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DISCRETE-TIME PILOT MODEL

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SUMMARY

The objective of this paper is to demonstrate the originality of our approach with regards to already existing pilot models and to present recently obtained results.

We consider the pilot's behavior as a discrete-time process where the decision making has a sequential nature. This model contrasts very clearly with previous approaches namely the quasi-linear model which follows from classical control theory and the optimal control model which considers the human operator as a Kalman estimator-predictor. We also consider that the pilot's objective may not be adequately formulated as a quadratic cost functional to be minimized, but rather as a more fuzzy measure of the closeness with which the aircraft follows a reference trajectory.

All model parameters, in the digital program simulating the pilot's behavior, have been successfully compared in terms of standard-deviation and performance with those of professionnal pilots in IFR configuration. The first practical application of our pilot model has been the study of its performance degradation when the aircraft model static margin decreases.

I. INTRODUCTION

Research on human operator models and especially on models of spacecraft, aircraft and helicopter operators has often been influenced by the current state-of-the-art. Before further investigation, the human operator appears as highly adaptative, versatile, complex and sufficiently creative so that we can always recognize in the diversity of all strategies he may use, one we know well and want to find.

The first approach to the problem was from the control specialists of the 1950's, attempting, at the beginning age of servomechanisms, to apply their basic tool, namely the linear transfer function of a phase lead regulator (ref. 1). These studies relied heavily on simulation techniques using analog computers.

One of the most-commonly accepted representations is the quasi-linear model of McRuer (ref. 2, 3, 4) so named because it represents the human operator by a linear transfer function, plus a remnant to describe that part of the human response that is not predicted by the linear approximation. The transfer function is essentially the result of an approximation to the first harmonic and the remnant accounts for higher-order effects and for other modeling errors. The most celebrated result from the above study is probably the "cross over model" which is based on the fact that the human operator adjusts the parameters of his own transfer function so that his open-loop response satisfies the closed-loop stability conditions with a reasonable error.

At the same time sampled-data models have been proposed (ref. 5). This type of models is suitable for numerical computation on digital computers. However, the assumption of fixed-rate sampling appears as a weakness of this representation.

An alternative to the quasi-linear model has been developed by Kleinman, Baron and

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Levison (ref. 6, 7, 8). This approach is based on advanced optimal control and estimation theory with the assumption that the well-trained human controller behaves in an optimal manner subject to his inherent limitations and contraints and the requirement of his task. However, is the human operator only a Kalman estimator whose objective may be formulated as the minimization of a given criterion ?

These modeling studies have advanced a great step forward when becoming interdisciplinary through the involvement of psychologists in the research teams. These scientists can probably be credited for the introduction of the concept of operating image (ref. 9, 10, 11, 12) which is an internal model of the vehicle allowing the human operator to predict its short-term response. The conventional approach and the purely psychological one are currently merging (ref. 13). Without repudiating previous philosophies, our current approach tries to make a synthesis of them and develop the model of a human operator based on a new and more accurate analysis of the aircraft pilot's behavior (ref. 14, 15, 16, 17).

II. ANALYSIS OF THE PILOT'S BEHAVIOR

Consider the behavior of the human operator in the case of aircraft control.

The aircraft position as sensed by the pilot from his instrument dials or outer sight is compared to the attitude required to follow the nominal flight path. As an example, if the horizontal bar of the ILS indicator lies above the central mark, the pilot analyzes this situation and selects the appropriate correction maneuver to carry out. Once the maneuver has been selected, the pilot's brain (i.e. the decision center) request from the eyes through an internal loop (fig. 1), to collect information relating to the longitudinal attitude. The difference between the actual attitude and the desired one is analyzed and the pilot selects the right control to actuate and determines the force to apply to it. In this example, the pilot pulls on the control stick with a force he judges as correct while requesting his arm, through another loop, to sense the applied force. Stick motion is stopped when the pilot feels that the desired force has been applied.

