FIG. 2

LIFT

THRUST

WEIGHT

FRICION

FIG. 3

START

FLIGHT MANUAL LOOKUP

AIRPLANE PERFORMANCE FOR \( \mu = 0.005 \)
\( \mu = 0.040 \)

CURVEFIT ACCELERATION VS TRUE AIRSPEED

STOP
FILTERING OF SENSED PARAMETERS

ENGINE PRESSURE RATIO PREDICTION

THRUST ESTIMATION

POINT MASS PERFORMANCE ESTIMATION

ESTIMATION OF ROLLING FRICTION COEFFICIENT

GENERATION OF BASIS FOR SCHEDULED PERFORMANCE

PREDICT RUNWAY REQUIRED TO ACHIEVE ROTATE SPEED

PREDICT RUNWAY REQUIRED TO STOP

GENERATE GO/ABORT SIGNAL COMMAND

FIG. 6
FIG. 7C

EPR = 1.92

V₂ = 134
FIG. 8C
EPR = 1.95

V_2 = 134
ORIGIN OF THE INVENTION

The invention described herein was jointly made by employees of the United States Government and a contract employee in the performance of work under NASA Grant No. 31-79, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the contractor has elected not to retain title.

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuing application of U.S. patent application Ser. No. 08/045,337, filed Apr. 6, 1993, now U.S. Pat. No. 5,363,022, which is a continuation of U.S. patent application Ser. No. 07/755,248, filed Sep. 5, 1991, now abandoned, which is a continuation-in-part of U.S. Ser. No. 08/192,562, filed May 11, 1988, now U.S. Pat. No. 5,047,942, which is a continuation-in-part of U.S. Ser. No. 08/082,766, filed Aug. 6, 1987, now U.S. Pat. No. 4,843,554.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention is related to the field of measuring and testing more particularly to a takeoff and landing performance monitoring system.

2. Description of the Prior Art

Prior art includes takeoff and landing performance monitoring systems which graphically display the position of an airplane on a runway relative to symbols which indicate (1) whether an option is still available, and (2) how much margin remains before the option becomes unavailable. For instance, see U.S. Pat. No. 4,638,437, Jan. 20, 1987, Cleary et al. Thus, the pilot using such an airplane performance monitoring system receives only an indication that, using scheduled thrust, the airplane is still capable of achieving a desired result, not an indication of whether this result can be achieved using scheduled thrust. Further, it does not indicate where on the runway particular speeds are expected to occur or where the airplane can be stopped from current position and speed.

A further limitation of the prior art is that once an estimate of the coefficient of rolling friction is input prior to takeoff, it remains constant. Likewise, the prior art fails to compensate for any change in the head wind during the takeoff run.

Another limitation of the prior art is that valuable status information, such as engine status and operating level are not displayed.

A further limitation of the prior art is that takeoff and stopping information are provided on two sides of the display, rather than being integrated into a single channel that controls an advisory flag.

OBJECTS AND SUMMARY

An object of this invention is to improve upon the prior art by continuously evaluating the status of the airplane and immediately announcing performance deficiencies, thereby informing the pilot of deficiencies while time for corrective action may still be available.

A further object of the present invention is to monitor the amount of runway already used as well as the amount of runway which can be used to achieve rotation speed or bring the airplane to a complete stop.

Another object of the present invention is to be responsive to differing ambient conditions, such as temperature, pressure altitude, runway winds, runway rolling friction coefficient, wing flap setting, and airplane loading characteristics such as weight and center of gravity.

Another object of the present invention is to provide a head-up display which provides airplane performance information to a pilot while he continues to watch the runway.

Another object of the present invention is to provide a head-up display in conjunction with a head-down display, thereby furnishing essential information to the pilot-flying via the head-up display and furnishing detailed information to the pilot-not-flying via the head-down display.

A further object of the present invention is to provide useful information to the pilot-flying by means of easily recognizable and distinguishable symbols focused at infinity and projected onto a transparent screen on or near the aircraft windshield.

Another object of the present invention is to provide a display warning the pilot that the airplane flap lever is in the wrong position for takeoff.

