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FINAL REPORT ON NASA GRANT NO. NAG-1-516, OPTIMAL FLIGHT TRAJECTORIES IN THE PRESENCE OF WINDSHEAR, 1984-86

by

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Final Report on NASA Grant No. NAG-1-516, Optimal Flight Trajectories in the Presence of Windshear, 1984-86[1]

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A. Miele[2]

[1]This work was supported by NASA-Langley Research Center, Grant No. NAG-1-516.

[2]Professor of Astronautics and Mathematical Sciences, Aero-Astronautics Group, Rice University, Houston, Texas.

Abstract. This report summarizes the research performed at Rice University during the period 1984-86 under NASA Grant No. NAG-1-516 on optimal flight trajectories in the presence of windshear. With particular reference to the take-off problem, the topics covered include: equations of motion, problem formulation, algorithms, optimal flight trajectories, advanced guidance schemes, simplified guidance schemes, and piloting strategies.

Key Words. Flight mechanics, take-off, optimal trajectories, optimal control, feedback control, windshear problems, sequential gradient-restoration algorithm, dual sequential gradient-restoration algorithm, guidance strategies, acceleration guidance, gamma guidance, theta guidance, piloting strategies.

Contents

Acknowledgment

The collaboration of Dr. T. Wang, Senior Research Associate, Rice University, Houston, Texas is gratefully acknowledged. Also gratefully acknowledged is the collaboration of Captain W. W. Melvin, Delta Airlines, Atlanta, Georgia. Captain Melvin is Chairman of the Airworthiness and Performance Committee of the Air Line Pilots Association (ALPA), Washington, DC. He introduced the author of this report to the windshear problem and acted as a consultant on this project.

1. Introduction

The objective of this study is the determination of optimal flight trajectories in the presence of windshear and the development of guidance schemes for near-optimum flight in a windshear. This is a wind characterized by sharp change in intensity and direction over a relatively small region of space. This problem is important in the take-off and landing of both civilian airplanes and military airplanes and is key to aircraft safety.

The research done under NASA Grant No. NAG-1-516 during the period 1984-86 is reviewed in Section 2. With particular reference to the take-off problem, the topics covered include: equations of motion, problem formulation, algorithms, optimal flight trajectories, advanced guidance schemes, simplified guidance schemes, and piloting strategies.

The publications completed or in progress are listed in Section 3. The abstracts of the publications completed are given in Section 4. Finally, a bibliography is presented in Section 5.

2. Research Review

2.1. Background. During the month of November 1983, Captain W. W. Melvin, Delta Airlines and ALPA, approached Dr. A. Miele, Professor of Astronautics and Mathematical Sciences at Rice University, asking him to become interested in the windshear problem. In a meeting which took place on the campus of Rice University, Captain Melvin stated his feeling that considerable research had been done on the meteorological, aerodynamic, instrumentation, and stability aspects of the windshear problem; however, relatively little had been done on the flight mechanics aspects; he felt that a fundamental study was needed in order to better understand the dynamic behavior of an aircraft in a windshear. In the ensuing discussion, Dr. Miele stated his feeling that the determination of good strategies for coping with windshear situations was essentially an optimal control problem; that the methods of optimal control theory were needed; and that, only after having found optimal control solutions, one could properly address the guidance problem.

As a result of this meeting, Dr. Miele prepared a research proposal on the optimization and guidance of flight trajectories in a windshear. The proposal was funded in August 1984 by NASA-Langley Research Center, with Dr. Miele acting as Principal Investigator and Captain Melvin acting as Consultant. Dr. R. L. Bowles of NASA-LRC is Project Monitor. Additional funds were subsequently obtained through the sponsorship of Boeing Commercial Aircraft Company (BCAC) and Air Line Pilots Association (ALPA).

During the past two years, the Aero-Astronautics Group of Rice University, under the direction of Dr. Miele, has done research on both the optimization and the guidance of flight trajectories in a windshear. In the first year, the Aero-Astronautics Group studied the optimization aspects of flight trajectories (Refs. 1-7 and 14); in the second year, the Aero-Astronautics

Group studied the guidance aspects (Refs. 8-13 and 15-19). The main results are summarized below.

2.2. Equations of Motion. In Ref. 1, the equations of motion under windshear conditions are derived employing three different coordinate systems: the Earth-fixed system; the relative wind-axes system; and the absolute wind-axes system. The following assumptions are employed: the aircraft is a particle of constant mass; flight takes place in a vertical plane; Newton's law is valid in an Earth-fixed system; and the wind flow field is steady.

For the optimization of flight trajectories, any of the previous coordinate systems can be used. However, the relative wind-axes system is to be preferred, because the windshear terms appear explicity in the dynamical equations. Therefore, use of the relative wind-axes system allows an easier physical understanding and interpretation of windshear phenomena.

