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CIRCULATION CONTROL – A BIBLIOGRAPHY OF NSRDC RESEARCH AND SELECTED OUTSIDE REFERENCES

by

Michael B. Stone and Robert J. Englar

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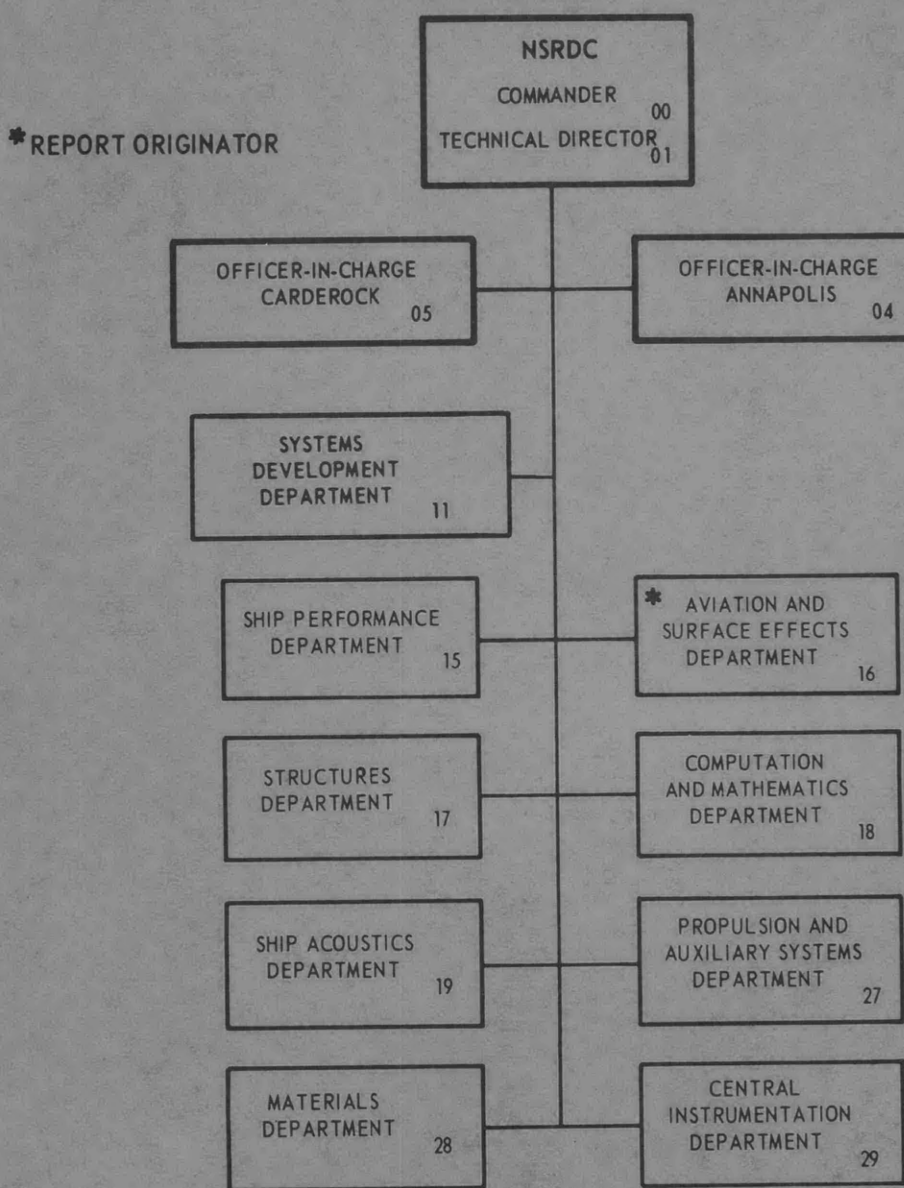

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ABSTRACT

This report presents a bibliography of technical notes, formal reports, and technical papers by personnel of the Rotary Wing Division of the Aviation and Surface Effects Department, Naval Ship Research and Development Center (NSRDC) from the beginning of calendar year 1969 until the end of fiscal year 1973.

