FEASIBILITY ANALYSIS OF ACHIEVING A STABILIZED APPROACH

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Abstract

Stabilized approaches and adhering to standard operating procedures (SOPs) improve safety in approach-and-landing flight operations. This paper describes the development of a computer simulation program that aims to predict whether a newly designed approach trajectory satisfies these constraints. Ultimately, the computer simulation is intended as an additional tool during the design of novel approach trajectories.

1 Introduction: A method to predict the difficulty of approaches

The Flight Safety Foundation Approach-and-Landing Accident Reduction (FSF ALAR) Task Force [1] has performed comprehensive research with respect to Approach and Landing Accident Reduction. Approach-and-landing phase accidents account for a significant proportion of air transport accidents. Approximately 59 percent of the world jet-fleet accidents to date occurred in these flight phases and accounted for 29 percent of all fatalities [2]. The most frequent causal factors are all related to crew performance. These statistics emphasize the need to understand which factors complicate an approach for a flight crew and which factors in an approach increase the chance of accidents.

Additionally, a phenomenal growth in the air transport industry is expected, with forecasts indicating that air traffic movements in Europe will more than double by 2015, compared with those for 1997 [3]. These extra movements are likely to create extra congestion and delays, and mean that there is an ever-growing pressure to upgrade the capacity of the overall system. Part of the solution is the design of new approach trajectories, possibly including curved approaches, the use of higher approach altitudes, continuous descent approaches et cetera. Before these new approaches can be introduced it is mandatory to understand their impact on the difficulty as experienced by the crew.

The current tests that are performed to check the feasibility of a newly designed approach do not include comprehensive tests which establish the level of difficulty for the pilot. As long as minor changes to existing approaches are considered, these tests are sufficient. However, with the large modifications in approach trajectories envisaged in the near future, combined with the fact that currently most accidents during the approach and landing phase are attributed to crew-related factors, it helps to have a method to predict the difficulty as experienced by the pilot. First, this would yield insight in how certain aspects of an approach actually influence the difficulty as experienced by the pilot. And second, during the design of approaches this method can then be used to rapidly evaluate a potential approach and to 'optimize' an approach with respect to the difficulty experienced by the pilot even before the approach is tested by flight crews in flight simulators.

2. Brief outline of envisaged method

This paper presents the first step towards a method to predict the difficulty of flying an approach. The final method should predict how 'busy' the pilot is when flying a published approach according to standard operating