2.3. Problem Formulation. In Ref. 2, we employ the equations of motion written for the relative wind-axes system. First, we supply an analytical description of the forces acting on the aircraft. Next, we supply a description of the wind flow field. Generally speaking, the wind flow field is two-dimensional; however, useful one-dimensional models can be developed if one refers to the near-the-ground behavior of a microburst.

With reference to take-off, we assume that the power setting is held at the maximum value. Indeed, it is logical to think that, if a plane takes off under less-than-ideal weather conditions, a prudent pilot employs the maximum thrust. With the power setting held at the maximum value, it is clear that the only control is the angle of attack α. To obtain realistic trajectories, inequality constraints must be imposed on both α and $\dot{\alpha}$. Specifically, the angle of attack α is subject to the inequality $\alpha \leq \alpha_*$, where α_* is a prescribed upper bound. In addition, its time derivative $\dot{\alpha}$ is subject to the double inequality

$-C \leq \dot{\alpha} \leq +C$, where C is a prescribed constant.

Concerning the initial conditions, we assume that the initial state is given. Concerning the final conditions, four cases are considered; hence, four types of boundary conditions are considered.

(BC0) The state is free at the final point.

(BC1) The final value of the path inclination is the same as the initial value.

(BC2) The final values of the velocity and the path inclination are the same as the initial values.

(BC3) The final values of the velocity, the path inclination, and the angle of attack are the same as the initial values. Therefore, this case implies that, if the initial values correspond to quasi-steady flight, then the final values also correspond to quasi-steady flight.

Concerning the performance indexes, we consider eight fundamental optimization problems.

(P1). This is a least-square problem involving $\Delta h = h - h_R$, the difference between the flight altitude and a reference altitude, assumed to be a linear function of the horizontal distance.

(P2) This is a least-square problem involving $\Delta\gamma = \gamma - \gamma_R$, the difference between the relative path inclination and a reference value, assumed constant.

(P3) This is a least-square problem involving $\Delta\gamma_e = \gamma_e - \gamma_{eR}$, the difference between the absolute path inclination and a reference value, assumed constant.

(P4) This is a minimax problem involving $\Delta h = h - h_R$, the difference between the flight altitude and a reference altitude, assumed constant.

(P5) This is a minimax problem involving $G\Delta h = G(h - h_R)$, the weighted difference between the flight altitude and a reference altitude, assumed constant, as in (P4). Here, $G(t)$ is a prescribed weighting function.

(P6) This is a minimax problem involving $\Delta h = h - h_R$, the difference between the flight altitude and a reference altitude, assumed to be a linear function of the horizontal distance, as in (P1).

(P7) This is a minimax problem involving $\Delta\gamma = \gamma - \gamma_R$, the difference between the relative path inclination and a reference value, assumed constant, as in (P2).

(P8) This is a minimax problem involving $\Delta\gamma_e = \gamma_e - \gamma_{eR}$, the difference between the absolute path inclination and a reference value, assumed constant, as in (P3).

Problems (P1)-(P3) are least-square problems of the Bolza type. Problems (P4)-(P8) are minimax problems of the Chebyshev type, which can be converted into Bolza problems through suitable transformations. Hence, Problems (P1)-(P8) are particular cases of the following general problem:

(P) Minimize a functional with respect to the state vector $x(t)$, the control vector $u(t)$, and the parameter vector π which satisfy a system of differential constraints, initial constraints, and final constraints.

2.4. Algorithms. From the previous section, it is clear that one is faced with a wide variety of problems of optimal control, depending on the particular performance index chosen and the particular type of boundary conditions chosen. These problems are further complicated by the presence of inequality constraints on the control (α) and the time derivative of the control ($\dot{\alpha}$). Therefore, a powerful algorithm is necessary to solve the problems under consideration.

In Ref. 3, we present the algorithm useful for solving Problem (P) on a digital computer, more specifically, the sequential gradient-restoration algorithm (SGRA). Both the primal formulation and the dual formulation are presented. Depending on whether the primal formulation is used or the dual formulation is used, one obtains a primal sequential gradient-restoration algorithm (PSGRA) or a dual sequential gradient-restoration algorithm (DSGRA).

The systems of Lagrange multipliers associated with the gradient phase of SGRA and the restoration phase of SGRA are examined. For each phase, it is shown that the Lagrange multipliers are endowed with a duality property: they minimize a special functional, quadratic in the multipliers, subject to the multiplier differential equations and boundary conditions, for given state, control, and parameter. These duality properties have considerable computational implications: they allow one to reduce the auxiliary optimal control problems associated with the gradient phase and the restoration phase of SGRA to mathematical programming problems involving a finite number of parameters as unknowns.

