TOOLS AND METHODS USED FOR CERTIFICATION OF THE FOKKER 100 AUTOMATIC LANDING SYSTEM PERFORMANCE

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Abstract

In order to demonstrate performance compliance of the Fokker 100 autoland system with the airworthiness requirements, the Monte Carlo simulation technique was applied. To verify the validity of the used simulation model an efficient, practicable and accurate correlation method was developed. Both the Fokker 100 autoland performance results as well as the described methods and tools have been accepted by the JAA, resulting in JAA approval for CAT IIIb operations, Decision Height 15 ft and a Runway Visual Range of 150 m.

1. Introduction

In the beginning of 1988 the Fokker 100 entered service with launch customer Swissair, where it is used on medium- and short-haul routes.

Figure 1.1 : The Fokker 100 aircraft

The aircraft is equipped with an Automatic Flight Control and Augmentation System (AFCAS) which provides a full flight regime autoflight system including CAT IIIb autoland capability and a fully integrated autothrottle. This system, the FCS-1000, developed jointly by Rockwell-Collins and the Fokker Aircraft Company, is based upon a classical triplex architecture interfaced with dual electromechanical servos. New features include full flight regime speed protection, coupled Windshear Escape and a new Flight Mode Annunciation philosophy. The AFCAS system provides the Fokker 100 aircraft all-weather capability and therefore a high schedule reliability.The AFCAS functions are defined to include autopilot, flight director, altitude alert and thrust management.

A block diagram showing the main components of the AFCAS subsystems and its sensor interfaces is presented in figure 1.2.

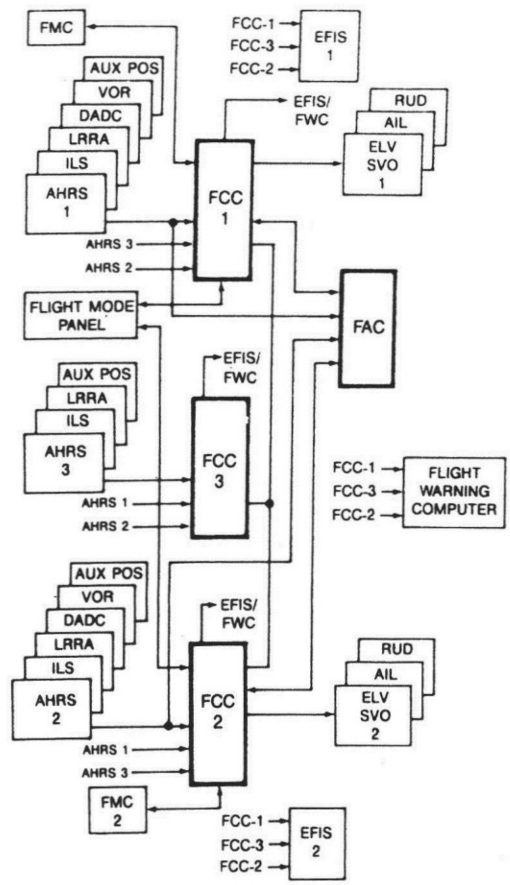

Figure 1.2 : AFCAS system interfaces

In order to obtain approval by the authorities for operations with the automatic landing system on the Fokker 100 an extensive program has been performed over a period of three years. It started in the beginning of 1985 with the development of the autoland control laws using simulations based on Fokker 100 aerodata as derived from windtunnel experiments with scale models.

On 30 november 1986 the first Fokker 100 prototype made its maiden flight, and in fact was completed with an automatic landing. During the subsequent flight test program the aeromodel of the Fokker 100 and the

autoland control laws were optimized using the flight test results.
In february 1988 the final version of the autoland control laws were established and the collection of the performance data started. JAA approval for CAT IIIb operations with Decision Height 15 ft and a Runway Visual Range of 150 m was obtained in june 1988.

2. The Joint Airworthiness Requirements

To obtain a certificate of airworthiness for an aircraft the manufacturer has to meet the airworthiness design requirements for the airframe, the power plant and the aircraft equipment.
In 1987 the Fokker Aircraft Company adopted the document Joint Airworthiness Requirements-All Weather Operations (JAR-AWO) [Ref.1] and the interpretation material of the Advisory Circular JAR.ACJ-AWO, as the certification basis for the Fokker 100 autoland system. These requirements have evolved from the cooperation between the airworthiness authorities of the European countries and the association of the European aerospace industries (AECMA).
Fokker has been among the first airframe manufacturers to base the autoland certification on advanced issues of the JAR - All Weather Operations document.