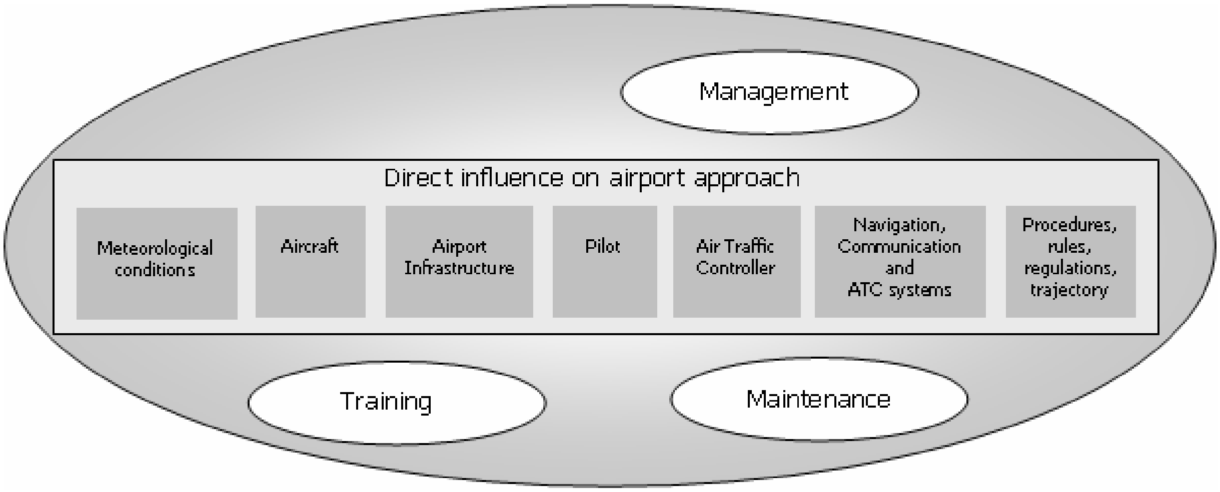


Fig. 1 Factors that influence an approach

procedures, with the constraint that the approach should be stabilized at 1,000 ft (using autopilots, autothrottle and flight management system). It should e.g. predict what the percentage of time is the pilot is performing actions, how large the 'margins in time' are for these actions etc. The goal is to link the difficulty of flying the approach first of all to the properties of the approach *trajectory*, in other words: to find out which elements of the approach trajectory (e.g., the number of legs, the amount of combined deceleration and descent, number of turns, etc.) are an important factor in the increase (or decrease) of the difficulty of flying the approach. Second to the properties of the approach trajectory the influence of other factors (such as wind conditions, aircraft weight etc.) are also considered.

3. Basic principles of the method

The goal of the research is to develop a computer simulation with which (new) airport approaches can be simulated and which will predict the level of difficulty of flying the approach experienced by the pilot. This section will explain the basic principles of the method, the assumptions and the choices that have been made as to what is, and what is not incorporated in the scope of this research.

3.1 Factors of the air transport system included

The difficulty of flying an approach depends on many different factors and the interactions between those factors. Examples of factors that influence an approach directly are meteorological conditions, the aircraft, the airport infrastructure, technical systems, procedures, rules, regulations, trajectory and last but not least the human operators: the pilot and air traffic controllers (see Fig.1). Examples of factors that influence an approach in an indirect way are management, training and maintenance.

This research concentrates on the "pilot" box in Fig.1. It will e.g. not consider the difficulty of an approach from the Air Traffic Controller's perspective. Additionally, to determine the difficulty experienced by the pilot, this research will only take into account the factors that have a direct influence on an approach (see Fig. 1), and will concentrate on the influence of the approach trajectory.

3.2 Difficulty in terms of Task Demand Load

There are many ways to express the difficulty of performing a certain task. Therefore, to formulate more accurately, this research aims to develop a method to quantify the pilot's Task Demand Load (TDL) of conducting an approach. Task demand load is defined as the mental workload imposed by the system to be controlled or supervised [4].

3.3 Boundary conditions: Stabilized approach and Standard Operating Procedures

Obviously, the TDL depends directly on the boundary conditions that are set, e.g. the accuracy with which the approach needs to be flown. The boundary conditions chosen for this research are that the approach should be a stabilized approach and should be performed according to Standard Operating Procedures. This decision is based on the conclusions of the ALAR Task Force [1] with respect to improving safety in approach-and-landing flight operations. One of these conclusions reads: "*Establishing and adhering to adequate standard operating procedures (SOPs) and flight-crew decision making processes improve approach-and-landing safety*". Additionally, the ALAR Task Force concluded that "*Unstabilized and rushed approaches contribute to approach-and-landing accidents*". Therefore, in order to fly an approach as safely as possible, the pilot should be able to conduct the approach stabilized and according to the SOPs.

The ALAR Task Force defined nine criteria that should be met at 1,000 feet above airport elevation (in Instrument Meteorological Conditions) for a stabilized approach [1]:

1. The aircraft is on the correct flight path;
2. Only small changes in heading/pitch are required to maintain the correct flight path
3. The aircraft speed is not more than V_{REF} + 20 knots Indicated Airspeed (IAS) and not less than V_{REF};
4. The aircraft is in the correct landing configuration;
5. Sink rate is no greater than 1,000 feet per minute; if an approach requires a sink rate greater than 1,000 feet per minute, a special briefing should be conducted;
6. Power setting is appropriate for the aircraft configuration and is not below the minimum power for approach as defined by the aircraft operating manual;
7. All briefings and checklists have been conducted;
8. Specific types of approaches are stabilized if they also fulfill the following: instrument landing system (ILS) approaches must be flown within one dot of the glide slope and localizer; a Category II or Category III ILS approach must be flown within the expanded localizer band; during a circling approach, wings should be level on final when the aircraft reaches 300 feet above airport elevation; and
9. Unique approach procedures or abnormal conditions requiring a deviation from the above elements of a stabilized approach require a special briefing.

The boundary condition for each approach that is evaluated within this research is that it meets these criteria for a stabilized approach plus the requirement that the approach must be conducted according to SOPs.