Numerical experimentation has shown that, for nonstiff problems of flight mechanics, DSGRA is computationally more efficient than PSGRA. In particular, for the problems under consideration, DSGRA is about 10% more efficient that PSGRA. Hence, the subsequent numerical experiments are based on the use of DSGRA.

2.5. Optimal Trajectories. Optimal trajectories were computed for the Boeing B-727 aircraft, using the sequential gradient-restoration algorithm and the NAS-AS-9000 computer of Rice University. Among the performance indexes (P1)-(P8), the most reliable one was found to be (P8), based on the deviation of the absolute path inclination from a reference value. After computing several hundred optimal trajectories, certain general conclusions became apparent (see Refs. 1-7 and 14):

(i) the optimal trajectories achieve minimum velocity near the time when the shear ends;

(ii) the optimal trajectories require an initial decrease in the angle of attack, followed by a gradual increase; the maximum permissible angle of attack α_* (stick-shaker angle of attack) is achieved near the time when the shear ends;

(iii) for weak-to-moderate windshears,the optimal trajectories are characterized by a monotonic climb; the average value of the path inclination decreases as the intensity of the shear increases;

(iv) for relatively severe windshears, the optimal trajectories are characterized by an initial climb, followed by nearly horizontal flight, followed by renewed climbing after the aircraft has passed through the shear region;

(v) weak-to-moderate windshears and relatively severe windshears are survivable employing an optimized flight strategy; however, extremely severe windshears are not survivable, even employing an optimized flight strategy;

(vi) in relatively severe windshears, optimal trajectories have a much better survival capability than constant angle of attack trajectories (for instance, maximum angle of attack trajectories or maximum lift-to-drag ratio trajectories); in addition, they have a better survival capability than constant pitch trajectories.

2.6. Advanced Guidance Schemes. The computation of the optimal trajectories requires global information of the wind flow field; that is, it requires the knowledge of the wind velocity components at every point of the region of space in which the aircraft is flying. In practice, this global information is not available; even if it were available, there would not be enough computing capability onboard and enough time to process it adequately. As a consequence, one must think of optimal trajectories as merely benchmark trajectories that it is desirable to approach in actual flight.

Since global information is not available, the best that one can do is to employ local information on the wind flow field, in particular, local information on the wind acceleration and the downdraft. Therefore, the guidance problem must be addressed in these terms: Assuming that local information is available on the wind acceleration, the downdraft, as well as the state of the aircraft, we wish to guide an aircraft automatically or semiautomatically in such a way that the key properties of the optimal trajectories are preserved.

Based on the idea of preserving the properties of the optimal trajectories, four guidance schemes were developed at Rice University:

(a) acceleration guidance, based on the relative acceleration;

(b) absolute gamma guidance, based on the absolute path inclination;

(c) relative gamma guidance, based on the relative path incliantion;

(d) theta guidance, based on the pitch attitude angle.

The details of these guidance schemes are omitted and can be found in Refs. 8-13 as well as in Refs. 15-17.

Guidance trajectories were computed for the Boeing B-727 aircraft using the above guidance schemes and the NAS-AS-9000 computer of Rice University. It was found that all of the above guidance schemes (in particular, the acceleration guidance and the gamma guidance) produce trajectories which are quite close to the optimum trajectories. In addition, the resulting near-optimum trajectories are superior to the trajectories arising from alternative guidance schemes (for instance, constant angle of attack trajectories and constant pitch trajectories).

2.7. Simplified Guidance Schemes and Piloting Strategies. As stated above, the previous advanced guidance schemes require local information on the wind flow field and the state of the aircraft. While this information will be available in future aircraft, it might not be available on current aircraft.

For current aircraft, one way to survive a windshear encounter is to use a constant pitch attitude technique; this technique has been advocated by many experts on the windshear problem. An alternative, simple technique is the quick transition to horizontal flight, based on the properties of the optimal trajectories.

The quick transition to horizontal flight requires an initial decrease of the angle of attack, so as to decrease the path inclination to nearly horizontal. Then, nearly horizontal flight is maintained during the shear encounter.

For relatively severe windshears, the quick horizontal flight transition technique yields trajectories which are competitive with those of the advanced guidance schemes discussed previously. In addition, for relatively severe windshears, the quick horizontal flight transition technique yields trajectories which have better survival capabilities than those associated with other guidance techniques, such as constant angle of attack or constant pitch.

Work on the quick horizontal flight transition technique is nearly completed and publication of two reports is expected shortly (Refs. 18-19).

3. Publications

3.1. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Flight Trajectories in the Presence of Windshear, Part 1, Equations of Motion, Rice University, Aero-Astronautics Report No. 191, 1985.

3.2. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Flight Trajectories in the Presence of Windshear, Part 2, Problem Formulation, Take-Off, Rice University, Aero-Astronautics Report No. 192, 1985.