2.1 Interpretation of the autoland performance requirements as prescribed in the JAR - All Weather Operations

The intent of the JAR-AWO requirements is to provide design directives and guidance material for analysis, such that it may be expected that an autoland system designed to this standard will demonstrate safe and adequate performance in real airline operation.The certification requirements are of a probabilistic nature. The overall probability of exceedance of the touchdown parameters shall be evaluated for both average and limit conditions. The JAR-AWO requirements define the probability of exceedance limits for the autoland performance parameters as follows;

- Longitudinal dispersion at touchdown	; XDEV	[ft]
- Lateral dispersion at touchdown	; YDEV	[ft]
- Sinkrate at touchdown	; HDOT	[ft/s]
- Bank angle at touchdown	; FIE	[deg]
- Slip angle at touchdown	; PSIDA	[deg]
- Lateral velocity at touchdown	; YDOT	[ft/s]
- Lateral deviation during roll-out	; YDEV	[ft]

The airworthiness requirements dictate for most of the touchdown parameters a probability of exceedance of 10^{-6} or less for average conditions and 10^{-5} or less for limit conditions. For the average case all variables vary according to their probability distributions. For the limit case one variable is held at its most adverse value, while the other variables vary according to their probability distributions.
For bank angle (wing tip touch at touchdown) these exceedance probabilities are 10^{-8} and 10^{-7}, respectively.

In addition the exceedance probability for Fokker 100 autoland has been assessed for parameters such as:

- Beam tracking accuracy (below 700 ft)
- Speed ratio to V_{stall} at threshold and at touchdown
- Peak value of angle of attack during flare
- Pitch angle at touchdown (nose-gear first or tail-scrape) ; TETA [deg]

In general simulation is used to show compliance with the probability of exceedance requirements. Therefore, validation of the simulation is an essential certification issue. With respect to this issue the JAR-AWO contains the statement that validation of the simulation must be demonstrated by flight test, using either statistical or deterministic methods.

3. Tools

During the process of evaluation and certification of the autoland performance various tools have been used, ranging from flight simulator to test aircraft.

3.1 The flight test set up

The autoland flight test program has been executed by using the two Fokker 100 prototypes. Both aircraft are equipped with an great number of transducers and an extensive measurement and data-processing system with telemetry capabilities. The system is capable of processing up to 1000 analog signals and up to 49 digital databusses, each with 1900 labels.
One of the key elements of this system with respect to autoland flight testing is the determination of the final approach and flare trajectory of the aircraft.

3.1.1 Trajectory measurement during autoland flight tests

The trajectory measurement system for the Fokker 100 autoland trials was developed by the National Aerospace Laboratory NLR [Ref.2]. Capabilities of the system include 3-dimensional aircraft trajectory measurement during approach, landing and roll-out, suitable not only for full stop landing,but also for touch-and-go's and go-arounds (aborted approaches). The standards achieved were:

- position accuracy (from runway threshold up to standstill): - 0.3 m standard deviation along track,
  - 0.15 m cross track and 0.15 m height.
- velocity accuracy (from runway threshold up to standstill): 0.025 m/s standard deviation for all three axes.
- turn-around time : the first data should be available within 24 hours after completion of a flight test.
- mobility: autoland trials were to take place on seven runways in Western Europe and change of location had to be possible at 24 hours notice.

The NLR system met these standards by combining a

forward-looking camera with inertial sensing.
The camera method was an obvious choice because of its mobility, but in itself does not meet the turn-around time requirement. Therefore the method was "speeded up" by combining it with an inertial navigation system. The coefficients of an INS-error model (position-,velocity- and acceleration off-sets and heading misalignment) are estimated by comparing the rough INS-trajectory with the set of photo-positions.
The rough trajectory is then corrected for these errors. The result, the final trajectory, gives continuous information on the aircraft position and speed from 4 km before the runway threshold.

3.2 The simulation set up

For the evaluation and certification of the Fokker 100 autoland performance, extensive use has been made of the Fokker engineering flight simulator facilities. This fixed-base simulator is capable of executing real-time simulations with AFCAS hardware in-the-loop as well as compressed-time simulations with just autoland control laws in-the-loop, both using the same Fokker 100 aeromodel. This extensive six degree-of-freedom model includes the complete Tay Mk620 and Mk650 engine models. The autoland control laws have been implemented on the simulator computer and contain ILS beam tracking, speed control, yaw damping, runway alignment, flare, nose lowering, throttle retard and roll out. The servos are also modelled and implemented in software.

4. Procedures and methods

On behalf of the various parts of the evaluation and certification process of the autoland performance several procedures and methods have been developed and applied.