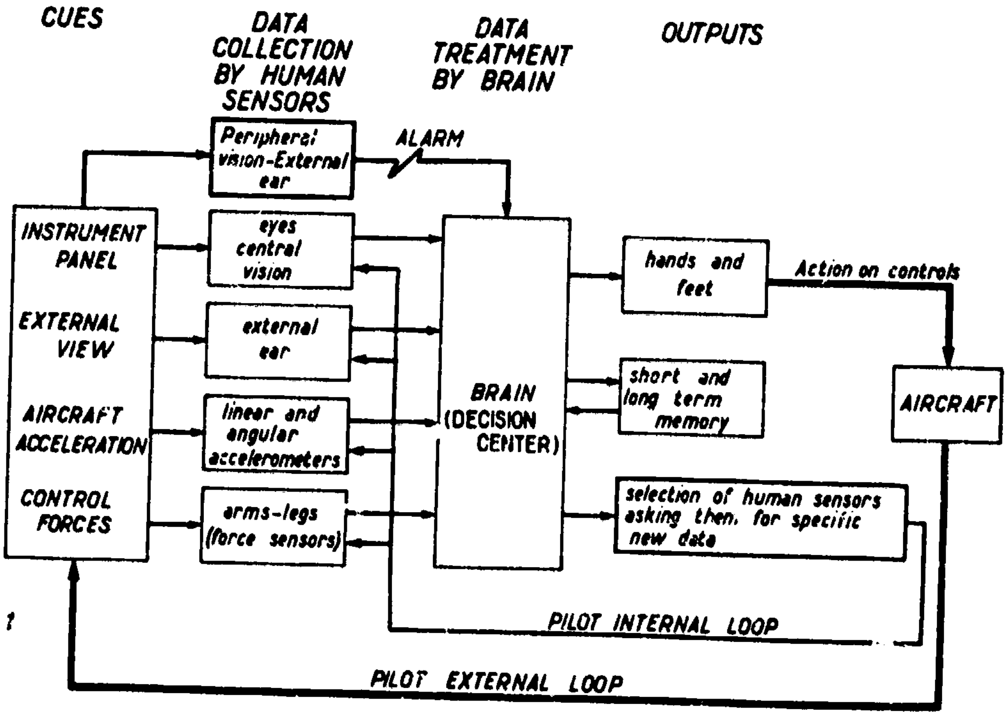

Fig. 1

Hence, the decision center (the brain) puts successively into action various loops while asking for further information from the human sensor. Three types of loops may be considered (fig. 2),