3.4 Approaches considered and automation used

This research focuses on Area Navigation (RNAV) Approaches. Although it is understood that non-precision approaches are, in general, more difficult for a pilot to fly than RNAV (precision) approaches, a deliberate choice is made to focus on RNAV approaches since these are expected to become more and more frequently used in the future.

The section of the approach that is concerned starts at the initial approach fix (IAF), and ends 1,000 ft above airport elevation. Based on interviews with pilots this section is in itself divided into two parts: the first part of the approach is flown using the Flight Management System (FMS), *autopilots* and autothrottle. The second part of the approach (starting at localizer intercept heading but before localizer capture) is flown using the FMS, *flight director* and autothrottle, which implies manual control by the pilot in the second part.

3.5 Non-nominal conditions and emergencies

Non-nominal conditions and emergencies such as engine failure are not considered in this research. The goal is to determine the TDL for published RNAV approaches under nominal conditions. When emergencies such as engine failure occur, the crew will most likely not be required to follow the RNAV approach anyway, but will be vectored to the runway in the most convenient way.

Additionally, the assumption for less severe non-nominal situations is that when flying under nominal conditions, the RNAV approach should provide enough 'margin' with respect to pilot TDL, such that the pilot has enough spare capacity and time to deal with non-nominal conditions. This implies that the TDL that is predicted by this research for nominal conditions should be well below the absolute maximum TDL a pilot can cope with in order to provide this margin.

3.6 Level of detail of computer simulation models

An obvious and frequently used method to determine TDL in general is what is referred to as "human performance modeling", where one attempts to construct a detailed model of the human operator (in this case the pilot) including all his/her limitations, both physically and mentally. These human operator models, however, easily become very complex, involving many variables that need to be 'tuned' and as a consequence they do not allow useful predictions to be made about situations that are beyond the conditions in which the models have been validated. Here a different approach is chosen, that is based on the principles of the 'cognitive work analysis' [5]. The main characteristic of cognitive work analysis is that it shifts the emphasis from investigating the constraints of the human operator (like memory capacity, time delay, etc.) to analyzing and describing the operator's *environment*.

The reason for this choice is that the constraints in the environment actually 'shape' the behavior of the human working in that environment. When one is investigating this behavior, and putting this behavior in a mathematical model, which is the classical approach as mentioned above, one is in fact modeling the 'consequences' of the environmental constraints on the ever-adapting human operator.

Therefore, within this research the environment of the pilot (i.e., the aircraft with its kinematic and dynamic constraints, the 3-D properties of the trajectory, the velocity profile, turbulence, wind, etc. In other words: the factors that have a direct influence on an approach as given in Fig. 1 are modeled as detailed and accurate as possible. Whereas the pilot model is kept as simple as possible: since the aim is not to replicate the exact actions of the pilot as they are performed in real flight, but only to obtain an "on average" indication of "how hard" pilots have to work. This simple pilot model is then used to understand how the environmental constraints affect the pilot TDL during an RNAV approach.

4. Focus of this paper

To arrive at the goal of predicting pilot TDL during an RNAV approach the research is split into two parts: the first step is to determine whether it is at all possible to fly the approach stabilized and according to the SOPs, and, if this is possible, the second step will be to determine the TDL the pilot experiences when flying according to SOPs and stabilized. The result of the research will thus be a quantitative indication of how the TDL evolves during the approach as a function of time, given a certain aircraft, given an approach trajectory and given the meteorological conditions (the direct factors in Fig. 1).

This paper will focus on the 'first step': to determine whether it is possible to fly the approach stabilized and according to the SOPs. The ultimate goal of this first step is to determine which elements of the approach *trajectory* (e.g., the number of legs, the amount of combined deceleration and descent, etc.) influence the possibility of achieving a stabilized approach. Additionally, and second to the properties of the approach trajectory, we will consider the effects of aircraft weight, center of gravity location and wind. This paper, however, presents a ‘proof of concept’ of the proposed method and therefore focuses on the question whether it is at all possible to use this method to predict the possibility of achieving a stabilized approach. Therefore the paper does not yet analyze the properties of the different approach trajectories. Rather, it determines for a given trajectory, still without indicating what the exact factors are that make the approach difficult (or easy), the probability of achieving a stabilized approach for that trajectory as a function of aircraft weight, center of gravity location and wind.