4.1 Validation of the simulation

The JAR-AWO document requires that a simulation being used to assess the autoland performance is validated by flight test. Two methods of validation were considered. A deterministic method was first evaluated with time histories of variables (such as mean wind, turbulence, windshear, beam noise and terrain profile) being entered into the closed loop simulation. However deriving the time histories out of flight test data turned out to be very cumbersome, as was the synchronisation of the signals.
A less demanding statistical method, which compares adjusted touchdown results of a set of flight test approaches with the results of a set of simulated approaches, was developed. This method has been applied after a deterministic control law verification by comparing the results of the implemented autoland control laws on the simulator and the results of autoland simulations with AFCAS hardware in-the-loop.

4.1.1 Validation flight test program

Four sets of autoland flight tests, two flapsettings and two approach speed settings, have been performed on Fokker 100 prototype number two. Specifically for the validation of the autoland simulation.
These four sets are:

- 37 runs with flaps 42 deg. and Vref + 5 kts.
- 40 runs with flaps 25 deg. and Vref + 5 kts.
- 37 runs with flaps 42 deg. and Vref + 10 kts.
- 39 runs with flaps 25 deg. and Vref + 10 kts.

Each set covers the mass - center of gravity envelope and the mean windspeed in each case was below 15 kts. The autolands were carried out on seven different runways spread over Western-Europe.

4.1.2 Statistical validation method

An ideal situation would be to be able to compare the touchdown statistics of a set of simulated approaches with the touchdown statistics of a set of flight test approaches, while keeping input variables (such as mass, center of gravity, wind) at a fixed value for both sets, i.e. a nominal reference condition. In that case dispersion of the touchdown values would only be caused by stochastic variables such as turbulence and beam noise. Unfortunately, it is impossible to keep the variables fixed during a set of flight test approaches. By applying a correction to the touchdown values obtained from flight tests, to compensate for the differences in value of the input variables, between the flight test condition and the reference condition. The results of the various flight tests are projected on one reference flight condition.
The corrections are obtained by simulating both the flight test condition and the simulated reference condition in a deterministic way and subtracting the reference touchdown results from the flight test touchdown results. The corrections are subsequently applied to the actual flight test touchdown values (see fig.4.1). Finally the statistics of the set of adjusted flight test touchdown values (sample size $n = \pm 40$) are compared with those of the stochastically simulated reference case ($n = 1500$). The reference flight condition to be correlated has been selected within the range (in general the midvalue) of weight, center of gravity and wind of the flight test cases.
The four sets of flight test approaches mentioned previously, have been processed according to this procedure.

The flight test adjustment procedure is based on the assumption that the mean value of each touchdown parameter over a set of runs with turbulence can be obtained by performing a single run with wind but without turbulence. This assumption has been demonstrated for the Fokker 100 model to be acceptable for a turbulence level up to about 15 kts with the JAR-AWO turbulence model.