The invention is an airplane takeoff and landing performance monitoring system which utilizes runway ambient condition, flap setting, and airplane loading characteristic information, input both manually and continuously from transducers to a computer, to generate acceleration history curves for predicting airplane performance during takeoff and landing. The results of the airplane performance predictions are compared with measured performance during the progress of the airplane down the runway, and are depicted on both a head-up and a head-down display driven by the computer. An improved estimate of the runway coefficient of rolling friction may be derived by comparing measured with predicted performance.

The takeoff and landing performance monitoring system provides the pilot with graphic and metric information to assist in decisions related to achieving rotation speed ($V_{R}$) within the safe zone of the runway or stopping the aircraft on the runway after landing or take-off abort.

One-time inputs of ambient temperature, pressure altitude, runway wind, airplane gross weight, center of gravity, selected flap and stabilizer setting are utilized in generating a set of standard acceleration-performance data. Runway length available for rotation, runway length available for stopping, an estimated runway rolling-friction coefficient and instantaneous measurements of throttle position, engine pressure ratios, ground speed, calibrated air speed, along-track acceleration, and ground speed are used in computing engine parameters and airplane acceleration, monitoring the runway distance used and runway distance remaining in predicting the runway distance needed to achieve rotation speed, and the runway needed to stop the airplane. A comparison of measured and predicted values is utilized in detecting performance deficiencies. These comparisons and the runway length computations lead to GO/ABORT signals. An important feature of the algorithm is that the estimated runway rolling friction is updated based on measured acceleration performance, resulting in more accurate predictions of future performance. Airplane performance predictions also reflect changes in head wind occurring as the takeoff run progresses.

The head-down display indicates the position of the airplane on the runway, indicating runway used and runway
available (to the ground roll limit line and to the end of the runway), summarizes the critical information into a single situation advisory flag, shows engine failures and off-nominal acceleration performance, and indicates where on the runway particular events such as decision speed (V), rotation speed (Vr) and expected stop points will occur based on both measured and predicted performance. This display also indicates air speed, wind vector, recommended and measured engine pressure ratios (EPR), second-segment climb speed, and minimum field length (MFL).

The head-up display features a subset of the information available on the head-down display. It presents information such as measured EPR, off-nominal acceleration, air speed, current position, ground roll limit line, expected point where rotation speed will occur, and predicted stop points.

DESCRIPTION OF THE DRAWINGS

Other objects, features, and advantages of the invention will become apparent from the following detailed description of some preferred embodiments when read in conjunction with the appended drawings wherein:

FIG. 1 is a block diagram of the invention;
FIG. 2 depicts the instantaneous forces acting on an airplane during takeoff roll;
FIG. 3 is a flowchart of the pretakeoff segment;
FIGS. 4A, 4B and 4C depict the axes system used in analyzing the forces acting on the airplane;
FIG. 5 is an example of two acceleration history curves generated by the takeoff and landing performance monitoring system for two extreme friction conditions having otherwise similar takeoff conditions;
FIG. 6 is a flowchart of the real-time segment;
FIG. 7A depicts the head-down display presented to the pilot indicating the minimum field length for a particular set of takeoff conditions;
FIG. 7B depicts the graphic rescaling that occurs on the head-down display after the pilot enters the actual runway length;
FIG. 7C shows a situation advisory flag warning the pilot that the runway length is insufficient for takeoff under typical conditions;
FIG. 7D depicts the takeoff display resulting from the airplane flap lever being positioned in the wrong detent when the takeoff begins;
FIG. 7E depicts the takeoff display indicating the airplane thrust performance exceeds nominal values;
FIG. 7F shows the head-down display indicating sub-nominal airplane thrust performance (but within acceptable limits);
FIG. 8C shows the head-down display indicating a correct thrust but an acceleration performance deficiency greater than a specified value;
FIG. 8D depicts the head-up display presented to the pilot indicating an acceptable takeoff underway, with essentially no acceleration deficiency;
FIG. 9A shows the head-down display indicating that the performance of an engine has become unacceptable prior to attainment of decision speed;
FIG. 9B shows the head-down display indicating that the performance of an engine has become unacceptable after attainment of decision speed and where inadequate stopping distance remains;
FIG. 9C shows the head-down display where both GO and STOP options remain possible, even though an engine has become "inoperative" by providing inadequate thrust;
FIG. 9D shows the head-up display indicating that the performance of an engine has become unacceptable before attainment of decision speed;
FIG. 10A shows the head-down display presented to the pilot in a landing or abort situation;
FIG. 10B depicts the head-up display indicating a similar landing or abort condition, and
FIG. 11 depicts the head-up display having an acceleration-error arrow.

