instrument. For mechanical instruments these errors are the result of manufacturing tolerances, hysteresis, temperature changes, friction, and the inertia of moving parts. For electronic instruments they are due to errors in the electronic element that converts pitot-static pressures into electronic signals.
- (b) **Position Errors.** Position errors are those that arise when the pitot and static pressures sensed by the pitot and static transducers on the aircraft are different to the true values of those pressures in the undisturbed freestream. These differences are caused by the pressure field and flow angularities around the aircraft. They are a function of aircraft configuration, angle of attack and Mach number, and are determined from flight test. They are called 'position errors' because the sign and magnitude of the errors are dependent on the mounting position of the pitot probe and the static source on the aircraft.
 - (i) **Pitot Error.** Pitot error is the total-pressure error resulting from design aspects of the pitot head, such as its size, shape, orientation and location. By proper manipulation of these design characteristics (see Annex B to this AC) this total-pressure error may be reduced to the point where it is insignificant for most flight conditions.
 - (ii) **Static-Pressure Error.** Static pressure is more difficult to measure accurately than is pitot pressure. The local value of static pressure can vary greatly depending on the position along the fuselage, or laterally across the planform, at which it is measured. The static pressure field varies easily with changes in aircraft configuration, angle of attack and airspeed. Static pressure measurement may also be sensitive to sideslip and require the installation of balanced static ports, one on each side of the fuselage. Because of these sensitivities, and since total-pressure (pitot) error is often of negligible proportion when compared to static-pressure error, some publications designate 'position error' to be static-pressure error alone.

- (c) **System Error.** System error is the combination of instrument error and position error. Other errors, such as those resulting from the installation of the equipment into the aircraft, may also have to be included. Pressure-system lag, resulting from any time delay in transmitting the measured pressures from their transducers to the display instrument, is one such error.

7.4 Airspeed Indicator Calibration

7.4.1 ASIs should be tested against a calibrated transfer standard by suitably qualified and experienced personnel. Civil Aviation Order (CAO) Part 108.56 describes the accuracy standard applicable to production ASIs. For ASIs that are to be used during certification flight testing there are more stringent requirements (see paragraph 7.6.4 below).

7.5 Calibration of the Production Airspeed Indicating System

7.5.1 The system error for the airspeed indicating system installed in the production aircraft (the ‘ship’s’ system) must be determined. Therefore, in addition to measuring the instrument errors and calibrating the individual ASIs, the position error associated with the aircraft, in its various configurations and measured across its operational speed range, must also be known.

7.5.2 A variety of flight test methods are available for use in determining position error. Information relating to these methods is contained in the references (Sections 23.49.b, 23.1323 and Appendix 9 of either FAA AC 23-8B or the JAR-23 FTG). Each method has its own advantages and disadvantages. Any of them should yield satisfactory results if conducted with appropriate flight test rigour and if any specified test equipment has been designed, constructed, installed and operated correctly. The method chosen should be suited to the general flight handling qualities and the speed regime of the aircraft under test. In all cases accurate results will probably best be achieved if test flying is conducted under very smooth, non-turbulent atmospheric conditions. Comments on the basic test methods are provided in the following paragraphs.

7.5.3 Speed Course Method. The Speed Course Method⁴ involves comparing the airspeed measured in the aircraft with the groundspeed of the aircraft as it is timed flying over a precisely known distance or along a designated ground course. The method, including test procedures and data reduction routines, is described in Appendix 9 of FAA AC 23-8B and discussed in some of the other references (e.g. NASA Reference 1046). This method is suitable for use in light low speed fixed-wing aircraft and helicopters. It will provide best results for a speed range beginning at a point safely above the relevant stall speed and extending out to approximately 150 knots. It is relatively simple to set up and conduct because it does not require the installation of expensive or complicated test equipment. The availability of a surveyed test course (e.g. a long runway)⁵ and a calibrated stopwatch are the only requirements. The accuracy of results, however, could be degraded at very low speeds, close to the stall, when it may be difficult for the pilot to hold a constant airspeed throughout the longer time taken to complete the course, or at high speed when a small error in stopwatch timing can translate into a significant groundspeed error. Wind effects may influence results and the flight testing is best conducted in the calm conditions of an early morning. Also, for optimum results the flight tests need to be flown close to the ground. This will lead to elevated levels of risk, especially at speeds near the stall, and should be carefully considered during the test planning process.

⁴ Also known as the ‘Ground Course Method’.

⁵ Long straight roads, with checkpoint distances measured accurately using GPS, may also be suitable.

7.5.4 GPS Methods. Global Positioning System (GPS) Methods operate on similar principles to the Speed Course Method in that the airspeed measured in the aircraft is compared to its groundspeed. The difference is that groundspeed is derived using GPS measuring equipment. There are various test procedures and data reduction programs available. Some are described in the references while others can be readily found by conducting an Internet search using terms such as ‘GPS airspeed method’ or similar. A GPS Method can produce accurate results over the entire speed range of the aircraft and is relatively simple and cost effective to carry out. It does not necessarily require operations close to the ground and therefore involves less risk than the Speed Course Method. The accuracy of results is sensitive to wind variations and is dependent on the pilot being able to hold not just a constant airspeed but also a very steady heading during test points.