3.3. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Flight Trajectories in the Presence of Windshear, Part 3, Algorithms, Rice University, Aero-Astronautics Report No. 193, 1985.

3.4. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Flight Trajectories in the Presence of Windshear, Part 4, Numerical Results, Take-Off, Rice University, Aero-Astronautics Report No. 194, 1985.

3.5. MIELE, A., Summary Report on NASA Grant No. NAG-1-516, Optimal Flight Trajectories in the Presence of Windshear, 1985-86, Rice University, Aero-Astronautics Report No. 195, 1985.

3.6. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Take-Off Trajectories in the Presence of Windshear, Paper No. AIAA-85-1843-CP, AIAA Flight Mechanics Conference, Snowmass, Colorado, 1985.

3.7. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Take-Off Trajectories in the Presence of Windshear, Journal of Optimization Theory and Applications, Vol. 49, No. 1, pp. 1-45, 1986.

3.8. MIELE, A., WANG, T., and MELVIN, W. W., Guidance Strategies for Near-Optimum Performance in a Windshear, Part 1, Take-Off, Basic Strategies, Rice University, Aero-Astronautics Report No. 201, 1986.

3.9. MIELE, A., WANG, T., and MELVIN, W. W., Guidance Strategies for Near-Optimum Performance in a Windshear, Part 2, Take-Off, Comparison Strategies, Rice University, Aero-Astronautics Report No. 202, 1986.

3.10. MIELE, A., WANG, T., and MELVIN, W. W., Guidance Strategies for Near-Optimum Take-Off Performance in a Windshear, Paper No. AIAA-86-0181, AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, 1986.

3.11. MIELE, A., WANG, T., and MELVIN, W. W., Guidance Strategies for Near-Optimum Take-Off Performance in a Windshear, Journal of Optimization Theory and Applications, Vol. 50, No. 1, pp. 1-47, 1986.

3.12. MIELE, A., WANG, T., and MELVIN, W. W., Optimization and Acceleration Guidance of Flight Trajectories in a Windshear, Paper No. AIAA-86-2036-CP, AIAA Guidance, Navigation, and Control Conference, Williamsburg, Virginia, 1986.

3.13. MIELE, A., WANG, T., and MELVIN, W. W., Optimization and Gamma/Theta Guidance of Flight Trajectories in a Windshear, Paper No. ICAS-86-564, 15th Congress of the International Council of the Aeronautical Sciences, London, England, 1986.

3.14. MIELE, A., WANG, T., and MELVIN, W. W., Quasi-Steady Flight to Quasi-Steady Flight Transition in a Windshear: Trajectory Optimization, 6th IFAC Workshop on Control Applications of Nonlinear Programming and Optimization, London, England, 1986.

Publications in Progress

3.15. MIELE, A., et al, Optimization and Acceleration Guidance of Flight Trajectories in a Windshear, Journal of Guidance, Control, and Dynamics (to appear).

3.16. MIELE, A., et al, Downdraft Effects on Optimization and Guidance of Take-Off Trajectories in a Windshear, Journal of Optimization Theory and Applications (to appear).

3.17. MIELE, A., et al, Quasi-Steady Flight to Quasi-Steady Flight Transition in a Windshear: Trajectory Guidance, Paper No. AIAA-87-0271, AIAA 25th Aerospace Sciences Meeting, Reno, Nevada, 1987 (to appear).

3.18. MIELE, A., et al, Near-Optimal Piloting Strategies for Flight in Severe Windshear (to appear).

3.19. MIELE, A., et al, Simple Piloting Strategies for Flight in Severe Windshear: Quick Transition to Horizontal Flight (to appear).

4. Abstracts of Publications

4.1. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Flight Trajectories in the Presence of Windshear, Part 1, Equations of Motion, Rice University, Aero-Astronautics Report No. 191, 1985.

Abstract. This report is the first of series dealing with the determination of optimal flight trajectories in the presence of windshear. This is a wind characterized by sharp change in intensity and direction over a relatively small region of space. This problem is important in the take-off and landing of both civilian airplanes and military airplanes and is key to aircraft safety.

It is assumed that: the aircraft is a particle of constant mass; flight takes place in a vertical plane; Newton's law is valid in an Earth-fixed system; and the wind flow field is steady.

Under the above assumptions, the equations of motion under windshear conditions are derived employing three different coordinate systems: the Earth-fixed system; the relative wind-axes system; and the absolute wind-axes system. Transformations are supplied which allow one to pass from one system to another.

4.2. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Flight Trajectories in the Presence of Windshear, Part 2, Problem Formulation, Take-Off, Rice University, Aero-Astronautics Report No. 192, 1985.