DETAILED DESCRIPTION OF THE INVENTION

A preferred embodiment of a system in accordance with the invention is illustrated in FIG. 1, as generally comprising a plurality of transducers 14 for measuring parameters affecting airplane performance, a computer means 15 for receiving and operating upon input data from said plurality of transducers and for driving displays 16, 17 arranged to graphically depict status information in an easily monitored format.

Conventional transducers 14 may be used to measure throttle position, engine pressure ratio, ground speed, along-track acceleration and calibrated air speed. As is well known, these transducers 14 may be positioned throughout the airplane, their outputs being collected at the cockpit and incorporated in to a conventional instrument panel such as may be found in a Boeing 737 manufactured by the Boeing Company. In the present invention, these transducer outputs are gathered together at a transducer interface panel 13, whence they become inputs to the computer means 15.

The preferred embodiment incorporates the flight control computer of the airplane, especially, a Norden model 11/70, as computer means 15; in this case, the inputs from many of the transducers are interfaced to the computer means 15 by the airplane manufacturer. Alternatively, many commercially available computers, such as a Digital Equipment Corp. microVAX, provide an acceptable substitute. Ambient temperature and pressure, runway wind, airplane weight, flap and stabilizer settings can be input from transducers 14 or manually, using a device such as the Navigation and Control Display Unit (NCDU) found in the Boeing 737-300 or -400 equivalent data entry device compatible with the selected computer means. The NCDU 17, which normally is used to enter navigational and other information into the flight control computer of the airplane, also serves as an input device in the preferred embodiment of the takeoff and landing performance monitoring system.

As will be explained, algorithms within the computer 15 operate on the input data to generate a prediction of the airplane's acceleration performance. During the progress of the airplane down the runway, these predictions are compared with measured airplane performance. Performance anomalies are determined and new predictions are made, taking into account the most recently measured performance data.

After the computer means 15 receives and operates upon selected information from the NCDU and the transducers 14, the results are transmitted to the head-down display device 16 and to the head-up display device 18 using...
computer-to-display interfacing techniques familiar to those skilled in the art. The preferred embodiment can utilize existing Horizontal Situation Indicator (HSI) screens found in many modern transports, e.g., Boeing 737, 757, and 767, as a head-down display device. However, as is known, a dedicated device such as a Sperry Arinc size D display could also be used. The HSI head-down display device 16 usually accommodates a map display used for navigation; however, while the airplane is on the ground this device serves as display unit for the takeoff and landing performance monitoring system. Once liftoff occurs, the takeoff and landing performance monitoring system head-down display is replaced by the normal HSI information. The head-up display 18 is accomplished by projecting, focused at infinity, displayed information onto a partially reflective transparent screen utilizing techniques familiar to those skilled in the art. During flight, projection of takeoff performance monitoring system information ceases. The preferred embodiment of the invention incorporates both a head-up and a head-down display; however, the invention may be practiced using either display independently.

The system in accordance with the invention monitors takeoff and landing performance by continuously comparing the actual performance of the airplane with a predicted nominal performance, including predictions of the runway length needed to attain rotation speed, the distance required to stop the airplane, and the remaining runway length.

At any point during the takeoff roll, the amount of additional runway required to achieve rotation speed is a function of the instantaneous speed of the airplane and how well it will accelerate until rotation speed is achieved. The instantaneous acceleration of the airplane is given by

\[
a = \frac{Th - D - \mu W - L}{m}
\]

where
- \( a \) = Acceleration (ft/sec^2/sec)
- \( Th \) = Thrust (lbs)
- \( D \) = drag (lbs)
- \( \mu \) = rolling friction coefficient
- \( L \) = lift (lbs)
- \( m \) = mass = \( W/g \) (slugs)
- \( g \) = gravitational acceleration (ft/sec^2/sec)
- \( W \) = weight (lbs)

FIG. 2 shows the forces acting on the airplane. The thrust varies with throttle setting and air speed and the friction coefficient depends on runway and tire condition.