7.5.5 Trailing Bomb. The Trailing Bomb Method involves comparing the airspeed measured in the aircraft with that derived from a pitot and/or static source that is outside the aircraft’s field of influence in that it is being towed below and behind the aircraft as part of a ‘trailing bomb’. (If the bomb only incorporates a static source then an accurate and independent source of pitot pressure is required.) The method, including test procedures and data reduction routines, is described in Appendix 9 of FAA AC 23-8B and discussed in some of the other references (e.g. NASA Reference 1046). The trailing bomb method can provide good results, especially at low speeds, but carries complications associated with system set up⁶ and with flight test risk mitigation. This method is suitable for use within an airspeed range between zero and approximately 200 knots. Trailing bombs can be used on fixed-wing aircraft but are best suited to use in helicopters where it is easier to deploy and recover the device. Care must be taken to reduce the risk of the bomb or its associated cable and pressure tubing becoming entangled with the tailplane, tail rotor or other parts of aircraft structure. This will more likely occur during deployment / recovery or at higher speeds when the bomb may become unstable or tend to fly further to the ‘trailing’ position behind the aircraft. The use of another aircraft in the safety chase role is strongly recommended.⁷ In the higher speed cases there is also a chance that the accuracy of the pressure measurements taken at the bomb will be compromised by the wake of the aircraft itself. Brief details of a generic bomb are presented at Annex C to this AC.

7.5.6 Trailing Cone. The Trailing Cone Method uses a similar philosophy to the Trailing Bomb Method in that accurate static pressure is measured at a point in the free stream clear of the aircraft’s direct field of influence. In this case the static source, stabilised in the airflow by a conic drogue, is towed at a distance sufficiently behind the aircraft so that all local pressure-field effects due to the flow around the aircraft will have decayed effectively to zero. As only static pressure is measured at the trailing cone an accurate and independent source of pitot pressure is required. This method is also described at Appendix 9 of FAA AC 23-8B. Further information has been gleaned from the literature and is presented at Annex D to this AC. The trailing cone method is best suited to use at airspeeds above approximately 70 knots although, with care, it can be adapted to use at lower speeds (see Annex D to this AC). The method is also subject to some of the flight test complications associated with a trailing bomb but the apparatus may be somewhat simpler to design, build and deploy.⁸

⁶ The Trailing Bomb, the Trailing Cone and the Pitot-Static Boom may be subject to errors induced by leaks, blockages or improper dynamic lag balancing. Dynamic lag balancing errors as discussed at Annex E.

⁷ Incorporation of an emergency jettison capability into the design of either a Trailing Bomb or a Trailing Cone apparatus is worthy of consideration.

⁸ See footnote 6.

7.5.7 Pitot-Static Boom. The Pitot-Static Boom Method involves comparing the airspeed measured in the aircraft with that derived from pitot and static sources that are outside the aircraft's field of influence through being located on a flight test boom. The boom is mounted on the aircraft so that the pitot-static head is well clear of any slipstream, boundary layer or shock wave effects. For best results the head will incorporate a swivelling, 'weather-vane' mechanism to allow alignment with the incoming airflow, thereby negating any effect of angle of attack or sideslip. Additional information is provided at Annex B to this AC. Commercial products, incorporating varying degrees of sophistication, are available. A search over the Internet using a term such as 'air data boom' will reveal sources. Test procedures and data reduction routines are at Appendix 9 of either FAA AC 23-8B or the JAR-23 FTG. If a well-made, properly mounted boom is used this method is capable of providing accurate results over the entire speed range of the aircraft and is probably the best for use in dynamic situations. It is very well suited to all phases of flight testing for aircraft at the lighter and lower-speed ends of the scale.⁹

7.5.8 Pacer Aircraft. The Pace Airplane Method involves flying the test aircraft in formation with another aircraft the airspeed measurement system of which has been previously calibrated to a high degree of accuracy using an independent test method. The airspeed indications of the two aircraft are then compared at different speeds and configurations. Comments on test procedures and data reduction methods are provided in Appendix 9 of the flight test guides. Depending on the availability of an accurately calibrated datum aircraft and of suitably qualified, experienced and skilful flight crew, this method can provide acceptable results over the entire speed range of the test aircraft. However, it could be considered expensive to conduct and there are various potential sources of, or amplifications for, error particularly if the datum aircraft is of a different type to the test aircraft.

7.5.9 Tower Fly-By. The Tower Fly-By Method determines static pressure error by flying the test aircraft past a datum point that is at a known height. The reading of a sensitive aneroid pressure gauge connected to the aircraft's static source is then compared to the reading of a similar gauge at the datum point. This method is described in the references. While it can produce accurate results, it is a time-consuming, expensive method that requires the use of special equipment and a surveyed test area if it is to be successful. For these reasons it is not ideally suited to light aircraft projects. It also involves the elevated levels of risk associated with operations close to the ground.

7.6 Calibration of the Flight Test Airspeed Measurement System

7.6.1 Any flight test airspeed measurement system, used in addition to the onboard production or 'ship's' system, should also be independently calibrated so that its system error is known. This is particularly applicable to a system that will be used during certification performance stall speed measurement since unstable or dynamic effects of the airflow around the aircraft as the stall is approached may lead to fluctuations in the measured pressures used to define the airspeed. For this reason airspeed measurement systems that have their pitot and static pressure transducers mounted, and flying stably, outside the aircraft's field of influence are recommended for certification flight testing. Section 23.49.b of FAA AC 23-8B advises that systems based on pitot-static booms, trailing bombs or trailing cones may be suitable for use during stalling speed measurement.

⁹ See footnote 6.

