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(R) Capacitive Fuel Gauging System Accuracies

RATIONALE

This document is intended as a complement to AIR5691, and gives more detail on error sources which should be considered in the design of capacitive gauging systems. Note that it is completely revised from Issue A, hence no change bars are provided in this issue.

FOREWORD

This document presents a concise overview of error sources in capacitive fuel gauging systems. The subject matter is directed at individuals who are responsible for specifying gauging system accuracies and, therefore, need insight into the predominant error sources in capacitive fuel gauging systems and means to minimize the errors.

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TABLE OF CONTENTS

1.	SCOPE.....	3
1.1	Purpose	3
2.	REFERENCES.....	3
2.1	Applicable Documents	3
2.1.1	SAE Publications.....	3
2.1.2	ARINC Documents.....	3
2.1.3	US Government Publications.....	3
2.2	Acronyms and Abbreviations	4
3.	GENERAL REQUIREMENTS.....	4
4.	DETAILED REQUIREMENTS	11
4.1	Errors Controlled by the Airframe Manufacturer	11
4.1.1	Fuel Tank Definition, Design and Manufacturing Process Variation Considerations	11
4.1.2	Tank Internal Structure.....	12
4.1.3	Tank Deflection, Expansion, Twist, Deformation	12
4.1.4	Fuel Probe Mounting Tolerances.....	12
4.1.5	Effects of Display Resolution and Rounding.....	13
4.1.6	Anomalous Fuel Distribution	13
4.1.7	Aircraft Attitude Effects.....	14
4.2	Errors Jointly Controlled by the Airframe Manufacturer and Gauging System Supplier.....	15
4.2.1	Tank Modelling.....	15
4.2.2	Implementation of the Tank Datum Model.....	15
4.2.3	Accuracy Verification.....	16
4.2.4	Effects of Aircraft Wiring.....	16
4.2.5	Fault Mode Analysis.....	17
4.3	Errors Mainly Controlled by the Gauging Supplier.....	17
4.3.1	Calculation Algorithms	17
4.3.2	Fuel Probe Manufacturing, Mechanical	18
4.3.3	Fuel Probe Linearity	18
4.3.4	Fuel Probe Mounted Electronic Circuits and Components	19
4.3.5	Probe Implementation	19
4.3.6	Signal Conditioning	19
4.4	Errors Jointly Not Controlled by the Airframe or the Gauging System Manufacturers	20
4.4.1	Fuel Probe Environment	20
4.4.2	Fuel Surface Shape and Formation	20
4.4.3	Fuel Temperature Stratification and Temperature Variation with Time	20
4.4.4	Fuel Type Variation	20
4.4.5	Density Characteristic Variation.....	21
4.4.6	Effects of Fuel Additives and Contaminants	21
4.4.7	Water Contamination	22
4.4.8	Microbial Growth	22
4.4.9	Tank Expansion, Contraction and Deformation	22
5.	CONCLUSION	22
6.	NOTES.....	25
6.1	Revision Indicator.....	25
TABLE 1	ERROR SOURCES (REF AIR5691).....	5

1. SCOPE

This report is intended to identify the various errors typically encountered in capacitance fuel quantity measurement systems. In addition to identification of error sources, it describes the basic factors which cause the errors. When coupled with appraisals of the relative costs of minimizing the errors, this knowledge will furnish a tool with which to optimize gauging system accuracy, and thus, to obtain the optimum overall system within the constraints imposed by both design and budgetary considerations.

Since the subject of fuel measurement accuracy using capacitance based sensing is quite complex, no attempt is made herein to present a fully-comprehensive evaluation of all factors affecting gauging system accuracy. Rather, the major contributors to gauging system inaccuracy are discussed and emphasis is given to simplicity and clarity, somewhat at the expense of completeness.

An overview of capacitive fuel gauging operation can be found in AIR5691. This document also discusses how to analyze fuel gauging system accuracy as a result of combining the effects of the error sources described here.

1.1 Purpose

This report identifies those sources or causes of error which adversely affect the accuracy of airborne capacitance-type fuel quantity gauging systems.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), <http://www.sae.org>

ARP1870 Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety

ARP5412 Aircraft Lightning Environment and Related Test Waveforms

AIR5691 Guidance for the Design and Installation of Fuel Quantity Indicating Systems

ARP8615 Fuel System Components: General Specification For

2.1.2 ARINC Documents

Available from ARINC, 2551 Riva Road, Annapolis, MD 21401-7435, Tel: 410-266-4000, www.arinc.com.

ARINC Report 611 Guidance for the Design and Installation of Fuel Quantity Systems

2.1.3 US Government Publications

Copies of these documents are available online at <http://quicksearch.dla.mil>.