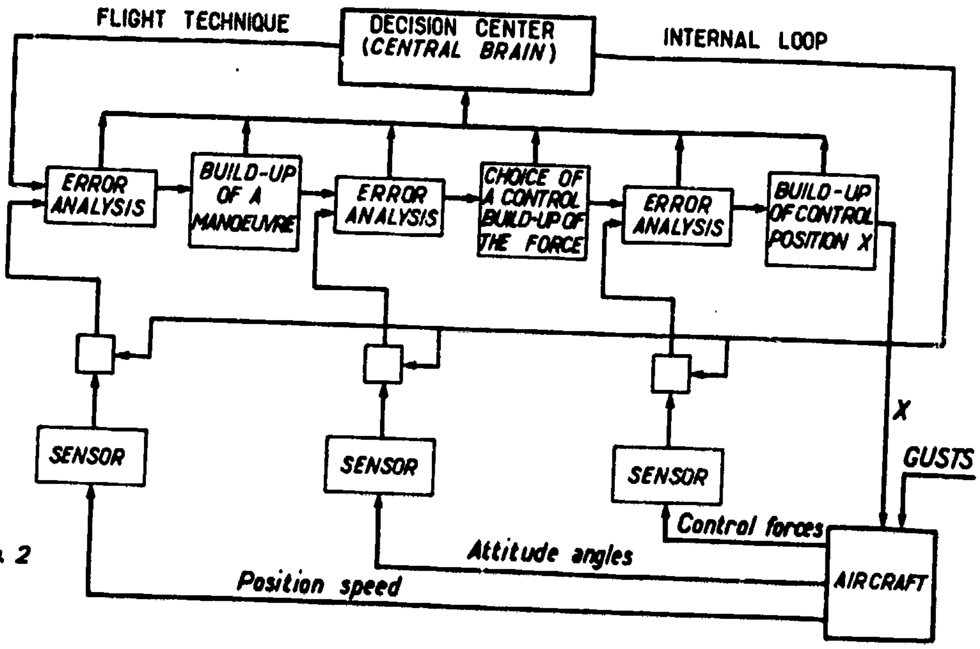

Fig. 2

– outer loops controlling the parameters related to the short-term safety, i.e. flight path, position and speed,

– loops controlling the parameters related to the immediate safety, i.e. the attitude angles, angle of attack, etc .... ,

– finally, the inner loops controlling the forces applied to the controls.

It should be noted that there is *only a single loop* in operation at a given time and this is one of the most fundamental differences between a human pilot and an autopilot. The selection of the currently operating loop is made by the decision center (brain) which designates the selected sensor to collect and transmit the necessary information through an internal loop (fig. 1).

An immediate consequence of this analysis is that it is impossible to determine directly the pilot's workload : at the present time, it seems virtually impossible to follow in detail the processing of data taking place within the brain.

Another consequence is that it is useless to determine experimentally a transfer function representing the pilot's behavior since there is not one, however complex, but a series of transfer functions used sequentially in an order determined by scanning of the various displays. This scanning itself depends on certain data, the environment, the pilot's training, etc... , that is partially on random phenomena. This random nature must be accounted for into some part of the pilot's behavior model.

III. RESPECT OF THE CONTROL LAW

The control law, which is the keeping of permissible deviations of the controlled parameters with respect to the nominal flight path, ensures the immediate safety as well as the short-term safety. This law is used by the pilot as a guideline, it depends on the objective set by the pilot and on his ability to adapt himself to the conditions of the flight phase execution.

First, the objective set by the pilot may not be formulated in the form of a criterion to be minimized (as proposed by Kleinman, Baron and Levison (ref. 6, 7, 8)). The pilot is neither a perfect being, nor a well-trained monkey who as it is well known, does a better work than a human operator when his task is that of a robot. The human brain can collect a great number of quantitative and qualitative data, some of them being only sensations. The brain is able to built a model of the situation, to compare it with typical situations held in memory, and decide upon an action even if the case has not been foreseen. Then, the objective is much fuzzier : it consists on controlling the plane to reference flight path as close as possible to the nominal flight path. This reference corresponds to the pilot's learning and his know ledge of the plane.

The pilot possesses rather remarkable capabilities of adaptation which are evidenced by the nature of his control commands. An interpretation of this adaptability is the concept of operating image or internal model. The pilot possesses a probably very simplified model of the aircraft which permits him to predict its short-term response given his previous actions.

This concept of internal model permit us to account for the predictive nature of a human pilot's control, as opposed to conventional autopilots.

IV. CHOICE OF A MULTILOOP SEQUENTIAL MODEL

Taking into account the above considerations, a mathematical model must satisfy the following conditions to be as close as possible to the human pilot's behavior (ref. 15).

a) The elementary activities of data collection, development of correction procedures and actuation of controls occur sequencially and not simultaneously as in continuous type models.

b) The various control loops must be identified according to the type of aircraft as well as the nature and number of observed parameters. The type of each loop must be defined, namely as flight path loop relating to short-term safety, attitude loop relating to immediate safety, or loop relating to the control action (see fig. 2).

c) The instants of time when the various loops are activated are not defined in a deterministic manner but are partially random (Poisson process). *Only a single loop* can be in operation at a given time and the pilot applies rules based on his proficiency and personal experience from one loop to another or to monitor the instrument panel. These rules are not strict and depend on the pilot's judgment. Definition of a precise model for the process of selecting among the various loops is one of the most difficult problems to solve and is fully ignored in single loop models.

d) The model must be conceived in such a way that its various characteristic parameters be adjustable from one model of aircraft to another within a given type of aircraft. Obviously, the model for a Mach-2 fighter is necessarily different from that of a conventional subsonic aircraft.

e) Finally, the model must provide a good evaluation of the pilot's workload.