The citations are arranged chronologically and represent the technology of circulation control as it has developed at NSRDC. This report also contains appendixes of selected outside references which are pertinent to circulation control.

ADMINISTRATIVE INFORMATION

The work represented by the studies reported herein was supported by the following sponsors: Naval Air Systems Command, Office of Naval Research, National Aeronautics and Space Administration, and in-house IR/IED programs of the Naval Ship Research and Development Center (NSRDC).

INTRODUCTION

The technology of circulation control has evolved steadily at NSRDC during the last four years, and many requests for information have been received from others working in the field. This compilation is an attempt to document in convenient form the work that has been accomplished to date.

The items are arranged chronologically and include short abstracts of the technical notes, formal reports, and technical papers prepared by the Rotary Wing Division of the Aviation and Surface Effects Department. The brief abstracts will enable researchers to determine whether the full report is of particular interest to them.

Two appendixes on outside sources of information are included and arranged in chronological order. The first is limited to presentations on the theory of circulation control; many of them represent the early foundations of circulation control theory. The second appendix consists mainly of technical papers and lectures that augment and supplement the in-house and theoretical presentations.

BIBLIOGRAPHY

1. Williams, Robert M., "Some Research on Rotor Circulation Control," Third CAL/AVLABS Symposium on Aerodynamics of Rotary Wing and V/STOL Aircraft, Cornell University, Buffalo, New York (18–20 Jun 1969) Vol. 2 of Proceedings.

Interest in the feasibility of a two-bladed stowed-rotor aircraft with relatively high disk loading led to a review of high lift schemes. The primary considerations for the choice of a rotor system were hover efficiency, size, gust insensitivity during the transition, and rigidity.

As a first step, the attempt was made to select the most efficient two-dimensional high lift airfoil section. This was done by defining an equivalent lift-to-drag ratio which included a penalty for the power required for either suction or blowing. The total power penalty can be expressed in terms of a drag coefficient defined by:

$$\text{Blowing: } C_{d_T} = (\text{wake drag} + \text{jet momentum flux} + \text{ram drag})/qS$$

$$\text{Suction: } C_{d_T} = (\text{wake drag} + \text{suction quantity} \times \text{pressure drop})/qS$$

Results show that the method of circulation control by tangential blowing over the rounded trailing edge of an ellipse is superior in efficiency. Also, this section adequately fulfills the other requirements for a stowable rotor with the additional advantage that it may completely eliminate mechanical cyclic control by modulation of the supply air. Inasmuch as considerable research had already been completed at the National Gas Turbine Establishment, this rotor system was ideally suited for further study.

2. Williams, Robert M. and Harvey J. Howe, "Two-Dimensional Subsonic Wind Tunnel Tests on a 20-Percent Thick, 5-Percent Cambered Circulation Control Airfoil," NSRDC Technical Note AL-176, AD 877-764 (Aug 1970).

An experimental program was undertaken to develop circulation control high lift airfoils for rotary wing vehicle application. The basic method involves ejecting a thin jet sheet of air tangentially over the rounded trailing edge of a thick airfoil, usually of modified elliptic cross section. The jet sheet remains attached to the rounded trailing edge but eventually separates on the underside. The present report presents results for a 20-percent-thick cambered ellipse. The lift, drag, and section equivalent lift-drag ratio data indicate that this model is one of the most efficient high lift airfoils yet tested.

3. Englar, Robert J., "Two-Dimensional Transonic Wind Tunnel Tests of Three 15-Percent-Thick Circulation Control Airfoils," NSRDC Technical Note AL-182, AD 882-075 (Dec 1970).