Abstract. This report is the second of a series dealing with the determination of optimal flight trajectories in the presence of windshear. We employ the equations of motion written for the relative wind-axes system. We supply an analytical description of the forces acting on the aircraft, as well as a description of the wind flow field. Then, with reference to take-off, we formulate eight fundamental optimization problems [Problems (P1)-(P8)] under the assumptions that the power setting is held at the maximum value and

that the airplane is controlled through the angle of attack.

Problems (P1)-(P3) are least-square problems of the Bolza type. Problems (P4)-(P8) are minimax problems of the Chebyshev type, which can be converted into Bolza problems through suitable transformations. Hence, (P1)-(P8) can be solved employing the family of sequential gradient-restoration algorithms (SGRA), developed for optimal control problems of the Bolza type.

4.3. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Flight Trajectories in the Presence of Windshear, Part 3, Algorithms, Rice University, Aero-Astronautics Report No. 193, 1985.

Abstract. This report is the third of a series dealing with the determination of optimal flight trajectories in the presence of windshear. We consider the following general problem of the Bolza type [Problem (P)]: Minimize a functional with respect to the state vector $x(t)$, the control vector $u(t)$, and the parameter vector π which satisfy a system of differential constraints, initial constraints, and final constraints.

We present the algorithms useful for solving Problem (P) on a digital computer, more specifically, sequential gradient-restoration algorithms (SGRA). Both the primal formulation and the dual formulation are presented. Depending on whether the primal formulation is used or the dual formulation is used, one obtains a primal sequential gradient-restoration algorithm (PSGRA) or a dual sequential gradient-restoration algorithm (DSGRA).

The system of Lagrange multipliers associated with the gradient phase of SGRA and the restoration phase of SGRA is examined. For each phase, it is shown that the Lagrange multipliers are endowed with a duality property: they minimize a special functional, quadratic in the multipliers, subject to the multiplier differential equations and boundary conditions, for given state, control, and parameter. These duality properties have considerable computational implications: they allow one to reduce the auxiliary optimal control problems associated with the gradient phase and the restoration phase of SGRA to mathematical programming problems involving a finite number of parameters as unknowns.

4.4. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Flight Trajectories in the Presence of Windshear, Part 4, Numerical Results, Take-Off, Rice University, Aero-Astronautics Report No. 194, 1985.

Abstract. This report is the fourth of a series dealing with the determination of optimal flight trajectories in the presence of windshear. We obtain numerical results for the take-off problem, employing the dual sequential gradient-restoration algorithm (DSGRA). We investigate a large number of combinations of performance indexes, boundary conditions, windshear models, and windshear intensities. Inequality constraints are imposed on only the angle of attack or on both the angle of attack and its time derivative.

The following conclusions are reached: (i) optimal trajectories are considerably superior to constant angle of attack trajectories; (ii) optimal trajectories achieve minimum velocity at about the time when the windshear ends; (iii) optimal trajectories can be found which transfer an aircraft from a quasi-steady condition to a quasi-steady condition through a windshear; (iv) among the optimal trajectories investigated, those minimaximizing $|\Delta\gamma|$ are of particular interest, because the altitude distribution exhibits a monotonic behavior; this is true for a moderate windshear and a relatively severe windshear; (v) an extremely severe windshear cannot be survived, even employing an optimized flight strategy; and (vi) the sequential gradient-restoration algorithm has proven to be a powerful algorithm for solving the problem of the optimal flight trajectories in a windshear.

4.5. MIELE, A., Summary Report on NASA Grant No. NAG-1-516, Optimal Flight Trajectories in the Presence of Windshear, 1985-86, Rice University, Aero-Astronautics Report No. 195, 1985.

Abstract. This report summarizes the research performed at Rice University during the period 1984-85 under NASA Grant No. NAG-1-516 on optimal flight trajectories in the presence of windshear. The topics covered include: equations of motion, problem formulation (take-off), algorithms, and numerical results (take-off).

4.6. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Take-Off Trajectories in the Presence of Windshear, Paper No. AIAA-85-1843-CP, AIAA Atmospheric Flight Mechanics Conference, Snowmass, Colorado, 1985.

Abstract. This paper is concerned with optimal flight trajectories in the presence of windshear. With particular reference to take-off, eight fundamental optimization problems [Problems (P1)-(P8)] are formulated under the assumptions that the power setting is held at the maximum value and that the airplane is controlled through the angle of attack.

Problems (P1)-(P3) are least-square problems of the Bolza type. Problems (P4)-(P8) are minimax problems of the Chebyshev type, which can be converted into Bolza problems through suitable transformations. These problems are solved employing the dual sequential gradient-restoration algorithm (DSGRA) for optimal control problems.