7.6.2 An airspeed measuring system installed for stall speed certification flight testing and more accurate than the production airspeed system, in that it takes its pitot and static measurements from the free-stream beyond the aircraft's field of influence, may also then be suitable for the calibration of the production system. This would often be the case for small aircraft whose speed range is not that great. However, caution is required with aircraft that can achieve maximum speeds significantly higher than their stall speeds in that some calibration methods (e.g. the trailing bomb method) may not be ideally suited to use at the higher speeds. Conversely, other methods (e.g. the trailing cone) may not fly well at very low speeds.

7.6.3 Calibration of a flight test airspeed measurement system involves the same principles as used in calibration of the production system – the system error needs to be determined. The flight test system error is essentially a combination of the instrument error inherent in the flight test ASI, the position errors associated with the flight test pitot and static transducers (normally, for stall speed measurement at least, different to those of the production system) and any other errors associated with the set-up of the system itself.

7.6.4 Flight Test System ASI. For ASIs that are to be used during certification flight testing the instrument calibration requirements outlined at Sections 23.21.b(2) of either FAA AC 23-8B or the JAR-23 FTG should be followed. The references advocate an accurate calibration testing of the instrument within 60 days of the flight tests and also stress that these calibrations should be accomplished at an approved facility.

7.6.5 Flight Test System Position Errors. If the pitot and static sources for the flight test airspeed measurement system are located well clear of the aircraft's field of influence then the only position errors that need to be taken into account are those associated with the pitot and/or static apparatus itself. These local position errors can generally be reduced to minimal levels if proven engineering practices are used (see Annexes B to D to this AC). This will be especially so if the transducer head, or source, flies parallel and steady with respect to the incoming airflow no matter what the speed, configuration, attitude or manoeuvre state of the test aircraft. For precision equipment (eg. air data booms, trailing bombs) acquired commercially the manufacturer should supply local position error information, calibration curves and possibly an ongoing calibration service. For independently produced equipment precise position error information may be obtained through testing in an accredited wind-tunnel facility. Appendix 9 of FAA AC 23-8B advises that, for a flight test pitot-static boom, if it 'is mounted on an airplane such that the pitot tube (total head) is not affected by flow angularity and the static source is outside the pressure field of the aircraft, then it can be assumed that the boom data is without position errors'.

7.6.6 Other Error Sources within the Flight Test System. Like the 'ship's' system the flight test airspeed measurement system must remain free from blockages, leaks and water ingestion. Due to the long lengths of pressure tubing that might be included in the flight test system assembly, it will probably also be subject to errors resulting from pressure equalisation lags that could occur whenever the test aircraft changes either speed and/or altitude. Dynamic lag balancing is discussed in Section 23.49.b of FAA AC 23-8B. See also Annex E to this AC. Other errors resulting from installation of the equipment and, if applicable, its integration with aircraft systems should be evaluated.

7.6.7 Flight Test System Error. While the instrument and position errors associated with a well made and competently installed flight test airspeed measurement system, incorporating the features described above, will probably be small the overall system error should, nevertheless, be known. At the very least, the system should be subject to a validation check to confirm that it is producing credible readings across its speed range. Acceptable means of conducting such a check or measuring overall system error are as follows:

- (a) Validation checking of the flight test airspeed measurement system can be achieved by comparing the system output against an equally accurate but independent system (i.e. not the 'ship's' system), or by conducting an independent calibration exercise applying any of the methods outlined above for use when calibrating the aircraft's production airspeed indicating system.
- (b) If the output of the flight test airspeed system subject to the check, over the speed range for which it is to be used during subsequent certification flight testing, is within 2 knots or 2% (whichever is greater)¹⁰ of that derived from the independent system or calibration method then the flight test airspeed system can be assumed sufficiently accurate for use during certification flight testing.
- (c) If the results of the validation checking are outside the 2 knot / 2% band then either:
 - (i) the cause of the discrepancy should be investigated, then corrected, and the checks re-flown until the two systems agree; or
 - (ii) the system or calibration method that produces the more conservative results should be taken to be the more accurate. If this is not the flight test airspeed system the difference between the two systems should be applied as a calibration error to any subsequent use of that system for certification flight testing.¹¹

8. SUMMARY

8.1 Modern aircraft continue to use systems that derive and display airspeed as a function of total and static air pressures. The principles involved, and the errors inherent, in this form of airspeed measurement have been known for some time.

¹⁰ Based on average accuracies of the various calibration methods given in NASA Reference 1046.

¹¹ In this context 'conservative' means that, for example, if the flight test system was to be used for the measurement of minimum certification speeds (stalling speeds, minimum control speeds) then it should be assumed to be under-reading by the discrepant amount.

8.2 This AC provides a summary of authoritative information as applicable to the airspeed measurement and airspeed indicating system calibration requirements during the certification flight testing of aircraft in the primary, normal, utility or acrobatic categories. It points out those sections of the appropriate airworthiness standards that define airspeed measurement and calibration requirements. It then provides some detail on methods of calibration of airspeed measurement systems and advice as to the applicability of those methods.

8.3 Not all relevant information is necessarily presented and the recommendation is that the References and other authoritative publications should also be consulted for a fuller understanding of the topic.