MIL-G-26988 Gage, Liquid Quantity, Capacitor Type Transistorized, General (now cancelled, but included as a historical reference)

2.2 Acronyms and Abbreviations

ARINC	Aeronautical Radio Incorporated
D to A	Digital to Analogue
EME	Electro-Magnetic Effects
FQI	Fuel Quantity Indication
FQ	Fuel Quantity
K	Permittivity
PSU	Power Supply Unit
RSS	Root Sum of Squares
TE	Test Equipment

3. GENERAL REQUIREMENTS

There are numerous ways in which the contributors to gauging system inaccuracy may be classified. Parameters for such classification may be general (e.g., temperature-induced errors, geometrical errors, etc.) or specific (e.g., tank errors, fuel probe errors, indicator errors, etc.). Indeed, the variety of possible classifications is virtually unlimited.

For the purpose of this report, four broad categories for classification of error-causes are listed:

1. Errors controlled by the airframe manufacturer.
2. Errors jointly controlled by the airframe manufacturer and gauging system supplier.
3. Errors mainly controlled by the gauging system supplier.
4. Errors not controlled by the airframe manufacturer or the gauging system supplier.

An initial list of possible error sources is given in AIR5691. The table of errors is re-produced here in table 1 to facilitate further discussion of those error sources. It has been modified slightly, and these modifications will be incorporated into the next issue of AIR5691. The table is arranged to show the errors which fall into each of the 4 categories described above.

In designing a gauging system, it is necessary to combine all sources of errors. Typical ways of approaching this are given in AIR5691, and will not be discussed any further in this document.

Table 1 - Error sources (ref AIR5691)

Part 1a: Errors controlled by the airframe manufacturer

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
Fuel tank definition, design and manufacturing process variation considerations	Fuel tank manufacturing tolerance resulting in a slight variation in the size and shape of each manufactured fuel tank as compared to nominal.	A – Specify tank shape and manufacturing tolerances. A – Digitized tank design for basis for analysis.	If there is a constant jig/deflection problem.	Global versus local coordinate systems; relative dimensions; tolerance build ups, non-linear shapes. Dependent on modelling fidelity.
		S – See tank modelling – digitized tank model for basis for studies and comparison with Airframer.		
Tank internal structure	Fidelity of tank studies caused by errors such as internal structure, tubing, etc.	A – Specify internal structures, e.g., pipes/tubing, spars, etc. Specify net volumes. S – See tank modelling.	Caused by irregular distribution of internal structure components within tank, e.g., pipes on floor of tank, etc.	Dependent on fidelity of modeling when flooding of internal structures occurs.
Tank deflection, expansion, twist, deformation	Errors due to distortion of the fuel tank from the normal datum shape and difference in pitch attitude and applied thrust, to be taken into account when designing the fuel measurement system.	A – Specify wing expansion, twist and deflection for various flight conditions and fuel loads. Specify typical aircraft flight profiles. S – See tank modelling.	The bias error is caused by error of deformation model during predominant flight conditions e.g., ground refuel, cruise, etc. It should be noted that different considerations may need to be given to bladder tanks where there may be up to a 70% increase in bladder material volume when fuel saturated. Also if the bladder changes shape during emptying, it may hold fuel around any gauging probes causing an offset in readings at near empty conditions adding to the unusable.	The random error is caused by error of deformation model during exceptional flight conditions e.g., turbulence, maneuvering, etc. Consideration should be given to whether the error can be reduced by using air vehicle attitude information.
Fuel probe mounting tolerances	The tolerances associated with the location of probes, mounting brackets, flanges plates or mounting holes, fringing affects to nearby structure.	A – Specify fuel probe mounting tolerances. S – Control fuel probe mounting point tolerances (hole location in brackets, flange dimensions etc.).	If a probe has been relocated during manufacturing and software is not updated.	Tolerances on fuel probe mounting points
Effects of display resolution and rounding	Display resolution and rounding.	A – Specify display resolution and format. S – Define effects.	Display truncation (i.e., loss of LS digit).	Effects of communication buses i.e., ARINC 429 resolution/rounding/truncation.

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
Anomalous fuel distribution	The effects of different fuel heights in cells, also known as unlevelling (e.g., due to proximity of flow restrictions and flow near those restrictions).	A – Specify ungaugeable / scavenged fuel quantities and flow restrictions. Specify typical fuel movement and transfer regimes within typical flight profiles. S – Model flow (e.g., using fluids dynamic software, e.g., Fluent) or empirical methods, then perform empirical tests.	Effects are only produced when fuel is moved by pumping or change in attitude, this effect may be seen in variations in the "Fuel On Board" quantity when fuel is moved from tank to tank. Air pockets above fuel probes may also cause anomalies if not properly vented.	Caused by tank geometry differences from aircraft to aircraft and between different variants of same aircraft.
Electromagnetic and lightning effects	Coupling of EME and lightning to fuel probe interface wiring.	A – Tank structure and materials (e.g., aluminum or composites) to provide shielding. S – Interface and harness design. Testing to mitigate.	Minimize by design of filter	Dependent on degree of coupling and the imposed threats.
Aircraft attitude effects	Operational attitudes for the aircraft	A – Specification of the attitude envelope over which the aircraft will operate and the different accuracy regimes (normal, relaxed, extreme). Note that attitudes for trimmable tanks, such as the horizontal tail plane should be considered, if relevant S – Placement of probes to optimize accuracy in the normal attitude range. Suitable algorithms to operate over full attitude range	The bias error is caused by tank modelling and probe placement, in that a certain attitude may always give the same error at the same fuel quantity, and is usually accounted for in the tank modelling bias error	