Numerical results are obtained for a large number of combinations of performance indexes, boundary conditions, windshear models, and windshear intensities. However, for the sake of brevity, the presentation of this paper is restricted to Problem (P6), minimax $|\Delta h|$, and Problem (P7), minimax $|\Delta \gamma|$. Inequality constraints are imposed on the angle of attack and the time derivative of the angle of attack.

The following conclusions are reached: (i) optimal trajectories are considerably superior to constant angle of attack trajectories; (ii) optimal trajectories achieve minimum velocity at about the time when the windshear ends; (iii) optimal trajectories can be found which transfer an aircraft from a quasi-steady condition to a quasi-steady condition through a windshear; (iv) among the optimal trajectories investigated, those minimaximizing $|\Delta\gamma|$ are of particular interest, because the altitude distribution exhibits a monotonic behavior; this is true for a moderate windshear and a relatively severe windshear; (v) an extremely severe windshear cannot be survived, even employing an optimized flight strategy; and (vi) the sequential gradient-restoration algorithm (SGRA) has proven to be a powerful algorithm for solving the problem of the optimal flight trajectories in a windshear.

4.7. MIELE, A., WANG, T., and MELVIN, W. W., Optimal Take-Off Trajectories in the Presence of Windshear, Journal of Optimization Theory and Applications, Vol. 49, No. 1, pp. 1-45, 1986.

Abstract. This paper is concerned with optimal flight trajectories in the presence of windshear. With particular reference to take-off, eight fundamental optimization problems [Problems (P1)-(P8)] are formulated under the assumptions that the power setting is held at the maximum value and that the airplane is controlled through the angle of attack.

Problems (P1)-(P3) are least-square problems of the Bolza type. Problems (P4)-(P8) are minimax problems of the Chebyshev type, which can be converted into Bolza problems through suitable transformations. These problems are solved employing the dual sequential gradient-restoration algorithm (DSGRA) for optimal control problems.

Numerical results are obtained for a large number of combinations of performance indexes, boundary conditions, windshear models, and windshear

intensities. However, for the sake of brevity, the presentation of this paper is restricted to Problem (P6), minimax $|\Delta h|$, and Problem (P7), minimax $|\Delta\gamma|$. Inequality constraints are imposed on the angle of attack and the time derivative of the angle of attack.

The following conclusions are reached: (i) optimal trajectories are considerably superior to constant-angle-of-attack trajectories; (ii) optimal trajectories achieve minimum velocity at about the time when the windshear ends; (iii) optimal trajectories can be found which transfer an aircraft from a quasi-steady condition to a quasi-steady condition through a windshear; (iv) as the boundary conditions are relaxed, a higher final altitude can be achieved, albeit at the expense of a considerable velocity loss; (v) among the optimal trajectories investigated, those solving Problem (P7) are to be preferred, because the altitude distribution exhibits a monotonic behavior; in addition, for boundary conditions BC2 and BC3, the peak angle of attack is below the maximum permissible value; (vi) moderate windshears and relatively severe windshears are survivable employing an optimized flight strategy; however, extremely severe windshears are not survivable, even employing an optimized flight strategy; and (vii) the sequential gradient-restoration algorithm (SGRA), employed in its dual form (DSGRA), has proven to be a powerful algorithm for solving the problem of the optimal flight trajectories in a windshear.

4.8. MIELE, A., WANG, T., and MELVIN, W. W., Guidance Strategies for Near-Optimum Performance in a Windshear, Part 1, Take-Off, Basic Strategies, Rice University, Aero-Astronautics Report No. 201, 1986.

Abstract. This paper is concerned with guidance strategies for near-optimum performance in a windshear. The take-off problem is considered with reference to flight in a vertical plane.

First, trajectories for optimum performance in a windshear are determined for different windshear models and different windshear intensities. Use is made of the methods of optimal control theory in conjunction with the dual sequential gradient-restoration algorithm (DSGRA) for optimal control problems. In this approach, global information on the wind flow field is needed.

Then, guidance strategies for near-optimum performance in a windshear are developed, starting from the optimal trajectories. Specifically, three guidance schemes are presented: (A) gamma guidance, based on the relative path inclination; (B) theta guidance, based on the pitch attitude angle; and (C) acceleration guidance, based on the relative acceleration. In this approach, local information on the wind flow field is needed.

Numerical experiments show that guidance schemes (A), (B), (C) produce trajectories which are quite close to the optimum trajectories. In addition, the near-optimum trajectories are considerably superior to the trajectories arising from alternative guidance schemes.

An important characteristic of guidance schemes (A), (B), (C) is their simplicity. Indeed, these guidance schemes are implementable using available instrumentation and/or modification of available instrumentation.

4.9. MIELE, A., WANG, T., and MELVIN, W. W., Guidance Strategies for Near-Optimum Performance in a Windshear, Part 2, Take-Off, Comparison Strategies, Rice University, Aero-Astronautics Report No. 202, 1986.