Richard Macfarlane
Acting Executive Manager
Aviation Safety Standards

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ANNEX A
TERMS AND ABBREVIATIONS

Symbol/Term	Definition
AC	Advisory Circular
ASI	Airspeed Indicator
CAS	Calibrated Airspeed
CAO	Civil Aviation Order
CASA	Civil Aviation Safety Authority
CASR	Civil Aviation Safety Regulations
EAS	Equivalent Airspeed
FAA	Federal Aviation Administration (of the USA)
FAR	Federal Aviation Regulations (of the USA)
ft	Feet
FTG	Flight Test Guide
GPS	Global Positioning System
IAS	Indicated Airspeed
IVSI	Instantaneous Vertical Speed Indicator
JAA	Joint Aviation Authority
JAR	Joint Aviation Regulation
kts	Knots
lb	Pound
M	Mach
MAC	Mean Aerodynamic Chord
mm	Millimetres
M_{MO}	Maximum Operating Limit Mach No.
MTOW	Maximum Takeoff Weight
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NATA	National Association of Testing Authorities
PVC	Polyvinyl Chloride
TN	Technical Note
TP	Test Pilot
TSO	Technical Standard Order
V_D	Design Diving Speed
VLA	Very Light Aircraft
V_{MO}	Maximum Operating Limit Speed
VSI	Vertical Speed Indicator

ANNEX B PITOT SOURCES AND PITOT-STATIC HEADS

Pitot (Total Head) Sources and Pitot-Static Heads

- 1 Measurement of total pressure is normally accomplished by means of a forward facing tube (pitot tube) that senses impact pressure from the impinging airstream. Detailed descriptions of various pitot tube designs, and discussion regarding their relative effectiveness, is available at NASA Reference Publication 1046, 'Measurement of Aircraft Speed and Altitude' by W. Gracey. Pitot tubes are normally more effective when aligned with the incoming airflow and Gracey discusses parameters for consideration when designing both this type of tube and for the case when the pitot tube will be inclined to the airflow (ie when it will be fixed to the airframe and subject to changed flow conditions when the aircraft changes angle of attack or sideslip). Often the pitot tube will also incorporate ports to enable simultaneous measurement of static pressure at the same location and such combination devices are known as pitot-static heads. FAA Technical Standard Order (TSO) C-16 - Airspeed Tubes (Electrically Heated) – gives criterion for the manufacture of pitot tubes for use on production aircraft.

General Criteria – Flight Test Pitot Heads

- 2 For a flight test pitot (or pitot/static) head to be the subject of minimum error it should meet the criteria provided below (cf NASA Reference 1046):
 - (a) The pitot head should be located at least one propeller diameter clear of any slipstream and outside any boundary layer. Also, if there is any possibility of wakes trailing from, or shock waves forming on, any part of the aircraft then impinging on the pitot head, flight demonstration is required to show that it will remain clear of those wakes or shock waves. This is defined as an error in dynamic pressure of less than 0.005 times that measured by a swivelling-vane type pitot head located in the free stream ahead of the aircraft. (The condition is normally satisfied simply by locating the pitot head at least one wing chord length ahead of the wing leading edge. For a boom system mounted on the nose of the aircraft the pitot-static source should be at least 1.5 fuselage diameters ahead of the nose.)
 - (b) The pitot head should be mounted on a swivelling 'weather-vane' arrangement such that it is free to align its axis with the local airflow. The distance from the pitot orifice to any vanes used to align the axis of the tube to the airflow must be such that the combination of aircraft attitude and local flow curvature effects at any angle of attack or yaw angle that is possible within the normal operating range of the aircraft will not result in a crossflow angle at the pitot orifice exceeding 5 degrees.¹²

¹² See NACA Report No 919, Figure 2.

- (c) The pitot head should be located such that the sum of $2y/b$ and x/c exceeds 1.5, where y is the distance of the pitot from the aircraft planform plane of symmetry, b is the wingspan, x is the distance by which the pitot orifice is ahead of the leading edge of the foremost lifting surface, and c is the local chord of that surface directly downstream of the pitot head.
- (d) The ratio of the orifice bore (at the point of entry to the tube) to the outer diameter of the body of the pitot tube itself should not be less than 0.5.¹³ Alternatively, a recognised form of shrouded pitot head should be used.¹⁴
- (e) The pitot orifice should be free from burrs and approximately normal to the axis of the pitot head.
- (f) The bore of the pitot tube should not be less than 3 mm for use in air free from visible moisture.
- (g) The pitot head and boom, when installed on the aircraft, should ‘fly’ steadily and be free from oscillation.
- (h) The pitot system should be completely free from blockages or leakage.

3 A pitot source that meets the above criteria should be accurate to within 0.5% of the total pressure for Mach numbers not exceeding M0.6, noting that to maintain this level of accuracy a correction for compressibility is required for Mach numbers exceeding M=0.1. This correction can be obtained through application of the following:

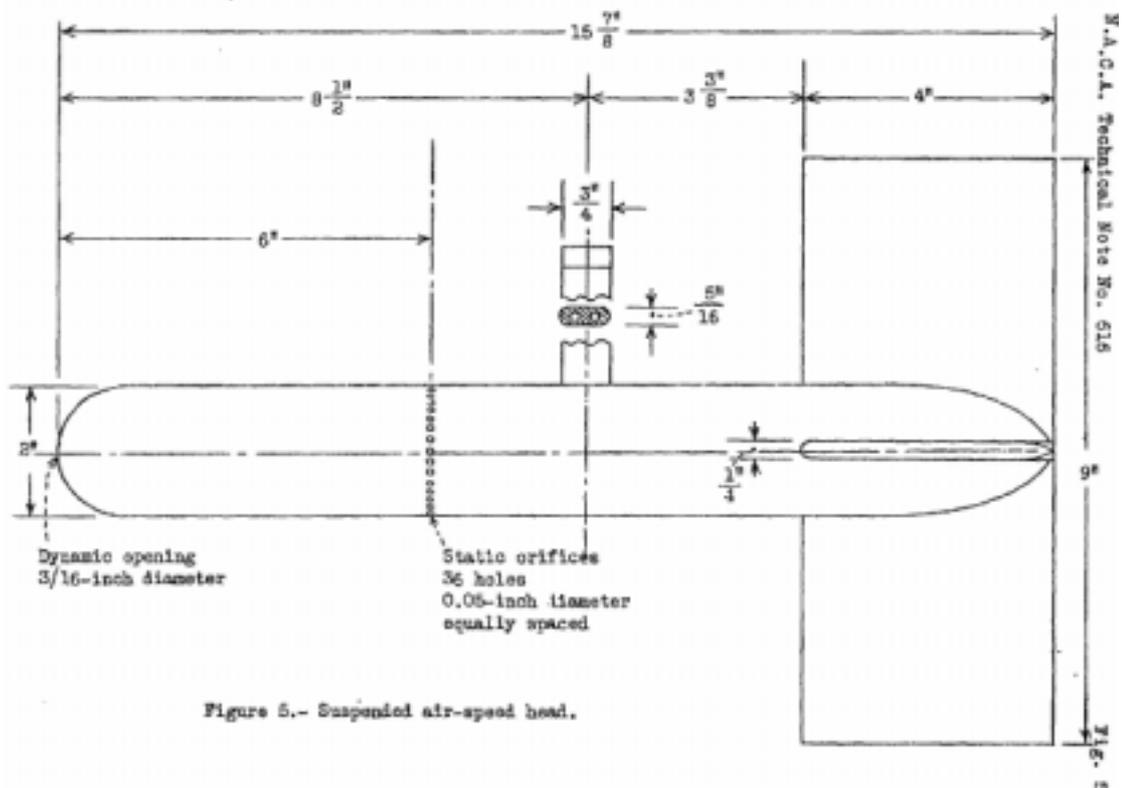
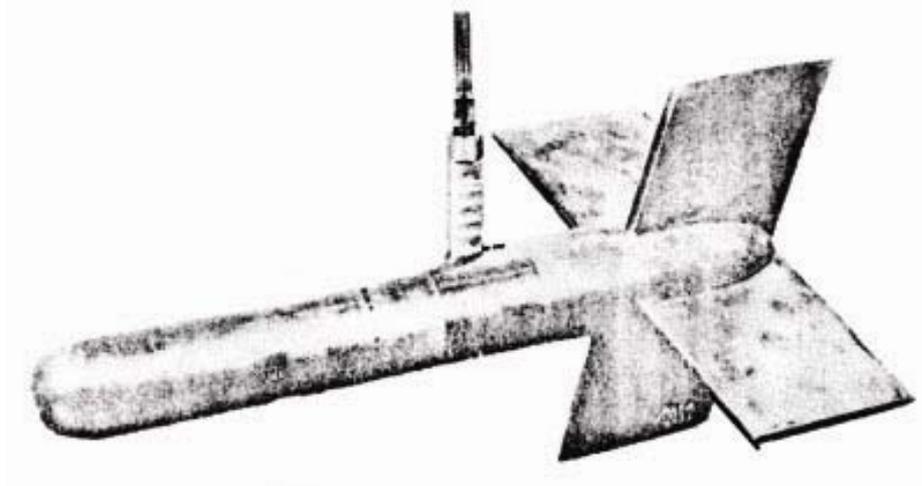
$$CAS = IAS \frac{1}{\sqrt{1 + 0.25M^2}}$$

¹³ *ibid.*

¹⁴ See NASA Reference Publication No 1046. In a shrouded form of pitot head the ‘outer diameter of the body of the pitot tube’ is the outer diameter of the inner ‘sting’ that contains the pitot orifice.

ANNEX C TRAILING-BOMB PITOT-STATIC SOURCE

- 1 The following diagrams, taken from NACA TN 616, illustrate the configuration and layout dimensions for typical 'trailing bombs'.

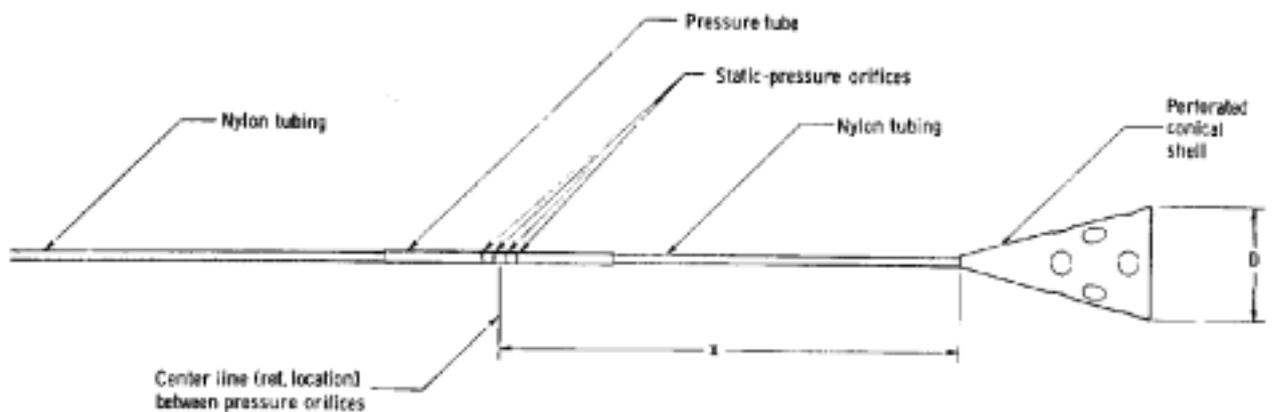


- 2 Although now slightly dated NACA TN 616 also provides sound advice regarding set up and suspension parameters for a trailing bomb and information on likely sources of error.