Research on such a multiloop model called "discrete-time model" because of its sequential nature, has been carried out in France, at ONERA (Office National d'Etudes et de Recherches Aérospatiales – French National Aerospace Agency) since 1973. These studies (ref. 16, 17) have led to the development of a computer program simulating the behavior of a pilot of a heavy transport plane (Airbus A300B) and capable to perform a particular flight path (final descent of an ILS approach). The model will soon be extended to make it adapt to various aircrafts of the same type (this version is currently being tested with a model of the Dassault Falcon 20).

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V. DESCRIPTION OF THE DISCRETE-TIME PILOT MODEL

In this model, it is assumed that, at a given time, the pilot can either make a decision or carry out one of the following three elementary actions :

– actuate a control,
– read an information on the instrument panel,
– monitor a given parameter displayed on a dial.

It is assumed that the pilot's strategy, that is the process of selecting among the various procedures of parameter correction, has a sequential nature and is a function of the flight situation defined by the aircraft type and condition, the flight phase and atmospheric conditions.

Experimental data have led to distinguish between three levels of activity in the pilot's operating mode (fig. 3). This classification is only an assumption, but seems to be close to reality and corresponds to the three types of loops discussed above.

LEVEL	*DEFINITION*	*OBJECTIVE*	*COST*
STRATEGY	*Choice of correction procedures*	*Short - term safety*	*Mental load (decision)*
CORRECTION PROCEDURE	*Algorithmic sequence of elementary actions*	*Immediate safety*	*Mental load (memorization)*
ELEMENTARY ACTION	• *Read indicator* • *Act on one control* • *Monitor one dial*		*Physical load*

Fig. 3 – Levels in operating mode.

The model selects the correction procedure to be used as a function of the followed strategy. This procedure is further divided into a sequence of elementary actions (instrument reading, monitoring of a parameter, action on a control) which are successively taken.

A dual integration is performed at each time in the model, namely the integration of the equations of motion and the integration of the equations describing the operating image of the situation as memorized by the model.

In the proposed strategy, care has been exercised to make a clear distinction between the selection of dials monitoring (a strategy with Markovian readings is used) and the selection of parameter correction procedures (a strategy with short term evaluation is used). The differenciation between these two strategies is based on the concept of seriousness of the instantaneous situation as perceived by the pilot's model and defined by :

$$G(O) = \underset{\substack{\text{on the main}\\ \text{parameters}}}{\text{Max.}} \left| \frac{\text{estimated deviation}}{\text{permissible deviation}} \right|$$

This is the maximum ratio, over the flight path main parameters, between the estimated deviation (as memorized or predicted by the internal model) of a given parameter and its permissible deviation. The permissible deviations are determined experimentally. If $G(O)$ is under a given minimum threshold of seriousness, the situation is evaluated as safe and the model adopts the dial monitoring strategy ; if $G(O)$ is above his threshold, the situation is evaluated as serious and the model applies the strategy of parameter correction procedures (fig. 4).