Abstract. In the previous paper, trajectories for optimum performance in a windshear were determined for different windshear models and different windshear intensities. Then, guidance strategies for near-optimum performance in a windshear were developed, starting from the optimal trajectories. Specifically, three guidance schemes were presented: (A) gamma guidance, based on the relative path inclination; (B) theta guidance, based on the pitch attitude angle; and (C) acceleration guidance, based on the relative acceleration.

In this report, several comparison strategies are investigated for the sake of completeness, more specifically: (D) constant alpha guidance; (E) constant velocity guidance; (F) constant theta guidance; (G) constant relative path inclination guidance; (H) constant absolute path inclination guidance; and (I) linear altitude distribution guidance.

Numerical experiments show that guidance schemes (D) through (I) are inferior to guidance schemes (A) through (C) for a variety of technical reasons. In particular, for the case where the wind velocity difference is $\Delta W_x = 120$ ft sec^{-1} and the windshear intensity is $\Delta W_x/\Delta x = 0.030$ sec^{-1}, it is shown that the trajectories associated with guidance schemes (D) through (I) hit the ground, while the trajectories associated with guidance schemes (A) through (C) clear the ground.

4.10. MIELE, A., WANG, T., and MELVIN, W. W., Guidance Strategies for Near-Optimum Take-Off Performance in a Windshear, Paper No. AIAA-86-0181, AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, 1986.

Abstract. This paper is concerned with guidance strategies for near-optimum performance in a windshear. The take-off problem is considered with reference to flight in a vertical plane.

First, trajectories for optimum performance in a windshear are determined for different windshear models and difference windshear intensities. Use is made of the methods of optimal control theory in conjunction with the dual sequential gradient-restoration algorithm (DSGRA) for optimal control problems. In this approach, global information on the wind flow field is needed.

Then, guidance strategies for near-optimum performance in a windshear are developed, starting from the optimal trajectories. Specifically, three guidance schemes are presented: (A) gamma guidance, based on the relative path inclination; (B) theta guidance, based on the pitch attitude angle; and (C) acceleration guidance, based on the relative acceleration. In this approach, local information on the wind flow field is needed.

Numerical experiments show that guidance schemes (A), (B), (C) produce trajectories which are quite close to the optimum trajectories. In addition, the near-optimum trajectories are considerably superior to the trajectories arising from alternative guidance schemes.

An important characteristic of guidance schemes (A), (B), (C) is their simplicity. Indeed, these guidance schemes are implementable using available instrumentation and/or modification of available instrumentation.

4.11. MIELE, A., WANG, T., and MELVIN, W. W., Guidance Strategies for Near-Optimum Take-Off Performance in a Windshear, Journal of Optimization Theory and Applications, Vol. 50, No. 1, pp. 1-47, 1986.

Abstract. This paper is concerned with guidance strategies for near-optimum performance in a windshear. The take-off problem is considered with reference to flight in a vertical plane.

First, trajectories for optimum performance in a windshear are determined for different windshear models and different windshear intensities. Use is made of the methods of optimal control theory in conjunction with the dual sequential gradient-restoration algorithm (DSGRA) for optimal control problems. In this approach, global information on the wind flow field is needed.

Then, guidance strategies for near-optimum performance in a windshear are developed, starting from the optimal trajectories. Specifically, three

guidance schemes are presented: (A) gamma guidance, based on the relative path inclination; (B) theta guidance, based on the pitch attitude angle; and (C) acceleration guidance, based on the relative acceleration. In this approach, local information on the wind flow field is needed.

Next, several alternative schemes are investigated for the sake of completeness, more specifically: (D) constant alpha guidance; (E) constant velocity guidance; (F) constant theta guidance; (G) constant relative path inclination guidance; (H) constant absolute path inclination guidance; and (I) linear altitude distribution guidance.

Numerical experiments show that guidance schemes (A)-(C) produce trajectories which are quite close to the optimum trajectories. In addition, the near-optimum trajectories associated with guidance schemes (A)-(C) are considerably superior to the trajectories arising from the alternative guidance schemes (D)-(I).

An important characteristic of guidance schemes (A)-(C) is their simplicity. Indeed, these guidance schemes are implementable using available instrumentation and/or modification of available instrumentation.

4.12. MIELE, A., WANG, T., and MELVIN, W. W., Optimization and Acceleration Guidance of Flight Trajectories in a Windshear, Paper No. AIAA-86-2036-CP, AIAA Guidance, Navigation, and Control Conference, Williamsburg, Virginia, 1986.

Abstract. This paper is concerned with guidance strategies for near-optimum performance in a windshear. The take-off problem is considered with reference to flight in a vertical plane. In addition to the horizontal shear, the presence of a downdraft is assumed.