ANNEX D TRAILING-CONE STATIC SOURCE

Trailing Cone

- 1 A trailing-cone static source comprises a length of tube, with a set of static pressure holes in it, which is towed along behind the aircraft. The tube should be long enough such that the static pressure holes will be located at a point sufficiently distant from the aircraft where all local pressure-field effects due to the flow around the aircraft will have decayed effectively to zero. The tube is plugged immediately behind the static pressure holes but continues as a mechanical connection to a conical drogue the function of which is to cause the tube to trail substantially horizontal, in the vicinity of the static holes, during level flight.
- 2 Because a pure-drag device such as a conical drogue cannot develop any lift the tangent of the angle of the force vector at the attachment of the cone will be, in effect, the ratio of weight to drag of the cone. Thus, at any point along the tube, the angle at which the tube is trailing will be the combined ratio of weight to drag of everything aft of that point. Consequently, the system can only ever approach the horizontal, the angle will never be exactly zero. Nonetheless, the higher the ratio of drag to weight the smaller will be the departure from true alignment with the airflow.
- 3 The literature contains detailed information on trailing-cone systems. One such set up is shown below:



Form of trailing-cone static investigated by NASA TN D-7217

General Criteria

- 4 If a trailing-cone static source, for use at Mach numbers not exceeding approximately $M=0.5$, is to be subject to minimum error it should meet the following criteria:
- (a) The static ports should consist of at least four staggered rows, each comprising four holes evenly distributed around the circumference of a piece of circular cross-section tube of essentially constant diameter along its length. The holes should be spaced along the tube such that the four rows are within a total length not exceeding three times the tube diameter.
 - (b) The length of tube containing the static holes should be essentially straight and have uniform circular cross-section for at least 250 mm either side of the holes.
 - (c) The static holes should be free from burrs or local distortion of the tube shape.
 - (d) The static holes should be at least one wingspan, and not more than 1.5 times the wingspan, to the rear of the aft-most part of the aircraft when the tube is laid out along a line parallel to the projected axis of the fuselage.
 - (e) The preferred position for attachment of the trailing static system to the aircraft is that which will minimise the impingement of the wake onto the static source. An attachment point at the top of the fin is often chosen for use with an aeroplane of conventional configuration. Regardless of what attachment position is used the overriding consideration would be to ensure that the trailing tube remains clear of any possibility of fouling flight controls.
 - (f) The conical drogue, the 'cone' itself, should be located downstream of the static holes by a distance not less than four times, nor greater than 4.25 times, the maximum diameter of the drogue (X and D respectively in the above diagram).
 - (g) The major portion of the conical drogue should have an included angle not more than 60 degrees and not less than 30 degrees. A cone with the higher included angle is preferable for use at lower flight speeds, and vice versa.
 - (h) The cone should be symmetric and perforated sufficiently to eliminate, or at least minimise, any tendency to 'fly' or to oscillate within the intended speed range.
 - (i) At the test airspeeds the system should trail such that the inclination of the tube to the airflow at the location of the static holes does not exceed 4 degrees. (This requirement may render the trailing-cone system unsuited to use at low speeds. Caution should be exercised if such a system is intended for use at speeds below approximately 60 knots and demonstration that the cone is indeed trailing horizontal in straight and level flight may be required if the accuracy of results below that speed is to be accepted.)
 - (j) The static system should be free from leakage.

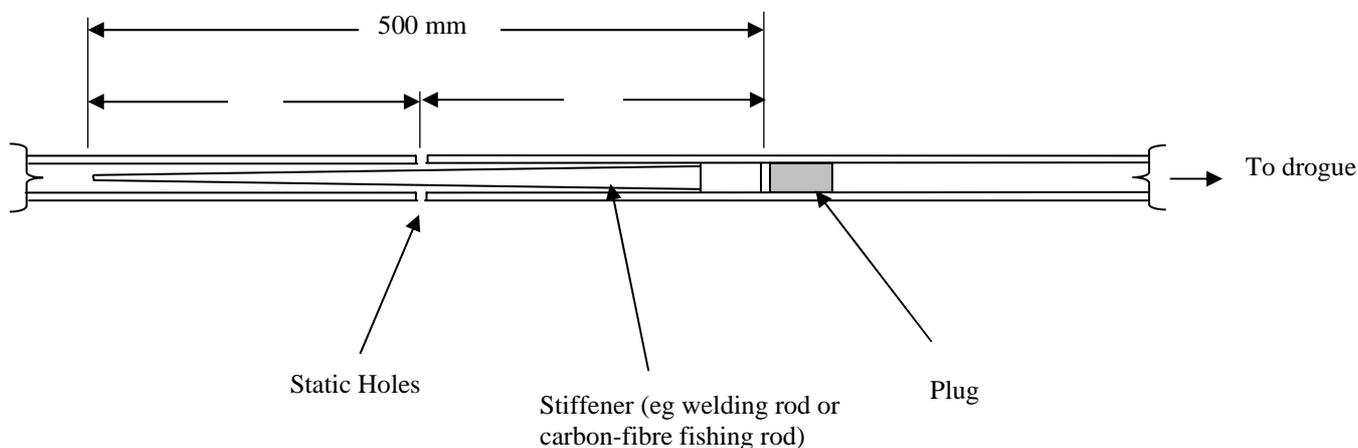
- 5 A static source that meets the foregoing criteria should be accurate to within 0.5% at speeds between that demonstrated at subpara 0 above and 0.5 Mach.