Two-dimensional transonic wind tunnel tests were conducted on three 15-percent circulation control elliptic airfoils over the range $0.3 \leqslant M_\infty \leqslant 0.9$. Model configurations

included a pure elliptical shape with both jet flap and tangential upper surface trailing edge blowing and an elliptical shape with a rounded trailing edge and tangential blowing. The rounded trailing edge configuration gave the best performance of the three at low speeds but performance deteriorated rapidly above $M_\infty = 0.55$ due to detachment of the Coanda jet. The elongated trailing edge and associated larger effective radius downstream of the slot enabled the tangentially blown pure ellipse to extend the jet detachment Mach number to 0.7; at this velocity, maximum equivalent lift-to-drag ratios of 22 at C_ℓ of 0.44 and $\alpha = -1.2$ degrees were achieved. The jet flap proved to be inferior to the tangentially blown configuration in all respects except its ability as a thrusting, drag-reducing body.

4. Williams, Robert M. and C.L. Bernitt, "Theoretical Performance of a Pure Jet Flap Rotor at High Advance Ratios," NSRDC Technical Note AL-189 (Dec 1970).

The theoretical performance of a jet flap rotor was examined at advance ratios greater than 1.0. The rotor was four bladed with purely elliptical airfoils of 15-percent thickness ratio. Each airfoil had two plenum chambers which supplied air to slots located beneath the leading and trailing edges. Since the rotor operated in cruise at advance ratios greater than unity, the retreating blade was immersed in reverse flow. The lift and moments were controlled by ejecting a jet sheet out of the trailing edge on the advancing side of the azimuth and out of both the leading and trailing edge on the retreating side of the azimuth.

Standard blade element theory was used to calculate jet flap rotor performance thrust coefficients representative of actual full-scale rotor operation. It was shown that good performance can be obtained by using the jet flap and that substantially better performance can be achieved by using a circulation control airfoil.

5. Ottensoser, Jonah, "Description and Calibration of a Wall Balance System for a 15- by 20-Inch Subsonic Wind Tunnel," NSRDC Technical Note AL-196 (Feb 1971).

A wall balance for a 15- by 20-inch subsonic wind tunnel was built and calibrated. This system uses a set of three concentric rings on each of the two walls of the tunnel test section to measure lift, drag, and pitching moment. Maximum loads are ±300 pounds in lift and ±50 pounds in drag. Calibration results indicate that the balance is reliable to within 1 percent in lift and drag. Moment results are only fair—at best their accuracy is only to within 5 percent.

6. Englar, Robert J. and Robert M. Williams, "Design of a Circulation Control Stern Plane for Submarine Applications," NSRDC Technical Note AL-200, AD 901-198 (Mar 1971).

A nondeflecting circulation control (CC) submarine stern plane was designed in order to provide maneuverability control and eliminate the possibility of catastrophic crash dives due to stern plane jamming. Symmetric elliptic sections with tangential blowing out of upper and lower slots over a rounded trailing edge were selected because of their high lift and equivalent aerodynamic (hydrodynamic) efficiencies. The CC model stern plane so designed was restricted by the requirement to maintain the same planform as a conventional stern plane, by the existence of a large boundary layer on the main body, and by the additional requirement of zero deflection. With moderate blowing, it was able to meet or exceed the prescribed lifting (maneuvering) requirements for the conventional deflecting control surface. In the event of a blowing failure, the fixed nature of the plane provides inherent stability.

The technical note includes a detailed design procedure, supporting experimental data, and the final geometry of the blown model stern plane. Also included is a similar study on an alternate blown configuration with end plates which demonstrated improved performance over the first design.

7. Englar, Robert J., "Two-Dimensional Subsonic Wind Tunnel Tests of Two 15-Percent-Thick Circulation Control Airfoils," NSRDC Technical Note AL-211, AD 900-210L (Aug 1971).