Part 1b: Errors jointly controlled by the airframe manufacturer and gauging system supplier

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
Tank modeling	Tank study fidelity including bulk correction factors (unmodeled structure factors) and accuracy of height versus volume curve(s).	A – Specify tank shape and agree fuel probe positions. S – Perform tank study and analyze errors – modelling of tank shape, location of fuel probes, interpolation errors for Height-Volume calculations/tables. Specify optimum locations for fuel probes	At a particular quantity and attitude where there is a discontinuity. Actual location of height fuel probe verses desired location.	Model fidelity.
Implementation of tank datum model	Implementation of the tank model into the gauging algorithms within the FQ system	A – Specify bulk volumes. S – Define effects of the gauging algorithm, interpolation etc.	At a particular point where the data is not stored but evaluated. May be due to lack of stored data, i.e., requires use of interpolation. Probes may not be positioned in ideal locations (leading to discontinuities)	Pseudo random due to mathematical processes, e.g., interpolation, non-linear shapes, etc.
Accuracy verification	The error associated with verifying the fuel system accuracy.	A – Accuracy of TE used and calibration process. S – Analysis of results based on information provided by Airframer.	Method of test causing offset (e.g., fuel already on board not accounted for, over wing fueling resulting in different distribution).	Tolerance of Test Equipment used.
Effects of aircraft wiring	Errors due to environment effects on fuel probe wiring.	A – Specify characteristics for relevant parameters for any harness sections provided by the Airframer (depends on specific solution and gauging technology). S – Define effects, if any, on gauging accuracy.	Effects of wire property variation in manufacture. This can include wire length, stray capacitance, shielded wire capacitance etc. Effects of rework without software compensation.	Variation as a function of time or environment and installation. Insulation effects over time.
Fault mode analysis	Effects of detected faults in probes, harness, interfaces, etc.	A – Details of any failures of Airframer owned parts of the system (e.g., displays, possibly some harnesses) to enable supplier analysis. S – Perform analysis of effects of failures.	Biased faults, e.g., under-reading, spatial concentrations of faults, etc.	Unbiased faults, irregular spatial distribution of faults, etc.

Part 1c: Errors mainly controlled by the gauging system supplier

Error Source	Description	Airframer (A) / Supplier (S) Contribution		Bias	Random
		A – None.	S – Perform analysis		
Calculation algorithms	Any errors due to software computation, sizing requirements and methodology.			Any truncation or ROM size requirements.	Any rounding.
Fuel probe manufacturing, mechanical	Fuel probe mechanical manufacturing tolerances.	A – Nothing required.		A constant manufacturing problem or a change for which software is not updated.	Length, tube spacing, target positions, non-linearity of section, etc.
Measurement linearity	The ability for the fuel probes to measure over the entire range.	S – Define effects, if any on gauging accuracy.		Constant error at points of non-linearity.	None: Covered by manufacturing tolerance.
		A – Nothing required.	S – Minimize discontinuities (inter-probe gaps), to ensure these do not create errors outside those allowable. Optimize probe design/construction to minimize "dead" capacitance		
Fuel probe mounted electronic circuit and components	Electronic errors of fuel probe mounted components.	A – Specify specialized environmental requirements.		An error not taken into account in algorithms (e.g. diode voltage).	Diode error or on probe circuit errors due to component tolerance and the environment.
		S – Define design features incorporated to meet above requirements, effects on gauging accuracy.			
Probe implementation	Errors due to the way the probe has been implemented.	A – Nothing required.		The effects of "fringing", parasitic capacitances, dewetting effects etc. (e.g., water adhesion to tube surfaces).	Similar effects to Bias but non-linearities caused by overlapping limited range effects.
Signal conditioning	E.g., both analogue and digital circuitry not mounted on the probe, used for capacitive measurement – PSU, tolerance effects etc.	S – Define design features incorporated to achieve gauging, effects on gauging accuracy.		An error not taken into account in algorithms. Reference variations.	Half the resolution of the A to D, component tolerance, temperature effects and PSU effects.
		A – Nothing required.	S – Perform empirical tests.		