Developing the Trailing Cone for Low Speed Applications

- 6 The construction details of the trailing-cone described in NASA TN D-7217 appear to make it optimised for use at Mach numbers between approximately $M=0.5$ and $M=0.9$. A number of modifications could be made to the design to make it more suited to work at slower airspeeds.
- 7 **Weight Reduction.** For a trailing-cone system, based on the overall NASA TN D-7217 design, to be consistent with a lower speed regime greater emphasis should be placed on minimum mass and increased drag. Some of the mass-increasing features of the design described in the NASA TN (e.g. the steel cable inside the tube to carry tension loads, the swivel bearing provision for the conical drogue, the tube protection skid and / or the stainless-steel sleeve embodying the static holes) could be omitted with advantage. Alternatively, these features of the design could be fashioned from materials of lighter weight.
- 8 **Tubing.** The NASA design used ¼ inch nylon pressure tube. This would seem an excellent material for the purpose provided it could be stored in a coil of sufficiently large diameter such that no residual ‘curl’ would remain when trailed under low speed flight loads. Alternatively, clear PVC flexible tube of approximately 6mm bore should have adequate strength for slow speed applications, and swivel provision should not be necessary. Flexible (‘soft’) tube has the advantage that flight loads could minimise the catenary curve shape provided the size of the cone is chosen correctly for the speed range as well as for the tube stiffness and strength. It could also be possible, by the use of such tube, to reduce the number of connections in the system thus eliminating potential sources of leakage. A short length of spiral spring may be needed inside the tube at the point where it is anchored to the airframe in order to prevent the tube from being crushed. The designer should also be aware however that the use of flexible tubing that is too soft may lead to dynamic lag balancing problems in that the tubing will probably be subject to some stretching under airloads thereby changing the volume on the static side of the test airspeed measurement system. (cf Annex E)
- 9 **Static Holes.** The static pressure orifices can be formed by pushing a piece of hot wire (1 mm diameter) through the wall of the flexible tube. This should produce a clean hole of approximately 1.5 mm diameter and four staggered rows each containing four equally spaced holes would be required. The holes should be de-burred at the external surface and any residual material removed from inside the tube.

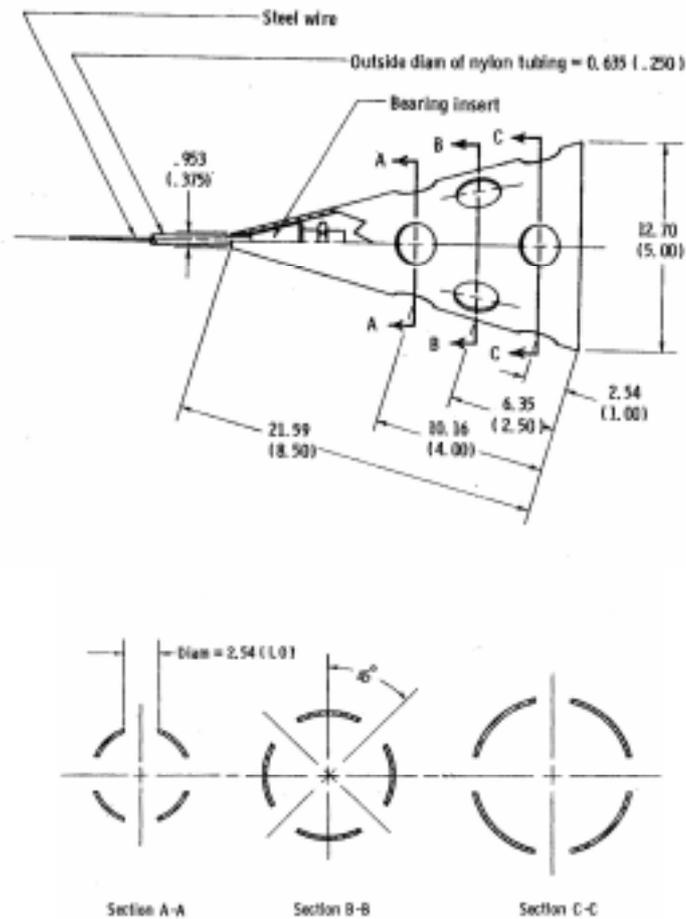
- 10 **Pressure Tube Curvature.** There is a requirement to ensure that the 500mm or so of the tube that contains the static holes remains straight. In the NASA TN system this was achieved by inserting a length of metal tube (the ‘pressure tube’ at the diagram in Annex C of that publication) of slightly larger diameter than the nylon tube. However this gives rise to the possibility of leakage at any connections. The integrity of the tubing at such connections can also be compromised due to the effects of wear during take-off and landing if the tube protection skid has not been incorporated. The use of heavy metal tubing may also be inconsistent with the aim of reducing the weight of the system. Alternate solutions could be as follows:

- (a) Lightweight metal or plastic tubing could be used in a ‘sleeve’ arrangement. This would eliminate the possibility of leakages but not necessarily the requirement for minimum weight. Also the sleeve would need to be of sufficiently tight fit around the flexible tubing to ensure it did not move during take-off, landing or operation and that the static port holes remained aligned.