Two relatively thin circulation control (CC) elliptic airfoils were tested subsonically to determine their characteristics as proposed helicopter rotor tip sections. These airfoils employ tangential trailing edge (Coanda) blowing and previous tests had demonstrated very promising transonic characteristics. It was the purpose of the subsonic retests to determine whether these thin sections could generate equally impressive characteristics at low speeds. Because of its more forward slot location, the 15-percent-thick pure elliptic section displayed effective subsonic operation at positive angle of attack, reducing drag while producing lift coefficients up to 3.5. The rounded trailing edge configuration, with further aft slot and better Coanda deflection of the jet, generated lift coefficients up to 4.25 (with a preference for negative incidence) but experienced higher drag levels. Leading edge separation limited the performance of both sections because of their small nose radii and the low test Reynolds number. At a fixed momentum coefficient, performance improved as slot height was reduced. This was due primarily to higher energy levels in the jet sheet, but the lower bound on slot height was limited by boundary layer buildup in very small nozzles. Circulation control gave both CC sections far greater lift capabilities than the more conventional NACA 0012 blade section but their equivalent efficiency was less at positive incidence due to blowing power requirements.

8. Williams, Robert M. and R.A. Hemmerly, "Determination of the (Ideal Practical) Hover Efficiency of Circulation Control Rotors," NSRDC Technical Note AL-212, AD 902-068L (Aug 1971).

Closed form equations were developed for an approximate analysis of the maximum performance of a circulation control rotor (CCR). They conveniently showed the contribution of the induced, profile, compressor, and coriolis powers in terms of the basic airfoil equivalent lift-to-drag ratios. A range of rotor taper ratios and solidities was examined under the constraint of ideal twist distribution. Comparison with a conventional rotor (using a NACA 0012 reference airfoil) indicated that the CCR can achieve comparable overall hover efficiencies (Figure of Merit) at significantly higher values of rotor thrust-coefficient-to-solidity ratio. The presentation includes a brief discussion of the implications of these characteristics for helicopter design.

9. Williams, Robert M., "Analysis of the Hover Performance of a High Speed Circulation Control Rotor," NSRDC Technical Note AL-221, AD 904-474 (Aug 1971).

The method described for calculating the detailed hover performance of any arbitrary CCR includes such higher order effects as nonuniform inflow, internal ducting losses, and experimental airfoil data. Calculations were performed on an untwisted constant chord blade with varying section thickness and camber. Calculated hover Figures of Merit exceeded 0.80 for this rotor at thrust-coefficient-to-solidity ratios of 0.20. The optimum pitch angle was determined for each thrust coefficient, and the effects of slot height and tip Mach number were also analyzed. A comparison was made with a conventional rotor system of the same solidity.

10. Englar, Robert J., "Two-Dimensional Subsonic Wind Tunnel Tests on a Cambered 30-Percent-Thick Circulation Control Airfoil," NSRDC Technical Note AL-201, AD 913-411L (May 1972).

A relatively thick CC elliptic airfoil section with a thickness-to-chord ratio of 0.30 and a circular arc camber of 1.5 percent at the midchord was tested subsonically to determine its aerodynamic properties as a midspan blade section on a blown helicopter rotor. The two-dimensional tests established the ability of the section to generate the required lift at low and negative incidence. Lift coefficients up to 6.5 were produced at moderate momentum coefficient ($C_\mu \leqslant 0.24$). High drag of the unblown bluff ellipse was greatly reduced by the application of very moderate blowing, and equivalent efficiencies of 47 (including power required for blowing) were generated at $C_\ell \approx 1.9$. Section performance was found to be heavily influenced by upper and lower aft surface flow separations, especially at the larger positive and negative angles of attack. In addition, both low Reynolds number and an increase in slot height were detrimental to section lift capability. Nevertheless, the ability to operate at high lift coefficients essentially independent of angle of attack, and with large lift augmentation from relatively low blowing, promises to provide an effective blade section for heavy lift application.

11. Englar, Robert J. and R.M. Williams, "Test Techniques for High Lift Two-Dimensional Airfoils with Boundary Layer and Circulation Control for Application to Rotary Wing Aircraft," Canadian Aeronautics and Space Journal, Vol. 19, No. 3, pp. 93–108 (Mar 1973).

Extensive testing experience with very high lift monoelement blown airfoils to be employed by rotary wing aircraft has necessitated the development of unconventional two-dimensional test techniques. The experimental and analytical results presented here should assist future investigators to conduct similar tests accurately.