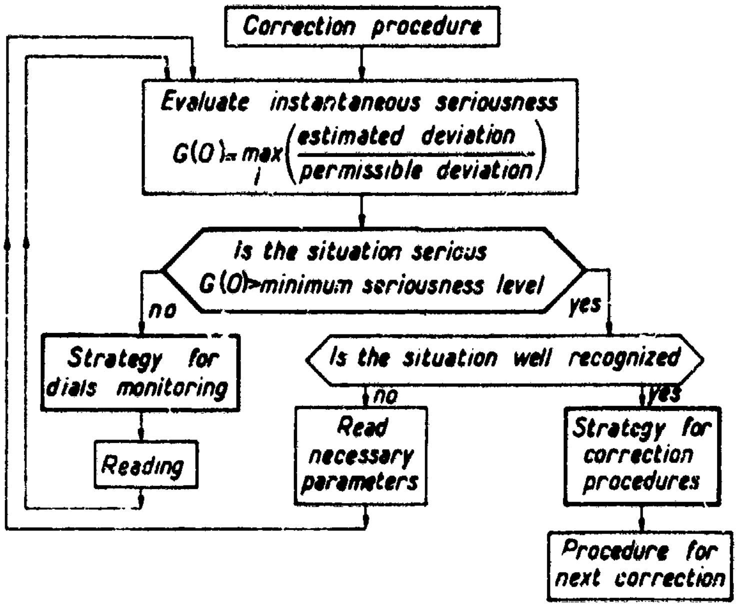

Fig. 4 – Overall strategy.

As far as the strategy of dials monitoring is concerned, the sequence of observed dials is governed by a matrix of conditional probabilities of reading each instrument after another one. This matrix is called "switching matrix". After each instrument reading, the value of a random variable determines which dial will be read next, depending on the switching matrix. The sequence of reading times is regarded as a Poisson process. Figure 5 gives an example of switching matrix in the case of the ILS approach phase of an Airbus A-300B. This matrix has been determined experimentally by means of an electro-oculometer. In retrospect, were observed in this matrix the features of elementary monitoring rules during IFR flight. For instance, the artificial horizon was mostly observed.

SWITCHING MATRIX

	εGL	εLOC	i	Φ	Θ	Ψ	F	z	V
εGL	0.03	0.10	0.11	0.04	0.15	0.03	0.06	0.21	0.20
εLOC	0.28	0.15	0.05	0.21	0.06	0.23	0.05	0.05	0.08
i	0	0.03	0.06	0.07	0.1[illegible]	0.05	0.06	0.11	0
Φ	0.10	0.39	0.12	0.29	0.18	0.28	0.17	0.09	0.10
Θ	0.40	0.14	0.20	0.16	0.29	0.13	0.19	0.21	0.18
Ψ	0.08	0.12	0.16	0.13	0.13	0.10	0	0.16	0.07
F	0	0.01	0.10	0.01	0	0.05	0.11	0	0.09
	0.03	0.04	0.13	0.07	0.07	0.11	0.12	0.12	0.08
V	0.08	0.02	0.07	0.0[illegible]	0.02	0.02	0.24	0.05	0.20
Σ	=1	=1	=1	=1	=1	=1	=1	=1	=1

MATRIX OBTAINED WITH EOM EQUIPMENT

- ALL PARAMETERS $x_i < L_i$ → INSTRUMENT READINGS ARE GOVERNED BY THE SWITCHING MATRIX
- ONE PARAMETER $x_i \geq L_i$ → READING OF x_i
- SEVERAL PARAMETERS $x_i \geq L_i$ → READING OF x WHICH HAS THE GREATEST PROBABILITY IN THE SWITCHING MATRIX

L_i LEVEL GIVEN IN ADVANCE FOR EACH PARAMETER x_i

Fig. 5 – Strategy for dials monitoring.

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The strategy of the correction procedures is based on the fact that the human pilot makes decisions depending on the short-term predicted evolution of the situation while taking into account all previous actions.

The model has no access to the equations governing the aircraft dynamics but, by using its operating image, it can predict approximately the short-term situation. This prediction capability is used by the model to select the best correction procedure to implement, each time it is necessary. This choice is made by developping a logical tree (fig. 6) in which,

- the root is the memorized situation (So) ;
- branches are the correction procedures whose implementation is considered ;
- nodes other than the root are situation predicted from the root by means of the operating image while taking into account the intented correction procedures.