5. Computer simulation

A computer simulation has been developed based on the basic principles and assumptions as explained in the previous section. When a newly designed approach (consisting of waypoints, altitude profiles and speed profiles) is entered into the computer simulation, the simulation predicts whether that particular approach can be flown stabilized and according to SOPs.

This section will briefly describe the aircraft model and pilot model that are used for the computer simulation. Then, an RNAV approach is described that will serve as a test case for the computer simulation. Using Monte Carlo simulation the RNAV approach will be analyzed w.r.t. the feasibility of achieving a stabilized approach. The variables chosen for this Monte Carlo simulation are also explained in this section.

5.1 Aircraft model and pilot model

The non-linear aircraft model used in the computer simulation is a Boeing 747-200, based on the documentation by Rodney and Hanke [6] and is modeled as detailed as possible. Autopilot, autothrottle and flight director models are also derived from [6].

To these highly detailed, non-linear models a relatively simple pilot manual control model for the flight director task is added, consisting of only a time delay (equal to 0.35 seconds) and pure gain (for now chosen equal to one for both pitch and roll), [7].

5.2 Test case: an RNAV approach

The RNAV approach that is to be evaluated by the computer simulation is defined by entering a list of subsequent waypoints (defined by name or lat-lon coordinates) with required altitude and Calibrated Airspeed (CAS) at each waypoint. As an example see the table in Fig. 2. In this figure the reference speed (V_{REF}) is used, which is defined as 1.3 times the stall speed. For this paper, as a first check on the feasibility of the computer simulation, the RNAV approach to be evaluated is based on an existing RNAV approach. The approach is specified as given in Fig. 2.

During the oral presentation at the conference a second RNAV approach will be presented, which is fictitious and designed such that it will result in many unstabilized approaches.

	Altitude [ft]	CAS [knots]
WP1	7000	220
WP2	7000	220
WP3	7000	220
WP4	4000	220
WP5	4000	180
WP6	2900	180
WP7	2000	$V_{REF} + 10$
WP8	Glide slope	$V_{REF} + 10$
RWY06	Glide slope	x

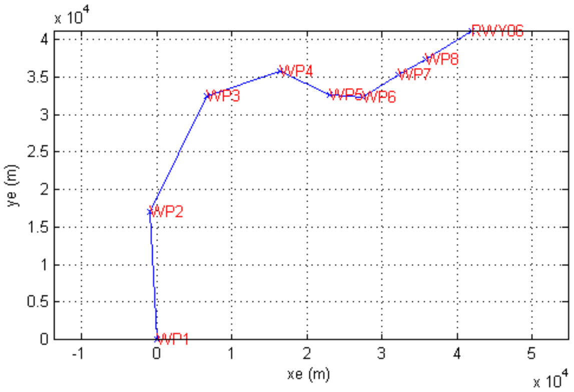
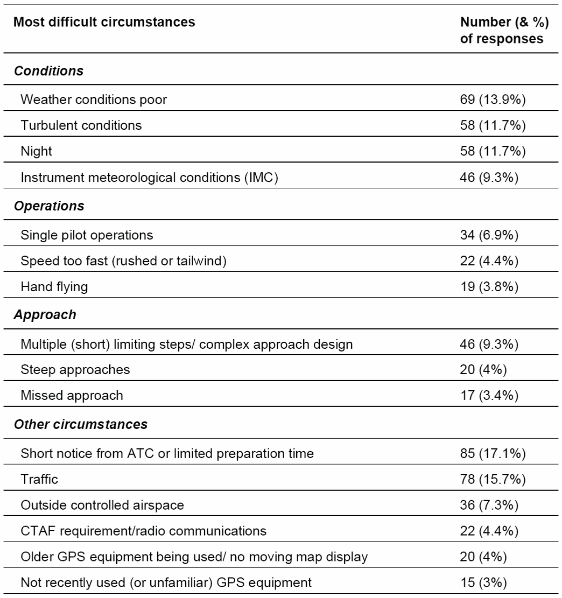


Fig. 2: RNAV approach

5.3 Monte Carlo simulation

The computer simulation predicts the probability of achieving a stabilized approach according to SOPs for the RNAV approach by using Monte Carlo simulation. The variables chosen for the Monte Carlo simulation are a first estimate of variables that are important and are largely based on common sense, although they have been checked against [8]. In [8] a

Table 1: Most difficult circumstances for an RNAV approach.