The primary problem of high lift two-dimensional testing, wall boundary layer separation due to severe adverse pressure gradients on the model, is discussed as are the serious errors introduced by this phenomenon. Closely related is the preference for pressure instrumentation (both lift and drag) over the simpler but considerably less accurate force balance. The detailed discussion concerns the additional considerations which must be given to blown airfoil testing, e.g., blowing coefficients, necessary modification to pitot-traverse drag calculations, and definition of an equivalent lift-drag ratio which takes into account the penalty for blowing. Such additional test problems as wall and blockage corrections, Reynolds number effects, leading edge separation, and flow visualization are also addressed.

12. Williams, Robert M. and E.O. Rogers, "Design Considerations of Circulation Control Rotors," Paper 603, 28th National Forum of the American Helicopter Society, Washington, D.C. (18–19 May 1972).

The concept of circulation control by means of tangential blowing about bluff trailing edge airfoils is introduced. The major aerodynamic characteristics which are applicable to rotor design are described. These include such revolutionary features as the generation of lift independent of velocity (in the region of boundary layer control) and the development of efficiencies comparable to present airfoils but at much higher lift coefficients. The application of these new airfoils to a rotor with no mechanical cyclic control is next discussed, and it is shown that a broad range of applications are possible. Significant improvements in rotor thrust capability, hover efficiency, cruise efficiency, and weight efficiency are predicted. Some experimental results are shown. A very high-speed helicopter design and a heavy lift helicopter design are used to illustrate the operational improvements which may be expected with the circulation control concept. It is demonstrated that this rotor may offer a breakthrough in helicopter design and performance resulting in a virtual doubling of productivity.

13. Rogers, Ernest O., "Critical Mach Numbers of Circulation Control Airfoils as Determined by Finite-Difference Methods," NSRDC Technical Note AL-273, AD 909-874L (Aug 1972).

The critical Mach number of several circulation control elliptic airfoils was calculated for various circulation and angle-of-attack conditions. The full inviscid compressible flow equations were solved by finite-difference relaxation methods. The sections examined are candidates for use on helicopter rotor blades. Comparisons with conventional sections indicated that the elliptic circulation control airfoils had a significantly higher critical Mach number.

14. Williams, Robert M., "Recent Developments in Circulation Control Rotor Technology," Meeting of Advisory Group for Aerodynamics R&D (Aerodynamics of Rotary Wings) Marseilles, France (13–15 Sep 1972); in AGARD-CPP-111.

The results of recent research on the historical concept of applying circulation control to rotor blades are presented. A high-speed helicopter application was used to illustrate the potential of this rotor for a major breakthrough in the areas of rotor efficiency, parasite drag, and weights, leading to a large improvement in aircraft productivity. Details of the hover, transition, and high-speed cruise performance are presented. Some problems of autorotation, vibrations, and blade dynamics are also discussed.

15. Englar, Robert J. and J. Ottensoser, "Calibration of Some Subsonic Wind Tunnel Inserts for Two-Dimensional Airfoil Experiments," NSRDC Technical Note AL-275 (Sep 1972).

The installation of parallel wall inserts in the NSRDC 8- x 10-foot subsonic tunnel provided a 3- x 8-foot channel to serve as a high flow quality two-dimensional test section for high lift testing. A detailed flow survey indicated good flow uniformity, negligible angularity, a thin wall boundary layer at the model station, and a pronounced effect of trailing edge wall flaps on controlling test section dynamic pressure. The lift and pressure distributions for a pair of two-dimensional airfoil sections tested in the facility were in good agreement with reference data but the agreement was less satisfactory for wake rake drag. The strong influence of model lift on test section dynamic pressure measurement was noted, and a measurement technique was developed which was independent of the static pressure field propagating from the airfoil.

16. Hoffman, J.A. et al., "A Study of Stability and Control Characteristics of a Circulation Control Rotor and Helicopter," Mechanics Research, Inc. under NAVAIR Contract N00019-72-C-0402 (23 Feb 1973).