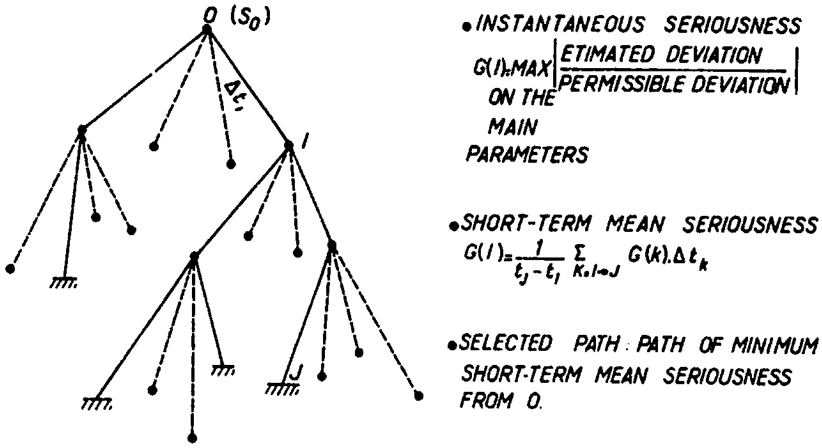


Fig. 6 – Strategy for correction procedures.

The instantaneous seriousness G(K) is computed at each node K. Considering that it remains constant during the time ΔtI elapsed from the previous node to the node I, the model computes a short-term mean seriousness $G(I)$ on each path leading to a terminal node. To that end, the instantaneous seriousness is weighted by the time elapsed on each branch and the result is divided by the total time elapsed on the path. The short-term mean seriousness of a path (I, J) is then expressed by

$$G([I,\ J]) = \frac{1}{t_J - t_I} \sum_{K = I \rightarrow J} G(K) \cdot \Delta tk$$

The mean seriousness of the best path $G([I,\ J])$ chosen at I is denoted $G(I)$. This choice is simply made by taking among all possible paths from I the one with the minimum mean seriousness.

The path from the root with the minimum mean seriousness is then chosen and the implementation of the correction procedure corresponding to its first branch can be initiated.

VI. PROGRAM APPLICATIONS

Two applications have been made to validate this program. Both apply to the simulation of the final descent of the ILS approach phase for an Airbus A-300B. First, a statistical comparison has been made between the performances of the model and those of professionnal pilots. Secondly, the performance loss of the model when the static margin of the simulated aircraft is decreased has been investigated.

VI,1. Comparison between the model and professionnal pilots

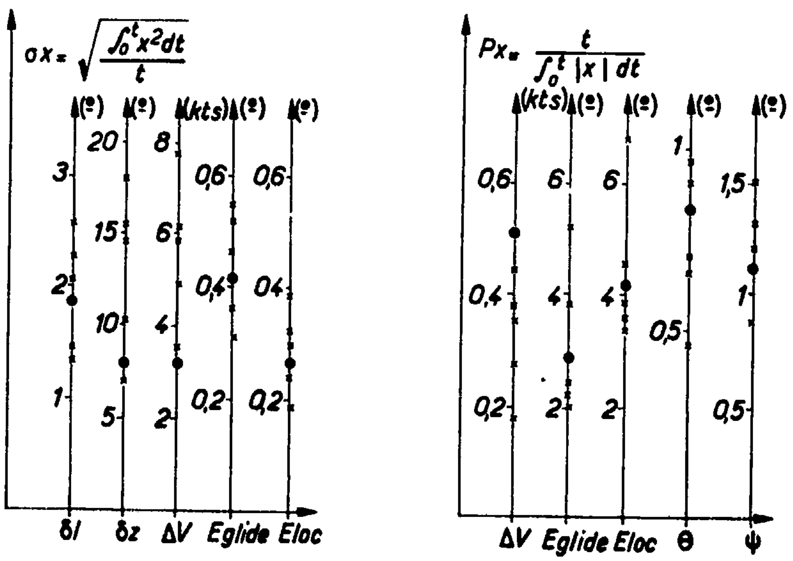
It is meaningless to compare the time responses obtained from the model and from human pilots. As good as it may be, the match between the curves cannot be perfect. A statistical comparison would be more meaningful. We have therefore chosen a comparison between the standard deviation and the performance, which are defined below for the various flight parameters.