Airplane acceleration represents a composite measure of the performance of the airplane; therefore, performance deficiencies can be detected by comparing actual instantaneous acceleration with a predicted nominal value.

The takeoff and landing performance monitoring system algorithm consists of two segments: a pretakeoff segment and a real-time segment. For each takeoff, the pretakeoff segment is utilized to generate nominal performance data particular to that takeoff run. The real-time segment keeps track of the runway (distance) used, the runway remaining, the runway needed to achieve rotation speed, and the runway needed to bring the airplane to a complete stop. These lengths and a comparison of the actual airplane performance with the nominal value from the pretakeoff segment are used in the GO/ABORT recommendation.

In the pretakeoff segment, the airplane acceleration performance is predicted for two extreme values of rolling friction coefficients: a low value (\( \mu = 0.005 \)) and a high value (\( \mu = 0.040 \)) using the inputs: pressure altitude, ambient temperature, runway wind, runway slope, airplane weight, center of gravity location, selected flap setting, and a throttle movement to a selected position.

The pretakeoff segment of the algorithm consists of three parts as shown in FIG. 3, and can be run off-line on the on-board computer 15 or on ground support computers (not shown) with the results downloaded to the airplane computers.

The first part performs a flight manual look-up to determine the recommended engine pressure ratio (EPR) for takeoff, the decision speed \( V_{d} \), the rotation speed \( V_{r} \) and the second segment climb speed \( V_{c} \). The throttle setting needed to achieve the engine pressure ratio is also computed.

The second part of this segment computes the "scheduled or nominal acceleration" performance of the airplane as follows. First the aerodynamic coefficients are extracted from the aerodynamic data base for the airplane as a function of the motion variables. The aerodynamic forces (\( F \)) and moments (\( M \)) are computed in the stability axis system of the airplane. These forces and moments are then transformed into the body axis system (as seen in FIGS. 4A, 4B and 4C). The components of the engine forces (\( THR_{X} \) and \( THR_{Y} \)) and along moments (\( THR_{M} \)) about the body axes are determined using a manufacturer-supplied engine model. A manufacturer-supplied landing gear model is utilized in computing the forces (\( LG_{X} \) and \( LG_{Z} \)) and moments (\( LG_{M} \)) generated by it along the body axis system.

The resultant forces (\( F_{X_{body}} \) and \( F_{Z_{body}} \)) acting through the center of gravity along the body X and Z axes are obtained as

\[
F_{X_{body}} = F_{X_{LS}} + THR_{X}L_{C_{LS}}
\]

\[
F_{Z_{body}} = F_{Z_{LS}} + THR_{Z}L_{C_{LS}}
\]

The resultant moment about the body Y-axis (the pitching moment) \( M_{Y_{body}} \) is given by

\[
M_{Y_{body}} = M_{Y_{LS}} + THR_{Y}L_{C_{LS}}
\]

Using these forces, moments and body X and Z components of gravitational acceleration, the airplane acceleration along the body axes is

\[
u_{x}=\frac{F_{x}+m}{m} - g \sin \theta - \frac{q}{2}W_{x}
\]

\[
u_{z}=\frac{F_{z}}{m} - g \cos \theta \frac{q}{2}W_{z}
\]

\[
i_{z}=\frac{W_{z}}{W_{x}} \sin \theta \cos \theta
\]

where \( \theta \) is defined in FIG. 4, \( q_{x} \) is the angular velocity about the \( Y_{x} \) axis, \( W_{x} \) is the speed along the \( X_{x} \) axis and \( u_{x} \) is the speed along the \( X_{x} \) axis and \( p_{x}=\omega_{x} \).