This study of the stability and control characteristics of a circulation control rotor (CCR) and helicopter essentially involved two separate activities: methods development and handling qualities evaluation studies. The methods development efforts concentrated on the modification of the MRI MOSTAB computer program to include mathematical models for the CC airfoils and the influence of certain high-frequency rotor blade aeroelastic modes. Stability and control derivatives generated by MOSTAB-CCR (the modified CCR version of MOSTAB) were then used to perform an exploratory investigation of the handling qualities of a typical CCR helicopter.

Because of its ready availability from the government inventory, its small size, and the absence of "built-in" stability augmentation systems, the Hughes OH-6A Helicopter was selected as a model for use during the CCR stability and control studies.

In the actual study, the methods development preceded the handling qualities evaluations, but documentation of these activities is presented in reverse order. The handling qualities considerations (i.e., the stability and control examinations) are presented first since this component led to the fundamental conclusions of interest. A detailed documentation of all new methods follows the discussion of handling qualities.

17. Wilkerson, Joseph B., "Design and Performance Analysis of a Prototype Circulation Control Helicopter Rotor," NSRDC Technical Note AL-290 (Mar 1973).

A circulation control rotor (CCR) was designed for application to existing, conventional-speed helicopters of the 5000- to 10,000-pound weight class. The design methodology tended to minimize rotor-induced power in hover while the rotor operates at near maximum airfoil section efficiency. The particular design was constrained by conventional disk loadings and blade tip speeds to be consistent with available helicopter engine/transmission combinations. The design is near optimum within these constraints and current available data. Circulation control airfoil and slot geometry design considerations are shown. Tip speed, solidity, and disk loading were varied to show performance sensitivity to those parameters and to define the conditions of best overall rotor aerodynamic efficiency. The constrained CCR design was found to operate best at a thrust coefficient/solidity ratio around 0.12. At this condition, the hover Figure of Merit improved with increased disk loading while cruise aerodynamic efficiency was relatively insensitive to changes in disk loading. Overall performance exceeded or equalled that of conventional rotor systems for the same weight class vehicle.

18. Stone, Michael B., "Higher Harmonic Circulation Control Rotor Model, Model Instrumentation and Data Acquisition," NSRDC Technical Note AL-288 (Apr 1973).

A higher harmonic CCR was tested in the 8- x 10-foot subsonic wind tunnel at various advance ratios, blade tip Mach numbers, blowing air pressures, shaft angles, and collective angles. The model was instrumented with strain gages, pressure transducers, thermocouples, magnetic pickups, and a pitch-roll trim resolver. This information was recorded on an analog to digital data acquisition system and on FM tape recorders for later digitization.

The purpose was to provide descriptive documentation of the model instrumentation and data acquisition portion of the test, and no attempt was made to elaborate on helicopter or higher harmonic theory.

19. Reader, Kenneth R., "Evaluation of a Pneumatic Valving System for Application to a Circulation Control Rotor," NSRDC Report 4070 (May 1973).

A cam-type pneumatic valving system was developed to provide helicopter rotor control/ trim forces. This valving system provides both first and second harmonic rotor control by means of modulating both blade pressures and mass flow rates. Data are presented for (1) constant one-per-rev and two-per-rev air modulation, (2) constant and tapered slot distributions, (3) two pipe volumes, and (4) three cam-nozzle gap distances.

The present study demonstrated that air pressure and mass flow rate can be modulated by means of a simple cam valve system. As the gap between the periphery of the cams and the nozzle was increased for a given cam geometry, the mean pressure and mass flow rate increased and the peak-to-peak pressure and mass flow rate decreased. It was also demonstrated that a smooth transfer of the total pressure and mass flow rate occurred in going from a one- to a two-per-rev component (or vice versa).

20. Wilkerson, Joseph B. et al., "The Application of Circulation Control Aerodynamics to a Helicopter Rotor Model," Paper 28, 29th Annual Forum of American Helicopter Society, Washington, D.C. (10–11 May 1973).