First, trajectories for optimum performance in a windshear are determined for different windshear models and different windshear intensities. Use is made of the methods of optimal control theory in conjunction with the dual sequential gradient-restoration algorithm (DSGRA) for optimal control problems. In this approach, global information on the wind flow field is needed.

Then, guidance strategies for near-optimum performance in a windshear are developed, starting from the optimal trajectories. Specifically, an acceleration guidance scheme, based on the relative acceleration, is presented in both analytical form and feedback control form. In this approach, local information on the wind flow field is needed.

Numerical experiments show that the acceleration guidance scheme produces trajectories which are quite close to the optimum trajectories. In addition, the near-optimum trajectories are considerably superior to the trajectories arising from alternative guidance schemes.

An important characteristic of the acceleration guidance scheme is its simplicity. Indeed, this guidance scheme is implementable using available instrumentation and/or modification of available instrumentation.

4.13. MIELE, A., WANG, T., and MELVIN, W. W., Optimization and Gamma/Theta Guidance of Flight Trajectories in a Windshear, Paper No. ICAS-86-564, 15th Congress of the International Council of the Aeronautical Sciences, London, England, 1986.

Abstract. This paper is concerned with guidance strategies for near-optimum performance in a windshear. The take-off problem is considered with reference to flight in a vertical plane. In addition to the horizontal shear, the presence of a downdraft is assumed.

First, trajectories for optimum performance in a windshear are determined for different windshear models and different windshear intensities. Use is made of the methods of optimal control theory in conjunction with the dual

sequential gradient-restoration algorithm (DSGRA) for optimal control problems. In this approach, global information on the wind flow field is needed.

Then, guidance strategies for near-optimum performance in a windshear are developed, starting from the optimal trajectories. Specifically, three guidance schemes are presented: the absolute gamma guidance scheme, based on the absolute path inclination; the relative gamma guidance scheme, based on the relative path inclination; and the theta guidance scheme, based on the pitch attitude angle. In this approach, local information on the wind flow field is needed.

Numerical experiments show that the gamma/theta guidance schemes produce trajectories which are quite close to the optimum trajectories. In addition, the near-optimum trajectories are considerably superior to the trajectories arising from alternative guidance schemes.

An important characteristic of the gamma/theta guidance schemes is their simplicity. Indeed, these guidance schemes are implementable using available instrumentation and/or modification of available instrumentation.

4.14. MIELE, A., WANG, T., and MELVIN, W. W., Quasi-Steady Flight to Quasi-Steady Flight Transition in a Windshear: Trajectory Optimization, 6th IFAC Workshop on Control Applications of Nonlinear Programming and Optimization, London, England, 1986.

Abstract. This paper is concerned with the optimal transition of an aircraft from quasi-steady flight to quasi-steady flight in a windshear. The take-off problem is considered with reference to flight in a vertical plane. In addition to the horizontal shear, the presence of a downdraft is considered. It is assumed that the power setting is held at the maximum value and that the aircraft is controlled through the angle of attack. Inequality constraints are imposed on both the angle of attack and its time derivative.

The optimal transition problem is formulated as a minimax problem or Chebyshev problem of optimal control: the performance index being minimized is the peak value of the modulus of the difference between the absolute path inclination and a reference value, assumed constant. By suitable transformation, the Chebyshev problem is converted into a Bolza problem. Then, the Bolza problem is solved employing the dual sequential gradient-restoration algorithm (DSGRA) for optimal control problems.

Numerical experiments are performed for different windshear intensities and different windshear models. Three basic windshear models are considered: (WS1) it includes the horizontal shear and neglects the downdraft; (WS2) it neglects the horizontal shear and includes the downdraft; (WS3) it includes both the horizontal shear and the downdraft.

The numerical results lead to the following conclusions: (i) not only the transition from quasi-steady flight to quasi-steady flight in a windshear is possible, but it can be performed in an optimal way; (ii) for weak-to-moderate shear/downdraft combinations, the optimal transition is characterized by a monotonic climb; in this monotonic climb, the absolute path inclination is nearly constant through the shear region; this constant value decreases as the shear/downdraft intensity increases; (iii) for severe shear/downdraft combinations, the optimal transition is characterized by an initial climb, followed by nearly horizontal flight in the shear region, followed by renewed climbing in the after-shear region; (iv) the relative velocity decreases in the shear region, achieves a minimum value at about the end of the shear, and then increases in the after-shear region; (v) in the after-shear region, the absolute path inclination increases at a rapid rate after the velocity recovery is almost completed; and (vi) the dual sequential gradient-restoration algorithm has proved to be a powerful algorithm for solving the problem of the optimal transition in a windshear.

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