- (b) Another option, provided the drogue produces an appropriate tension for speeds below 150 knots, may be to omit any metallic ‘pressure tube’ element altogether. Instead, the flexible tube could be stabilised and straightened by introducing an internal stiffener within the portion of the tube containing the pressure holes. (Approximately 500 mm from an appropriately sized welding rod or the tapered tip segment of a bare carbon-fibre fishing rod could be suitable.) The stiffener should be inserted such that the static holes are located midway along its length. A ferrule at the end of the stiffener may be used as a plug to seal the rear end of the pressure tube. (If fishing rod is used an additional dedicated plug will probably be required.) Care should be taken to ensure the annular clearance between the bore of the tube and the stiffener, at the location of the static holes, is adequate when the tube is under tension from the drogue. This set-up also avoids any leakage inducing joints or discontinuities and may, depending on the material being used as the stiffener, also offer weight advantages.

- 11 **Trailing Cone.** The funnel that serves as the conical drogue should be attached securely to the tube and may benefit from incorporation of a swivel bearing mechanism to minimise twisting. A suitable pattern for the cone is shown in the following diagrams (reproduced from NASA TN D-7217). For low speed applications the included angle would need to be increased, over that shown, by adjusting the diameter and height of the cone in suitable proportion.



ANNEX E DYNAMIC LAG BALANCING

- 1 When an airspeed system is used under dynamic conditions (ie under other than constant altitude flight at a constant airspeed) errors will occur due to the fact that it takes a finite time for the internal volumes of the plumbing and instruments that are connected to the system to respond to the changing pressures. In other words the system lags behind the actual pressure change. NASA Reference Publication 1046, 'Measurement of Aircraft Speed and Altitude' by W.Gracey, provides detailed information regarding errors due to pressure system lags and leaks. This publication discusses two types of system lag:
 - (a) Acoustic Lag arises because of the time taken for the pressure change to propagate along the tubing and depends only on the speed of sound. Especially at the lower altitudes where the speed of sound is of the order of 1000ft/sec acoustic lag is only of consequence for systems employing very long lengths of tubing.
 - (b) Pressure Lag arises because of the actual pressure drop associated with the flow through the tubing.
- 2 These errors can be significant if the lag of one side of the system differs from that on the other side of the system and this will give rise to the necessity for dynamic lag balancing of any airspeed system that is to be used under other than steady-state conditions.
- 3 Dynamic lag balancing can be achieved by exposing both the pitot and the static pressure sides of the system to the same rate of pressure change, and adjusting the relative internal volumes of the two sides until the system shows no sensitivity to the rate of pressure change. In the case of a flight test airspeed measurement system, particularly one using a static source located on a trailing bomb or cone, this usually entails adding volume to the pitot side of the system (for example, an increased length of tubing can be used to connect the pitot source to the pitot inlet of the ASI).
- 4 One dynamic lag balancing method is illustrated in the diagram at Appendix 1. The method involves placing the *entire* airspeed measurement system - both the pitot and static sources, the instruments¹⁵ that are normally connected to them, and all their associated plumbing, inside a suitably sized chamber that can withstand a reduction in pressure. At the ASI end of the system under test an instrument capable of precisely measuring pressure variation (eg an IVSI or aU-tube manometer containing a small quantity of water) is teed in to both the pitot and static lines. The U-tube manometer and its connections need to be of small internal capacity compared with the overall system, and the two sides of this manometer 'sub-system' need to be of approximately equal volume. The chamber is connected to a vacuum source via a three-way, rate-adjustable valve

¹⁵ It is not strictly necessary to place the ASI inside the pressure chamber since the instrument should be a sealed unit. Either way the important point is that the ASI must be connected to the system as per its normal set-up.

that can select either the vacuum source or the outside air. The set-up also needs to include a VSI or an altimeter that senses the pressure change inside the chamber. Select the vacuum source and ensure that the system can achieve a 'rate of climb' of 3500+/-500 feet per minute on the VSI / altimeter. Select outside air and meter the opening to give a 'descent' rate of the same 3500+/-500 feet per minute. Cycle the system in this manner and observe the IVSI or U-tube manometer. Adjust the volumes of the plumbing on either side of the system under test until no detectable change is observed on the manometer between 'climbing' and 'descending'. Note that the instruments connected to the system will affect the dynamic lag balancing; any change in the instruments will necessitate a repeat of the balancing exercise. It is therefore advisable to keep the total number of instruments used during the flight test program to a minimum. Finally, for any pressure system, minimising the number of bends and connections in the tubing set-up can reduce the pressure lag.

- 5 Dynamic lag balancing does not eliminate lag, it merely eliminates, or minimises, any reading offset due to the difference in the lag between the two sides of the system. The absolute lag remains and may be a cause of some error. Nevertheless, when a balanced test airspeed system is used it is often unnecessary to determine the actual amount of lag present. When such a determination is considered necessary a method for accounting for lag errors can be found in NASA Reference Publication 1046.

APPENDIX 1 TO ANNEX E