On the basis of several years of two-dimensional research in the field of circulation control airfoils, a higher harmonic CCR model was designed, built, and tested at NSRDC. Unique features of the model included blades with elliptical-shaped circulation control airfoils and a simple cyclic control mechanism based on the variation of blade pressure rather than blade pitch. The model demonstrated that trimmed flight could be achieved without any moving parts other than the rotating blades and, further, that the high lift capability and efficiency of circulation control airfoils could be extended into the three-dimensional regime.

Aerodynamic trends displayed by the model were coupled with two-dimensional results to improve the theoretical programs used to predict model performance. Variables such as slot height-to-chord ratios, slot height-to-trailing edge radius ratio, Reynolds number, and Mach number have been identified as factors which significantly affect the performance of circulation control airfoils. These effects have therefore been incorporated into the programs. Good agreement between theory and model results have led to a second generation rotor design.

21. Rogers, E.O., "Numerical Solution of Subcritical Flow Past Airfoils," NSRDC Report 4112 (May 1973).

A finite-difference solution technique was developed for subsonic two-dimensional inviscid flow past lifting airfoils. This work is an adaptation of the method used by Sells (1967). The full governing equations of compressible flow are written in terms of a translated velocity potential which is continuous throughout the flow field. This simplifies solutions for bluff airfoils (no Kutta condition) where both angle of attack and lift coefficient are specified. The computational plane is the interior of a unit circle obtained by mapping the flow field into the interior of the circle. A line over-relaxation matrix method is used for solution of the partial differential equation which in the iteration scheme is coupled with an algebraic equation. The numerical procedure is accurate and well behaved for all subsonic flow conditions.

22. Englar, Robert J., "Subsonic Two-Dimensional Wind Tunnel Investigation of the High Lift Capability of a Circulation Control Wing," NSRDC Technical Note AL-274 (May 1973).

A two-dimensional circulation control wing airfoil section was formed by the deflection of a 15-percent chord flap through 180 degrees to produce a circular cylinder trailing edge with tangential upper surface blowing; it was tested subsonically to investigate its high lift capability for STOL application. The thin section, a NACA 66-210 which was 11.5-percent thick after flap deflection, employed nose droop varying from 0 to 45 degrees to control separation from the leading edge at very high lift. A section lift coefficient of 6.0 was produced at a momentum coefficient (C_μ) of 0.24 and $\alpha = 6$ degrees; this represents a threefold increase over the standard airfoil with 60-degree split flap tested at six times the present test Reynolds number (500,000). No lift dropoff with additional blowing (C_μ – stall) was indicated—the above maximum was limited by experimental conditions. Section drag coefficient variation between –0.10 and +0.25 was obtained by variation in the blowing rate. This ability to produce high lift and drag at low incidence promises to provide an effective means of reducing both approach speed and incidence for STOL aircraft.

23. Linck, Drew W., "Hover Investigation of the Higher Harmonic Circulation Control Rotor," NSRDC Technical Note AL-289 (May 1973).

The higher harmonic circulation control (HHCC) rotor model, which had previously been tested in forward flight, was tested on a hover stand. The model proved the high lift capability of circulation control by achieving thrust coefficient-to-solidity ratios of 0.26. Design flexibility was demonstrated by achieving fairly constant values of Figure of Merit over a wide range of thrust coefficients. Likewise, many levels of thrust were obtained at constant geometric collective angles by varying compressor power. The hover test provided Figures of Merit lower than those predicted by a theoretical hover program which had been based on pure two-dimensional circulation control airfoil data. However, when two-dimensional Reynolds number, slot height, and compressibility effects were included in the program, a correlation with the test results was achievable. The correlation indicates that subsequent circulation control rotor designs need to consider slot height-to-chord and slot height-to-trailing edge radius ratios as important design parameters.

24. Englar, Robert J., "Subsonic Wind Tunnel Investigation of the High Lift Capability of a Circulation Control Wing on a 1/5-Scale T-2C Aircraft Model," NSRDC Technical Note AL-299 (May 1973).