The pitching moment (\( M_{y_{LS}} \)) and the body Y-axis moment of inertia (\( I_{y_{LS}} \)) are used in computing the pitch acceleration using

\[
u_{y}=\frac{M_{y_{LS}}}{I_{y_{LS}}}
\]

The rate of change of pitch attitude is written as

\[
u_{\phi}=\theta_{\phi}
\]

The parameters (\( \theta_{\phi}, \phi_{\phi}, \phi_{\phi}, \phi_{\phi} \)) are integrated using
Throttle position serves as the input to a throttle servo with the following first order dynamics:

\[ x_{n+1} = x_n + a_1 x_n + a_2 V_n + a_3 V_n^2 + a_4 V_n^3. \]  

\[ y_n = \Phi x_n + \epsilon_n. \]  

where \( \Phi \) and \( \epsilon \) are filter constants and \( x_n \) is the filtered ground speed and \( a_m \) is the accelerometer output.

The measured acceleration and ground speed are processed through a second order complementary filter to estimate the bias present in the acceleration signal as follows:

\[ x_{n+1} = \Phi x_n + \epsilon_n. \]  

\[ a = A_0 + A_1 V + A_2 V^2 + A_3 V^3. \]  

These sensor outputs are processed through a filter implementation. The measured acceleration and ground speed are processed through a second order complementary filter to estimate the bias present in the acceleration signal as follows:

\[ x_{n+1} = \Phi x_n + \epsilon_n. \]  

where \( \Phi \) and \( \epsilon \) are filter constants and \( x_n \) is the filtered ground speed and \( a_m \) is the accelerometer output.

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where \( \Phi \) and \( \epsilon \) are filter constants and \( x_n \) is the filtered ground speed and \( a_m \) is the accelerometer output.
Another salient feature of this algorithm is the update of the runway friction coefficient in real-time. The estimation takes place as follows. First, the thrust is represented as a cubic in air speed

\[ THR = T_T + T_F + T_V + T_Y + T_V + T_W. \]  

At any true air speed, the acceleration corresponding to two rolling friction coefficients can be written as

\[ a = gW \left( T_T - \mu W_0 \right) + T_F + \left( T_F - 1/2 \rho SC_0 + 1/2 \rho V^2 \right) + T_Y + T_V + T_W. \]  

Subtracting \( a \) from \( a \) and solving for the difference in friction coefficients

\[ \Delta a = \left( \mu - \mu_0 \right) \left( 1/2 \rho SC_0 V^2 + W \right) \]

where \( \mu \) = estimate of the actual runway friction coefficient

\[ \mu_0 \] = assumed friction coefficient

\[ \Delta \mu \] = estimated difference in the friction coefficients.

Thus the actual rolling friction coefficient is estimated as

\[ \hat{\mu} = \mu_0 + \Delta \mu. \]

Immediately after this process the basis for scheduled performance is recomputed with \( \hat{\mu} \) as the present estimate of the friction coefficient. This process can be repeated during the run as many times as appropriate.

The runway required to achieve rotation speed is computed by a ten step rectangular integration scheme between the present true air speed and the true air speed for rotation. The acceleration in each interval is assumed to remain constant at a value given by the scheduled performance basis for the true air speed at the midpoint of the interval.

To calculate the estimated stopping distance, the system simulates the effect of a series of commands to deploy the flight and ground spoilers, to reduce the throttle to an idle setting, and to apply full braking. The computations are based on the following assumptions:

1. The flight and ground spoilers are commanded through servos modelled as first order lags.
2. With full braking the rolling friction coefficient is increased by a constant amount over the present value. A more sophisticated model can be substituted.
3. Maximum wheel braking is achieved in a ramp fashion per given time period.
4. Thrust is assumed to vary linearly with throttle position from the present value to idle thrust, reaching idle thrust for a throttle position of zero.
5. Changes in lift and drag coefficients produced by flight and ground spoilers are assumed to vary linearly with deflection.