Most difficult circumstances	Number (& %) of responses
Conditions	
Weather conditions poor	69 (13.9%)
Turbulent conditions	58 (11.7%)
Night	58 (11.7%)
Instrument meteorological conditions (IMC)	46 (9.3%)
Operations	
Single pilot operations	34 (6.9%)
Speed too fast (rushed or tailwind)	22 (4.4%)
Hand flying	19 (3.8%)
Approach	
Multiple (short) limiting steps/ complex approach design	46 (9.3%)
Steep approaches	20 (4%)
Missed approach	17 (3.4%)
Other circumstances	
Short notice from ATC or limited preparation time	85 (17.1%)
Traffic	78 (15.7%)
Outside controlled airspace	36 (7.3%)
CTAF requirement/radio communications	22 (4.4%)
Older GPS equipment being used/ no moving map display	20 (4%)
Not recently used (or unfamiliar) GPS equipment	15 (3%)

table is presented with the most difficult circumstances for an RNAV approach (repeated here in Table 1).

5.3.1 Variables

The variables that will be analyzed w.r.t. their influence on whether or not a stabilized approach according to SOPs can be achieved for a *given* RNAV approach are aircraft weight, center of gravity (cg) location, wind speed and wind direction. Although aircraft weight and cg location are not mentioned in Table 1 it is assumed that they will have an influence. Wind speed and wind direction are mentioned in Table 1 as 'tailwind'. The values chosen for the variables are given in Table 2 (in which mac = mean aerodynamic chord). For now, wind speed is chosen to be constant with altitude. It is noted that the highest weight (650,000 lbs) used in the simulation is higher than the maximum landing weight, and therefore not realistic. However, it serves very well to investigate the effects of aircraft weight on achieving a stabilized approach.

Table 2: Values of variables.

Weight	400,000 lbs	525,000 lbs	650,000 lbs
CG location	0.22 mac	0.25 mac	0.28 mac
Wind speed	Weibull distribution $\lambda = 12.5$ kts, $k = 2.0$		
Wind direction	Normal distribution μ = runway heading $\sigma^2 = 900\ \text{deg}^2$		

5.3.2 Random variables

Variables which are *not* analyzed w.r.t. their influence on whether or not a stabilized approach according to SOPs can be achieved, but are varied within the Monte Carlo simulation to replicate variation in normal operating conditions are flap select speeds, the timing of the switch from autopilot to flight director and finally, turbulence. The latter two of these are also mentioned in Table 1 as 'Hand flying' and 'Turbulent conditions', respectively.

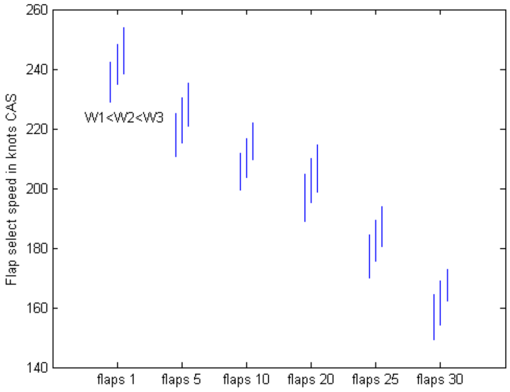


Fig. 3 Ranges of flap select speeds depending on aircraft weight (W1 = 400,000 lbs, W2 = 525,000 lbs, W3 = 650,000 lbs).

Selection of flaps (for now) only depends on whether the aircraft has decelerated to a predetermined flap select speed. It does not yet depend on a certain position in the approach. Although this is not realistic it suffices for the purpose of this paper: a proof of concept of the proposed method. The variation of the flap select speeds is chosen based on the available B747-200 documentation [6]. It is assumed that flaps are selected *at* these flap select speeds or at lower speeds, modeled by a constant minus a Weibull distribution. Selection at lower speeds simulates that the pilot does not immediately notice that flap select speed has been reached and reacts later (at lower speeds). It is assumed that flaps are never selected at speeds higher than flap select speeds. These assumptions result in the ranges of flap select speeds as given in Fig. 3.

The switch from autopilot flight to manual control based on flight director is varied in time, but is always achieved after the aircraft has reached localizer intercept heading and always before localizer capture.