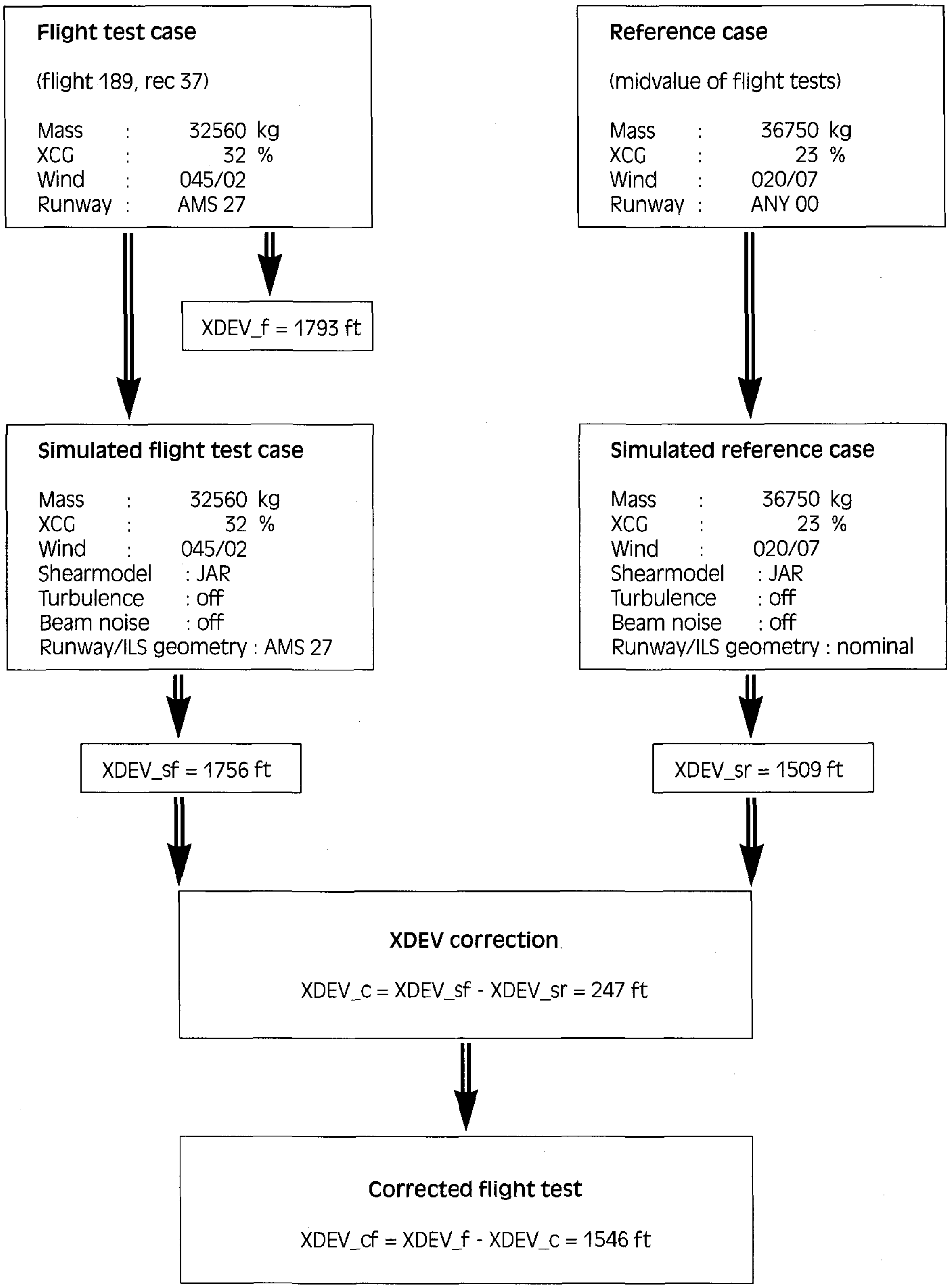

fig. 4.1: Correction procedure for a touchdown distance XDEV [ft]

If the simulation, aeromodel plus control laws, does not represent reality, inaccurate correction values will result, and inadequate correlation can be concluded. Such a case of model error was initially identified when the ground effect was incorrectly modelled, causing correlation of pitch attitude,sink rate and landing distance to be rejected for that situation.

4.1.3 Validation requirements

In absence of validation requirements by the authorities the aircraft manufacturer has to establish his own criteria. The following criteria were applied to show an acceptable degree of correlation between the 1500 simulation and about 40 flight test runs.
The statistical validity of the simulation was assessed for the mean values and 10^{-2} exceedance probability (= mean value + 2.33 * standard deviation).The mean value accuracy shall be within 5%, and the parameter value at 10^{-2} exceedance probability shall be within 20% of the touchdown parameter range. These criteria are considered to be acceptable when taking into account the various effects of error sources, as they are discussed in section 5.

Some correlation results of the set flaps 42, Vref + 5 are presented in table 4.1.

	HDOT ft/s	TETA deg	FIE deg	XDEV ft	YDEV ft	CAS kts
mean	1.36	2.41	-0.35	1616	-1.38	124.5
sigma	0.48	0.59	0.48	248	6.09	5.8

Table 4.1.a: Statistics of 37 flight test runs

	HDOT	TETA	FIE	XDEV	YDEV	CAS
mean	1.49	2.96	-0.25	1431	-1.67	122.1
sigma	0.40	0.41	0.41	172	7.39	2.3

Table 4.1.b: Statistics of to the reference condition adjusted flight test runs

	HDOT	TETA	FIE	XDEV	YDEV	CAS
mean	1.74	3.40	0.00	1417	-0.12	122.8
sigma	0.39	0.33	0.31	112	2.89	1.2

Table 4.1.c: Statistics of 1500 simulated runs (reference case)

4.2 The Monte Carlo simulation method

The autoland touchdown performance has been assessed by using the Monte Carlo simulation method. In this method a stochastic environment of flight conditions is generated by defining probability density functions for a number of input variables. The input variables are assumed to be stochastically independent. Advantages of this method are:

- A more realistic simulated environment.
- A reduction of the total number of runs and therefore less computation time.
- No need to combine somewhat arbitrarily weighted results, as needed for simulations of discrete flight conditions.

Disadvantages are:

- Need for representative probability density functions for the input variables.
- The sensitivity of the performance parameters to certain input variables is hidden in the overall results.

A sensitivity analysis was carried out to overcome the problem of the hidden sensitivities. As a result the input variables were divided into three categories and treated accordingly.

4.2.1 Randomly selected initial variables

The variables of this group are set to an initial value at the start of a run and the value will remain constant during the run. The 1500 initial values of a variable are distributed according to a specified distribution. These values are generated by a method, where uniform distributed samples (0-1) are used for searching in a table of a specified cumulative probability function. Variables belonging to this group are : mass, center of gravity, moments of inertia, mean windspeed, mean winddirection, selected approach speed and the course datum error. The selected approach speed is a function of the mass, flapsetting and wind.