Using these assumptions in a numerical integration scheme based on incremental time, the stopping distance is computed in a point mass formulation with the lift and drag coefficients computed as

\[ C_L = C_{L_{0,0}} + \Delta C_{L_{0,0}} + \Delta C_{L_{0,0}}. \]

where the subscripts FSP and GSP respectively denote flight spoilers and ground spoilers and the friction coefficient is computed as

\[ \mu = \mu_{\text{nominal}} + \Delta \mu_{\text{fric}}. \]

The engine pressure ratio is used as a check on engine status. After allowing time for the engine transients to die out, the measured value is compared with the predicted value corresponding to the measured throttle position for each engine. If this difference is more than a preselected limit an engine failure flag is set.

\[ \frac{EPR - EPR_{\text{predicted}}}{EPR_{\text{error limit}}} \]

Similar differences in other engine parameters could also be incorporated. At any time after the rolling friction coefficient is estimated, any difference between the measured and the predicted acceleration which exceeds a preselected limit causes a performance failure flag to be set.

Based on these flags and other particular conditions, the following situation advisory signals are generated:

A “NULL” advisory signal will exist indicating that the takeoff is proceeding satisfactorily when no engine or performance flags are set and there is adequate distance left to stop on the runway or to reach rotation speed before reaching the ground roll limit for safe takeoff, viz., the “ground roll-limit line”.

A “GO” advisory signal will result when zero or one engine-failure flags are set, the airplane can still reach rotation speed before reaching the ground roll-limit line, and the runway remaining is less than that required for stopping the airplane.

“ABORT” advisory signals will result when:

(a) The runway length available for reaching rotation speed is less than required;
(b) A performance-failure flag is set;
(c) One engine-failure flag is set at a speed less than decision speed;
(d) Multiple engine flags are set.

4. Optionally, an “OPTION” advisory signal can result indicating that both the GO and ABORT options are available when one engine-failure flag is set at a speed equal to or greater than decision speed, the airplane can reach rotation speed before reaching the ground roll-limit line, and the runway distance remaining is greater than that required for stopping.

As stated previously, the system algorithm is composed of two segments. The pretakeoff segment is activated prior to the start of the takeoff roll, when the pilot enters ambient condition, loading and configuration information into the system through an appropriate input device such as the NCDU 17. Once the pretakeoff computations are complete, the head-down display, the HSI in the preferred embodiment, presents the format shown in FIG. 7A. The number at the departure end of the runway, shown as 4556 in the figure, represents the minimum field length (MFL) calculated for the given conditions. The minimum field length is the initial ground roll distance plus the greater of the remaining distance needed for the airplane to clear a predetermined height at the departure end of the runway, e.g., 35' in the
Tracking the lateral movement of the airplane on the runway is about 400 ft. from the starting end of the runway; this left side indicates the V\textsubscript{s}, speed and where it will be achieved. Further denotes this position, and the number on the right side indicates the V\textsubscript{2}, speed in knots. Similarly, the number and line at the bottom left corner of the display for the airplane to reach rotation speed, or the distance required to brake to a stop at a decision speed, or the distance required to brake to a stop when the airplane performance is below expectation, that is, it is taking more distance than expected to achieve rotation speed. Since the EPR bars 56, 57 are below the EPR target line and show no signs of engine failure, the underperformance is verified to be caused by a lower than recommended throttle setting.

FIG. 8A shows a head-down display that contains a situation advisory flag 65 at the far end of the runway symbol 21 and an acceleration-error arrow 70. Whenever the acceleration error is less than some lower limit, e.g., 5% used in the preferred embodiment, there is no flag or arrow; however, for larger errors the arrow grows linearly toward the approaching airplane symbol 22. When the error arrow reaches an unacceptable-limit line 72, e.g. 15% in the preferred embodiment, the situation advisory flag 65 and the error bar 35 indicate the predicted stop point appears. The GRILL 54 could double as limit line 72. In FIGS. 8A and 8B, there were no advisory flags or error arrows because the higher or lower than nominal accelerations were not considered errors since they were nominal for the throttle settings being used.

FIG. 8D depicts the head-up display for an acceptable takeoff underway on a near-minimum length runway for the existing conditions. The two triangles 52, 62 are superimposed and remain so as long as acceleration performance is nominal. The EPR bars 56, 57 indicate that both engines are operating satisfactorily and at approximately the same level.