Turbulence is modeled according to the Dryden spectra [9], the longitudinal scale (L_g) is fixed in the simulation at 300 m whereas the turbulence intensity (σ) is varied (Weibull distribution, $\lambda = 2$ m/s, $k = 2$).

5.3.3 Constants

Finally, there are, at the moment, two constants incorporated in the computer simulation. First, gear down is always selected at glide slope capture. And second, spoilers are not used. This choice is made since, generally, pilots try to avoid the use of spoilers, and therefore spoilers are not considered as part of the SOPs.

6. Computer simulation Results

As a first proof of concept a Monte Carlo simulation consisting of 9,000 runs has been performed for the RNAV approach. Fig. 4 gives an indication of the 3D trajectories.

To determine whether an approach is stabilized the criteria from paragraph 2.3 have been quantified as follows:

1. Heading change and pitch change are within 5 deg/s
2. The Calibrated Airspeed (CAS) is not more than V_{REF} + 20 knots and not less than V_{REF};
3. Flaps are at 30 degrees, landing gear is down;
4. Sink rate is not larger than 1,000 feet per minute;
5. Localizer and glide slope are within one dot;

These criteria are evaluated at 1000 ft above airport elevation. An average value is calculated for each of the criteria, for the time slot starting 5 seconds before reaching 1000 ft and ending at 1000 ft. A larger time slot is taken to calculate the average sink rate, since this criterium does not directly refer to the 1000 ft point in itself, but refers to the approach. The time slot chosen to calculate the sink rate starts 1 minute before reaching 1000 ft, and ends at 1000 ft.

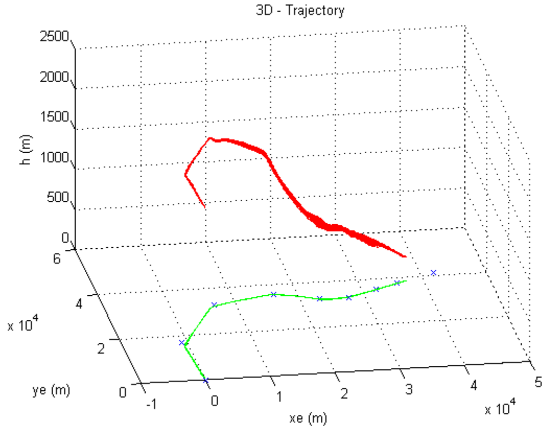


Fig. 4 Selection of 3D-trajectories resulting from Monte Carlo simulation

Table 3: Percentage of unstabilized approaches as a function of aircraft weight and center of gravity location.

		CG location		
		0.22 mac	0.25 mac	0.28 mac
Weight	400,000lbs	2.5%	3.2%	2.2%
	525,000lbs	0.1%	0.3%	0.1%
	650,000lbs	0%	0%	0%

The results for RNAV approach 1 are shown in Fig. 5 and are summarized in Table 3. The results do not seem to depend on center of gravity location, wind speed or wind direction. They do, however, vary with aircraft weight. The highest percentage of unstabilized approaches is found for the lowest aircraft weight (400,000 lbs). When further analyzing this result it shows that all of these unstabilized approaches are due to the fact that flaps are not at 30 degrees, but are at 25 degrees. This can be explained by the fact that for the lowest aircraft weight, the flap select speed for flaps 30 degrees is also lowest (see Fig. 3). When flaps remain at 25 degrees this means that during the simulation the aircraft has not reached (decelerated to) this low flap select speed for flaps 30 degrees, and therefore flaps 30 degrees are not selected. Although flaps are not at 30 degrees this does not mean that the approach is not safe, it is also allowed to land with flaps 25 degrees. However, flaps 25 degrees does not meet the criteria as stated for this research.