4.2.2 Deterministic variables

These variables remain at a fixed value during all 1500 runs.
Variables belonging to this group are : flapsetting, speedbrakes, atmospherical variables, sensor variables and geometry variables of ILS beam, runway and terrain.
In a sensitivity analysis the Fokker 100 autoland performance (in general the touchdown distance) was found to be affected significantly by variations in (limit) windspeed, glide slope angle, runway down-slope and radio altimeter off-sets. Therefore, these variables have been treated in so-called "JAR limit" simulations.

4.2.3 Stochastic variables

These variables vary at random in time during each run, such as wind turbulence (longitudinal ,lateral and vertical) and ILS beam noise (glide slope and localizer). The noise spectrum of these variables is represented by a white noise passed through a low pass first order filter. The spectra are prescibed in JAR-AWO (ACJ.AWO 131). Normal windshear is not a real stochastic variable but it is placed in this category because the mean windspeed is assumed to vary as a specified function of height (ACJ.AWO 131) during each run.

4.2.4 Autoland performance results

The Monte Carlo simulation as used has been based on 1500 runs. This number has been based on the confidence intervals of the sample mean and sample sigma (see section 5).
Some typical results of the Monte Carlo simulation as they have been used for the Fokker 100 autoland certification are presented in figure 4.2 (on a Gaussian scale) and figure 4.3.

In addition to the simulation program an autoland demonstration flight test program has been carried out, as required by JAR-AWO. Therefore, some 125 autolands have been performed under a variety of conditions, such as various aircraft configurations, ILS beams, airfield characteristics and runway conditions and in particular meteorological conditions, such as limit wind conditions.

4.3. Application of the simulation performance results

In the Airplane Flight Manual the overall landing distance for autoland has to be published. Therefore a regression model for the airborne landing distance and touchdown speed of the autoland system was developed. The scheduled autoland landing distance has been determined in accordance with the requirements of the draft ACJ to JAR-AWO 142 (JAR Flight Study Group WP 364, issue 1, May 1988).

4.3.1 The overall landing distance

The autoland landing distance is the sum of the airborne landing distance (from the threshold to touchdown) and the ground landing distance (from touchdown to a complete stop).
The ground landing distance for autoland is derived from the results of the manual landing distance measurements and the touchdown speeds appropriate for autoland operation, as specified in JAR FWP 364. The ground distance for manual landing is a minimum distance at maximum brake application, in accordance with JAR 25.125(a) and FAR 25.125.