FIG. 9A shows the head-down display that appears when the performance of an engine becomes unacceptable after decision speed is attained. The EPR bar on the right side 57 diminishes in length and changes color to indicate the acceleration error arrow 70 also appears. FIG. 9B depicts the head-up display where the performance of an engine becomes unacceptable after decision speed has been attained. The location of the star 35 beyond the end of the runway indicates that inadequate stopping distance remains. The situation advisory flag 24, which may be green, recommends continuing with takeoff in spite of the engine failure indication 57, because insufficient runway remains for stopping. Because of the decrease in thrust, the acceleration-error arrow 70 also appears.

FIG. 9C illustrates the head-down display where the performance of an engine becomes unacceptable after decision speed has been attained, but where adequate stopping distance is still available. The situation advisory flag 41 is presented as a flashing amber inverted triangle to indicate that both GO and STOP options are available although current FAA regulations might require the pilot to proceed with takeoff.
FIG. 9D shows the head-up display for the same situation depicted in FIG. 9A, i.e., right-engine failure at about 85 knots on a runway somewhat longer than a minimum field. The EPR bar on the right side 57 has turned red and is shrinking, the acceleration-error arrow 70 is growing, and the red situation advisory flag (STOP sign) 65 has appeared. Further, the triangles 52, 62 have separated significantly. Just ahead of the airplane symbol, 51, the star symbol 63 has appeared indicating the point at which calculations indicate the airplane will stop if maximum braking is initiated immediately.

The acceleration-error arrow 70 shown in FIGS. 8C and 9A-D can be programmed to disappear from the display when the abort flag 65 appears, or it can remain on the screen until the abort maneuver is initiated.

The initiation of an abort executed by a rapid pull back of the throttles causes most of the takeoff information to be removed from the head-down display leaving only information pertinent to the abort. FIG. 10A shows an head-down abort display. The shaded and open triangles, the $V_1$ and $V_{sp}$ lines, the ground roll limit line, the $V_2$ and EPR numerics, the wind vector, the acceleration-error arrow, and the engine flags disappear from the display. However, the calibrated air speed 23 in the box to the left of the airplane symbol is replaced by ground speed in knots. The star 35, however, remains, representing the stop point using maximum braking, full spoilers, but no reverse thrust, and a new oval symbol 36 appears on the display. This new symbol 36 indicates the position where the airplane will stop using the present level of deceleration, in this case is less than full braking.

FIG. 10B shows the head-up abort display for the same situation as shown in FIG. 10A. As with the head-down display, all takeoff-related information has disappeared and the only symbols left are the airplane 51, its ground speed 53, the predicted stop-point using maximum braking 63 and the predicted stop-point using the current level of measured acceleration 64. This display also shows that less than full braking is being applied.

In the preferred embodiment, specific colors and shapes of the situation advisory flag(s) have specific meanings for different conditions, viz.:  

<table>
<thead>
<tr>
<th>COLOR/SHAPE</th>
<th>FLIGHT CONDITION</th>
<th>RECOMMENDATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Flag</td>
<td>Takeoff is proceeding normally</td>
<td>Continue takeoff</td>
</tr>
<tr>
<td>Green/Arrow</td>
<td>Airplane can reach $V_{sp}$ before reaching ground-roll limit line, but its predicted stop point is beyond end of runway</td>
<td>Takeoff</td>
</tr>
<tr>
<td>Amber/Triangle (Blinking)</td>
<td>Same as (3) except airplane predicted stop point is on the runway.</td>
<td>Continue or abort the take-off (please option)</td>
</tr>
<tr>
<td>Red/Stop-sign</td>
<td>Airplane will reach $V_{sp}$ after it has passed the ground roll limit line.</td>
<td>Abort</td>
</tr>
</tbody>
</table>

A failed engine is indicated by change in the length and color of the associated EPR bar—attached to the side of the runway graphic. Specifically, the bar shrinks in length and turns red when the EPR error exceeds a specified amount.

A performance arrow indicates deviation of the measured longitudinal acceleration from the nominal acceleration curve of values determined by the algorithm for the throttle setting being used. When the deviation exceeds a specified limit (see advisory flag condition (8) above), the abort flag comes on.