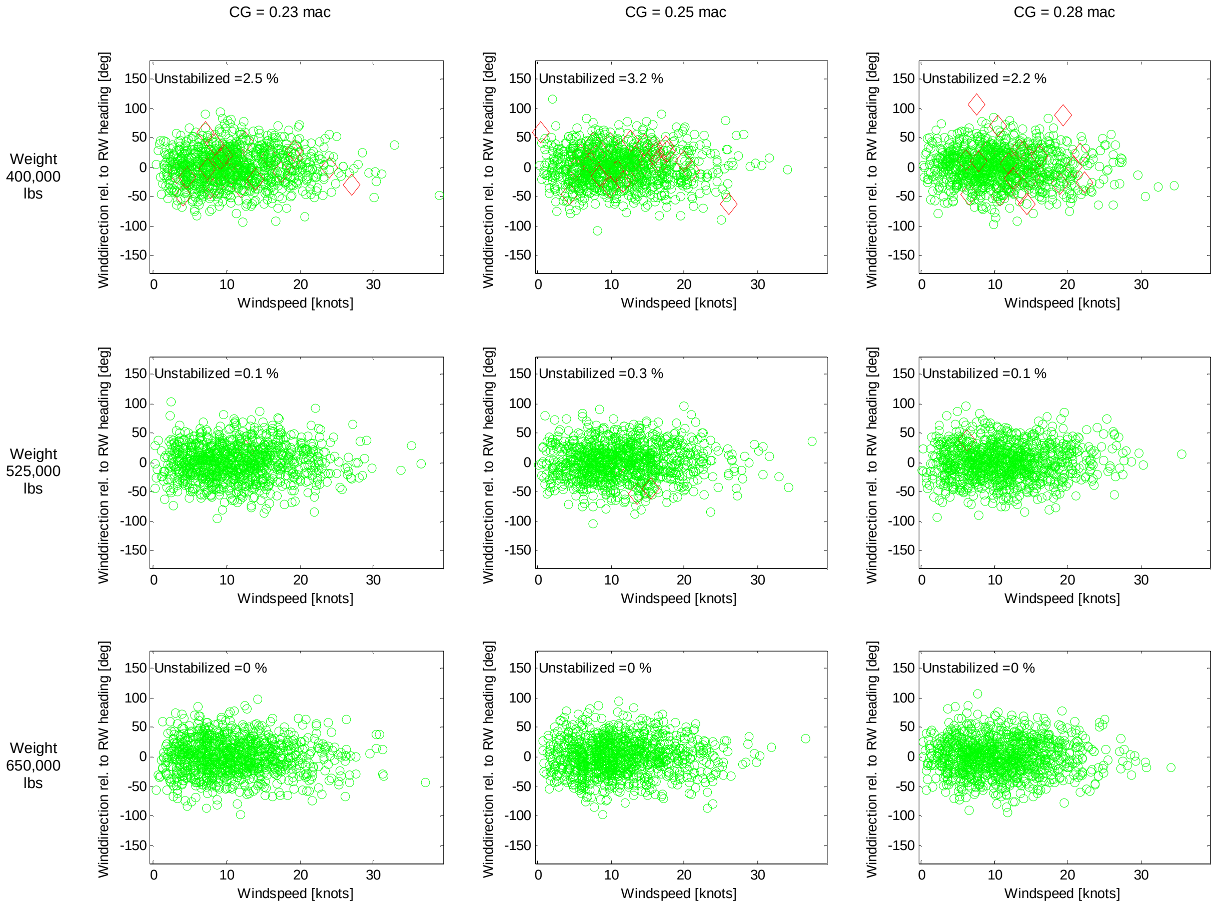


Fig. 5 Stabilized (green circle) and unstabilized (red diamond) approaches as a function of aircraft weight, center of gravity location, wind speed, and wind direction relative to runway heading for RNAV Approach 1.

7. Conclusions and recommendations

This paper shows that the proposed method to predict the possibility of achieving a stabilizedapproach can indeed predict whether under given circumstances an approach is stabilized or unstabilized. The results of the method however, will have to be validated using data of stabilized and unstabilized approaches.

To arrive at the end goal: a method to predict the difficulty of approaches, many steps still have to be taken. Starting with the work presented in this paper, it is necessary to base the flap select speeds, the timing of gear down, the switch from autopilot to flight director, on data from real flights and on SOPs as they are in use today. Additionally, the wind data need to be more realistic: the change of wind with altitude needs to be incorporated in the computer simulation.

In addition to the work presented in this paper, pilot actions such as reading checklists, contact with air traffic control etc, will have to be included. Once all actions are included, the task demand load as experienced by the pilot needs to be determined. And finally, the task demand load needs to be linked to the properties of the approach trajectory in order to find out which elements of the approach trajectory are an important factor in the increase (or decrease) of the difficulty of flying the approach.

Acknowledgements

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