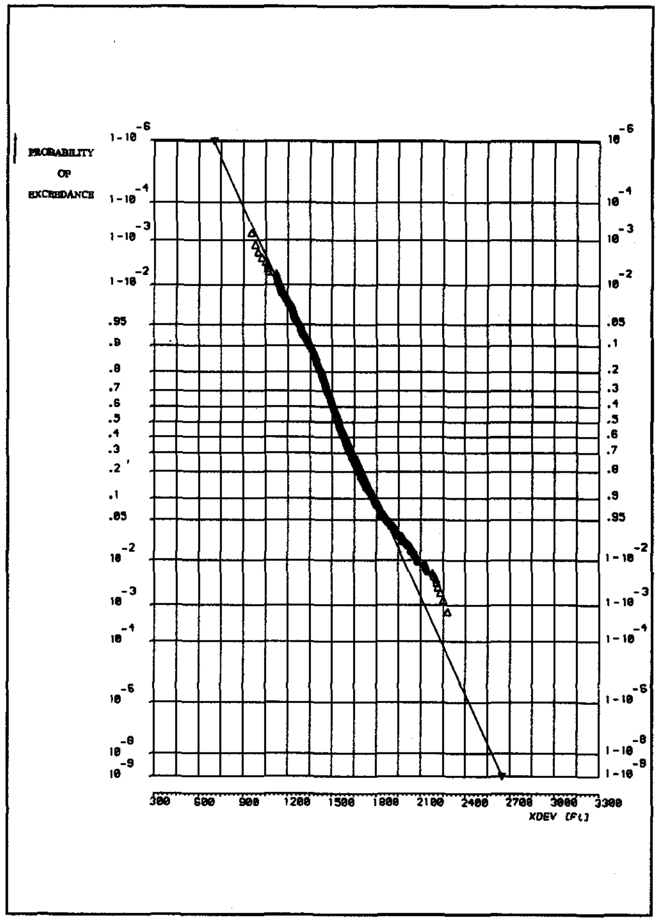

Figure 4.2: Touchdown distance probility of exceedance

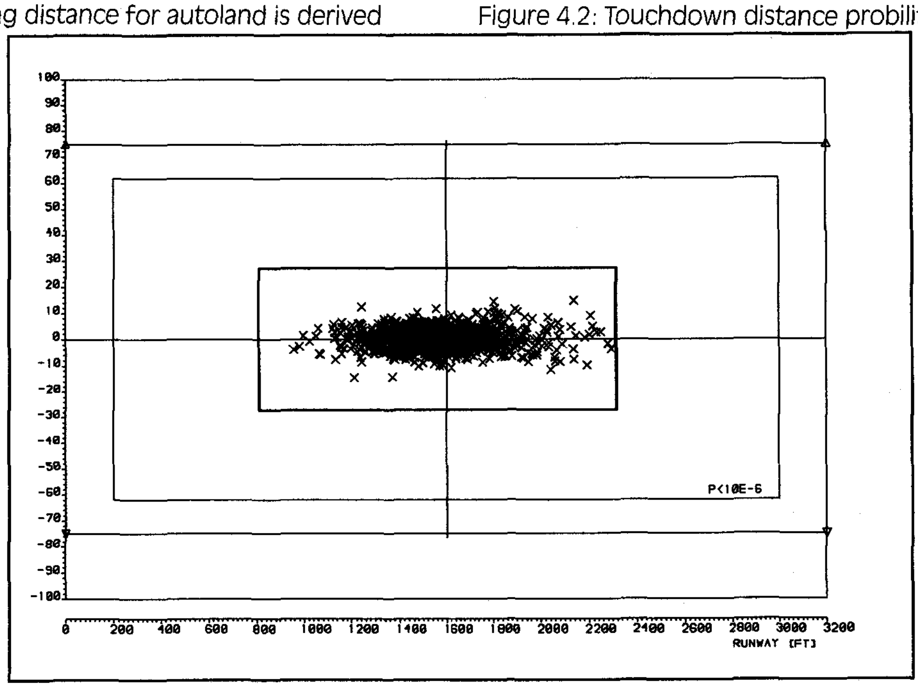

Figure 4.3: Touchdown dispersion; "footprint"

The assessment of the airborne landing distance has been based on the results of the Monte Carlo simulations for autoland. The relevant parameters to determine the overall landing distance are the upper bound of the distance of the touchdown point to the runway threshold D_{AM} and the upper bound of the touchdown speed V_{TDM}.

The overall landing distance D_{TOT} is

$$D_{TOT} = D_{AM} + K * D_{GM}$$

where D_{GM} = upper bound of ground distance.

Expressions for D_{AM} and V_{TDM} are derived below. The calculation of the ground roll distance must be based on the upper bound of the touchdown speed. The ground roll distance (safety) factor K is in accordance with FAR 121. Based on JAR Flight Study Group WP 364 the distance factor for ground roll will be equal to 1.15.

The independent variables to be examined in assessing the effect on airborne landing distance and touchdown speed are flaps, weight, center of gravity, target airspeed, wind, temperature, runway altitude, runway slope, glide beam angle, ILS reference datum, radio altimeter error, and terrain profile. Regression functions for the airborne distance XDEV and the touchdown speed VTD at selected parameter reference values are derived, both at 42 degrees and 25 degrees of flap.
The reference regression functions for XDEV and VTD are valid for any weight and center of gravity (over the full range of landing weights), at wind conditions following the JAR AWO atmospheric probability distribution model (ACJ AWO 131, par. 3), and for the reference value of the parameters (runway characteristics, beam properties, field elevation, etc.). The remaining parameters, which have no influence on XDEV and VTD, are set at the "mid-value".

Incremental regression functions $\triangle$ XDEV and $\triangle$ VTD are derived from the simulation results, with each parameter (one at a time) set to a specific value. The incremental functions may be used to evaluate a specified landing condition. They may be applied either to show the influence of a particular variable, or to correct the subject reference relation to the limit value of that variable.
A landing condition therefore may be evaluated by summation of the reference and the incremental regression function values.

The expression for the airborne landing distance is:

$$D_{AM} = 1.15 \left\{ r_{XDEV} \frac{S_{XDEV}}{S_{VWIND}} \left(VWIND - \overline{VWIND} \right) + \overline{XDEV} + 3\,\hat{\sigma}_{XDEV} \right\}$$

where r_{XDEV} = correlation coefficient of XDEV vs. VWIND.

S_{XDEV} = sample standard deviation of XDEV.

S_{VWIND} = sample standard deviation of VWIND.

VWIND = headwind or tailwind component.