FIG. 11 depicts the head-up display employing a displayed acceleration-error arrow 70. The acceleration-error is a function of the difference between a predicted airplane acceleration and a currently measured airplane acceleration. The arrow 70 grows from the end of runway 58 toward the approaching plane 51 as a function of the acceleration fluctuations. In a preferred embodiment, arrow 70 appears when the acceleration error is at a minimum of, e.g., 5%, and is scaled to reach line 54 when the error is at a maximum of, e.g., 15%, at which time a stop advisory flap 65 would appear. The acceleration-error arrow is also implemented on the head-down displays, as already shown on FIGS. 8C, 9A, 9B, 9C, and 9D.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. In an airplane takeoff and landing performance monitoring system with a display means for graphically and continuously depicting the position of an airplane on a runway, the improvement comprising:

   a. means for generating a value indicative of a rotation speed of the airplane necessary to achieve take-off;
   b. means for continuously displaying both a stationary symbol indicative of an initial prediction of a position where the rotation speed should occur and a movable symbol indicative of a current prediction of a position where the airplane should reach the rotation speed on the runway wherein the movable symbol is superimposed on the stationary symbol when there is no difference between the initially predicted position of the airplane and currently predicted position of where the airplane should reach the rotation speed and wherein the movable symbol is spatially distanced from the stationary symbol along the runway when there is a difference between the initially predicted position and the currently predicted position; and
   c. means for displaying an abort symbol when an acceleration error of the airplane exceeds a specified tolerance band, wherein the acceleration error is defined by a difference in a measured acceleration and an initially predicted acceleration of the airplane.

2. The monitoring system according to claim 1, further comprising means for displaying a symbol on the displayed runway indicative of where the airplane can be stopped when the abort symbol is displayed.

3. The monitoring system according to claim 1, further comprising means for displaying a go symbol when the acceleration error is within the specified tolerance band and the current speed of the airplane exceeds a predetermined decision speed.
4. The monitoring system according to claim 1, further comprising means for displaying a go symbol when the airplane acceleration error falls within the specified tolerance band but inadequate runway remains for the airplane to stop in a determined safe manner.

5. The monitoring system according to claim 1, further comprising means for displaying a symbol on the displayed runway indicative of a position of a ground roll limit distance, wherein the ground roll limit distance is defined as the distance from the point where the takeoff roll begins to the last point on the runway at which the airplane upon achieving rotation speed, can, with one engine inoperative and using scheduled throttle settings, clear a predetermined height at the departure of the runway.

6. A method of monitoring an airplane takeoff and landing performance including graphically and continuously depicting the position of an airplane on a displayed runway, the improvement comprising:

- generating a value indicative of a rotation speed necessary to achieve takeoff;
- continuously displaying a stationary symbol on the runway indicative of an initial prediction of a position where the rotation speed of the airplane necessary to achieve take-off should occur;
- continuously displaying a movable symbol on the runway indicative of a current prediction of a position where the rotation speed should occur, wherein the movable symbol is superimposed on the stationary symbol when there is no difference between the initially predicted position where the rotation speed of the airplane should occur and currently predicted position of where the rotation speed of the airplane should occur, wherein the movable symbol is spatially distanced from the stationary symbol along the runway when there is a difference between the initially predicted position and the currently predicted position; and
- displaying an abort symbol when an acceleration error of the airplane exceeds a specified tolerance band, wherein the acceleration error is defined by a difference in a measured acceleration of the airplane and to initially predict acceleration of the airplane.

7. The monitoring method according to claim 6, further comprising displaying a symbol on the displayed runway indicative of where the airplane can be stopped when the abort symbol is displayed.

8. The monitoring method according to claim 6, further comprising displaying a go symbol when the airplane acceleration error is within the specified tolerance band and the current speed of the airplane exceeds a predetermined decision speed.

9. The monitoring method according to claim 6, further comprising displaying a go symbol when the acceleration error falls within the specified tolerance band but inadequate runway remains for the airplane to stop in a determined safe manner.

10. The monitoring method according to claim 6, further comprising displaying a symbol on the displayed runway indicative of the position of a ground roll limit distance, wherein the ground roll limit distance is defined as the distance from the point where the takeoff roll begins to the last point on the runway at which the airplane upon achieving rotation speed, can, with one engine inoperative and using scheduled throttle settings, clear a predetermined height at the departure of the runway.

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