$$\text{Standard deviation } \sigma x = \sqrt{\frac{\int_0^t x^2\,dt}{t}}$$

$$\text{Performance } \quad Px = \sqrt{\frac{t}{\int_0^t |x|\,dt}}$$

where t is the duration of the final descent of the ILS approach phase.

The results from the model have been compared to those of five professionnal pilots performing final descents in IFR conditions on a flight simulator representing the heavy transport plane considered in this study. The comparison is illustrated in figure 7 ; it can be seen that the model exhibits a behavior close to the pilot's as far as the above defined standard deviations and performances are concerned.



Model-pilot initial deviations at 1900 feet

x human pilot

● model

Localizer deviation : – 0,6°
Glide path deviation : 0,65°
ΔV = + 8 kts (Va = 137 kts)

Fig. 7 – Standard-deviations and performances.

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VI,2. Application of the model to flight control with reduced static margin

One of the first practical applications of the model has been the study of its performance loss when the static margin of the simulated aircraft decreases, i.e. when the center of gravity moves backward, progressively destabilizing the plane. It appears that the performance of the model decreases when the static margin is reduced, which seems realistic. The loss of control occurs suddenly (fig. 8) when the workload resulting from a decrease in static margin becomes excessive. The most interesting result of this study is that, whenever control difficulties appear on the pitch axis, the overall aircraft control is impaired ; for most of the cases losses of control occur on the transversal axis.

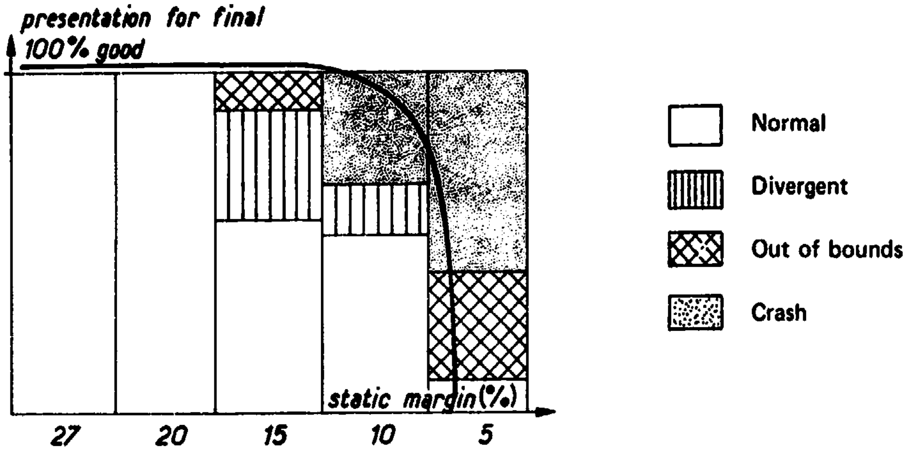

Fig. 8 – Basic ILS approaches with reduced static margins.

VII. CONCLUSION

The model described in this paper is expected to be more conform to the actual pilot's behavior than those of previous studies. It tries to make a synthesis between the mathematical approach and the psychological approach through the introduction of the aircraft internal model.

In the future, studies will attempt to introduce the concept of pilot adaptativity to a new type of aircraft as well as the concept of learning which could take into account the degree of professionnal development of individual pilots.

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