$\hat{\sigma}_{XDEV}$ = residual sum of squares, or sum of squares due to deviation from regression, where

$$\hat{\sigma}_{XDEV} = S_{XDEV} \sqrt{\frac{n-1}{n-2} \left(1 - r_{XDEV}^2 \right)}$$

n = number of runs

The regression coefficient of the airborne landing distance XDEV vs. VWIND is given by.

$$r_{XDEV} = \frac{S_{XDEV}}{S_{VWIND}}$$

Similarly the expression for the upper bound of the touchdown speed for autoland will become:

$$V_{TDM} = r_{VTD} \frac{S_{VTD}}{S_{VWIND}} \left(VWIND - \overline{VWIND} \right) + \overline{VTD} + 3\,\hat{\sigma}_{VTD}$$

with the parameter subscripts now related to VTD. The calculation of the ground roll distance is based on the upper bound of the touchdown speed as obtained from this expression.

5 Discussion of results

The autoland performance certification evidence is based on the predictions from the Monte Carlo simulation. During the evaluation and certification process various problems were encountered.

5.1 Accuracy of the autoland performance assessment

Obvious error sources in the autoland performance assessment are measurement errors in the flight test touchdown results and simulation model errors. However, the measuring errors are very small (see 3.1.1) and significant errors in the simulation model are detected in the validation process. Beside these two error sources one should be aware of the following error contributions.

5.1.1 Statistical accuracy of the method of comparison

When comparing the flight test data and the simulation data, the touchdown parameter mean value accuracy shall be adequate. However the actual flight test disturbance levels may not be in accordance with the simulated JAR-AWO wind model and turbulence levels. Therefore, statistical tests (with hypotheses to be tested when comparing mean values, variances, distribution functions, or probability of exceedance

values) are unnecessarily stringent and cannot be used. The corrected flight test mean value and the parameter value at 10^{-2} exceedance probability of a touchdown parameter are compared with the simulated reference flight condition results. This involves comparison of the relatively small flight test sample size (say n = 40) with the large simulation sample size (n = 1500). The order of magnitude of the statistical error is assessed below for the parameters such as landing distance, sink rate at touchdown and pitch angle at touchdown.
It is assumed that the sample mean value $\underline{\overline{X}}$ and the sample standard deviation $\underline{S}$ are stochastic variables which are approximately Gaussian distributed if the sample size is sufficiently large (n > 30), so that

$$\underline{\overline{X}} \leftharpoondown N(\mu, \frac{\sigma}{\sqrt{n}})$$

$$\underline{S} \leftharpoondown N(\sigma, \frac{\sigma}{\sqrt{2(n-1)}}),$$

which are the notations for a normally distributed random variable with the mean value and the standard deviation presented within the brackets.
It then follows for a probability of exceedance γ that

$$\underline{\overline{X}} + z_{1-\gamma}\underline{S} \leftharpoondown N(\mu + z_{1-\gamma}\sigma, \sigma\sqrt{\frac{1}{n} + \frac{z^2_{1-\gamma}}{2(n-1)}}),$$

in which $Z_{1-\gamma}$ is the 1 - γ fractile of the standard normal distribution.

The half length $\triangle$ of the two-sided confidence region has been calculated (see table 5.1) for a typical standard deviation (σ = 150 ft for landing distance, σ = 0.75 ft/sec for sink rate, σ = 0.9 deg for pitch angle), at a confidence level ß, so that

$$\triangle = z_{\frac{1+\beta}{2}}\sigma\sqrt{\frac{1}{n} + \frac{z^2_{1-\gamma}}{2(n-1)}}$$

The values presented in table 5.1 provide an indication of the statistical error contribution due to different sample size, and these values increase proportional with the standard deviation of the touchdown parameter. It is concluded that the accuracy is adequate.

5.1.2 Required number of Monte Carlo simulation runs

The results of the Monte Carlo simulation are based on a large number of runs. A lower boundary n of the number of simulation runs to obtain a desired accuracy of the mean value may be assessed from Tsjebysjev's inequality

$$P[|\overline{X} - \mu| \leq \varepsilon] \geq 1 - \frac{\sigma^2}{n\varepsilon^2}, \quad \varepsilon > 0$$

for a stochastic variable at mean value μ and variance σ^2, and for any distribution of the touchdown parameters (i.e. independent of the nature of distribution function).

The accuracy of the sample standard deviations may be assessed from

$$\chi_{\frac{\alpha}{2}}(n-1) \leq (n-1)\frac{s^2}{\sigma^2} \leq \chi_{1-\frac{\alpha}{2}}(n-1),$$

where the quantity $(n-1)\frac{s^2}{\sigma^2}$ has a Chi-squared probability distribution at n - 1 degrees of freedom.

It has been decided that the Monte Carlo simulations will be based on n = 1500 runs. The mean value accuracy is better than $\pm$ 50 ft (95%) for landing distance and the standard deviation accuracy is approx. $\pm$ 3.5% (95%). It is concluded that these accuracies are adequate to provide certification evidence based on the predictions from the Monte Carlo simulation.

5.1.3 Extrapolation to 10^{-5} (or 10^{-6}) exceedance probability.

The probability of exceedance plot for 1500 simulation runs will have data points of the touchdown parameter up to 1/1500 = $6.7 \ast 10^{-4}$ exceedance probability (see figure 4.2). Extrapolation beyond this point to 10^{-5} (or 10^{-6}) exceedance probability may be accomplished by fitting an analytical probability distribution function (such as a Gaussian, a lognormal, or a Weibull function).

Sample size	Probability of exceedance	Touchdown distance (ft)		Sinkrate (ft/sec)		Pitch angle (deg.)	
n	γ	ß = 95%	ß = 99%	ß = 95%	ß = 99%	ß = 95%	ß = 99%
40	0.5	46	61	0.23	0.31	0.28	0.37
	10^{-2}	90	119	0.45	0.59	0.54	0.71
1500	0.5	8	10	0.04	0.07	0.05	0.06
	10^{-2}	15	19	0.07	0.10	0.09	0.12

Table 5.1: Inaccuracies due to the sample size

It is thought acceptable to extrapolate by analytical fitting of the data points only when for a touchdown parameter an upper bound for certification is reached. A fit of a probability distribution function for a touchdown parameter may not be statistically significant (and may not meet a statistical test criterion). In that case, and in all other cases, when the the exceedance probability is less marginal, for all practical purposes, the parameter value for 10^{-5} (or 10^{-6}) exceedance probability may also be assessed by extrapolating along a line which is tangent to the exceedance probability curve at its data points near 10^{-2}. The data points near 10^{-2} exceedance probability for a sample size n =1500 have an accurate location on the probability plot. The final (say 10) data points of the exceedance probability plot are within a certain confidence interval, and therefore have uncertainty in their location. A socalled (ß, p) lower limit can be defined, where ß is the statistical confidence that the interval (x_i, ∞) contains at least a fraction p of the population from which the sample is taken. Use is made of the binomial distribution and for the lower bound is:

$$p\left[\int_{x_i}^{\infty} f(x)\,dx \geq p\right] = \sum_{j=i}^{n} \binom{n}{j} (1-p)^{j} p^{n-j} = \beta$$

For sample size n = 1500 and the final data point i = 1499 is the nominal value 1/1500 = $6.7 \cdot 10^{-4}$ and the lower limit is $9.6 \cdot 10^{-5}$ (ß= 99%).
For data point i = 1490 is the nominal value 10/1500 = $6.7 \cdot 10^{-3}$ and the lower limit is $3.2 \cdot 10^{-3}$ (ß = 99%).
The data points near 10^{-2} therefore have a more accurate location on the probability plot. It is therefore recommended to extrapolate the exceedance probability curve by a line which is tangent at its data points near 10^{-2}.

5.2 Desired amendments of the JAR-AWO requirements

The JAR-AWO requirements do no provide directives on all aspects of the analysis. Some critical considerations are:

- The accuracy of the autoland simulation model is not prescribed. There is no means of compliance mentioned with respect to the validation method.

- The JAR-AWO wind model exceedance probabilities of the total wind and three wind components cannot be decomposed into a wind direction distribution and a wind magnitude exceedance probability.
  The wind distributions as prescribed are incompatible with a six degree-of-freedom simulation with windspeed and winddirection as input variables. Either the headwind/tailwind ratio is conservative, or the crosswind distribution will be conservative.

- The structural limit load exceedance probability should be evaluated rather than just the sinkrate exceedance probability. For the Fokker 100 it turned out to be that the sink rate is not a correct parameter for assessing structural loads. Therefore a structural load analysis has been performed with the Monte Carlo touchdown results, such as sinkrate, pitch angle, bank angle, slip angle, lateral velocity and longitudinal velocity, as inputs.

- Both the lateral velocity and the slip angle at touchdown shall be evaluated. They represent structural load cases which shall be evaluated independently.

6. Concluding remarks

To obtain JAA approval for operations with the automatic landing system on the Fokker 100 various tools and methods were developed and applied.
The method for statistical autoland performance certification is based on the Monte Carlo simulation technique, which has been adapted by recognizing three categories of input variables. In absence of adequate certification guidelines, an efficient and practicable validation method was developed to verify the credibility of the simulation model by statistical correlation against a series of flight test results. These flight results were obtained using an accurate trajectory measurement system which combines a forward-looking camera with inertial sensing.
Although the autoland certification requirements of JAR-AWO have been met for the Fokker 100, some recommendations for amendments of the requirements have been made with respect to the simulation inputs, structural load evaluation and simulation validation.

7. References

1. JAR — All Weather Operations
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