A circulation control wing, formed by the deflection of a 15-percent chord flap through 180 degrees to produce a circular cylinder trailing edge with tangential upper surface blowing, was applied to a 1/5-scale model T-2C. The flap span/wing semispan ratio was 0.495, consistent with the flapped span of the conventional aircraft. Subsonic tests were conducted in the NSRDC 8- x 10-foot wind tunnel over a dynamic pressure range from 5 to 40 psf (Reynolds number based on mean aerodynamic chord of 0.59 to 1.68 million). Flap deflection was varied from 0 to 180 degrees, thus comparing the configurations of blown flap (moderate to high lift, lower drag for takeoff) and the Coanda trailing edge (high lift and high drag for landing). At a dynamic pressure of 30 psf (Reynolds number of 1.43 million), a maximum lift coefficient of 3.33 was generated by a momentum coefficient of 0.156, compared to $C_{L_{max}} = 1.70$ for the conventional aircraft with a 37-percent chord slotted flap deflected 33 degrees.

APPENDIX A

SOURCES OF INFORMATION ON THE THEORY OF CIRCULATION CONTROL BY TANGENTIAL BLOWING ABOUT A ROUNDED TRAILING EDGE

Wygnansky, I. and B.G. Newman, "The Effect of Jet Entrainment on Lift and Moment for a Thin Airfoil with Blowing," Aeron. Quart., Vol. XV, Pt. 2 (May 1964).

Dunham, J., "Circulation Control Applied to a Circular Cylinder," Nat. Gas Turbine Est. (England) Report R. 287 (Jul 1967).

Kind, R.J., "A Proposed Method of Circulation Control," PhD Dissertation, University of Cambridge, England (1967).

Kind, R.J. and D.J. Maull, "An Experimental Investigation of a Low-Speed Circulation-Controlled Aerofoil," Aeron. Quart., Vol. XIX, pp. 170–182 (May 1968).

Kind, R.J., "A Calculation Method for Circulation Control by Tangential Blowing around a Bluff Trailing Edge," Aeron. Quart., Vol. XIX, pp. 205–223 (Aug 1968).

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Gartshore, I.S. and B.G. Newman, "The Turbulent Wall Jet in an Arbitrary Pressure Gradient," Aeron. Quart., pp. 25–56 (Feb 1969).

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Jones, D,G., "The Performance of Circulation-Controlled Airfoils," PhD Dissertation, University of Cambridge, Churchill College (Jul 1970).

Harness, G.S., "An Experimental Investigation of a Circulation Controlled Cambered Elliptical Airfoil," Master's Thesis, West Virginia University, Department of Aerospace Engineering (1970).

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Ambrosiani, J.P. and N. Ness, "Analysis of Circulation Controlled Elliptical Airfoil," West Virginia University, College of Engineering, TR-30 (Apr 1971).

Kind, R.J., "A Calculation Method for Boundary Layer Control by Tangential Blowing," Trans. Canad. Aeron. and Space Inst., Vol. 4, No. 2 (Sep 1971).

Walters, R.E. et al., "Circulation Control by Steady and Pulsed Blowing for a Cambered Elliptical Airfoil," Prepared under West Virginia University for ONR (Code 461) Contract N00014-68-A-0512, NR 215-163 (Jul 1972).

Levinsky, E.S. and T.T. Yeh, "Analytical and Experimental Investigations of Circulation Control by Means of a Turbulent Coanda Jet," NASA CR-2114 (Sep 1972).

Dvorak, F.A., "Calculation of Turbulent Boundary Layers and Wall Jets over Curved Surfaces," Accepted for publication in AIAA J. (Nov 1972).

Myer, D.P., "An Experimental Investigation of a Circulation Controlled Cambered Elliptical Airfoil with a Rounded Trailing Edge," M.S. thesis, West Virginia University, Department of Aerospace Engineering (1972).

APPENDIX B

OUTSIDE PUBLICATIONS AND LECTURES ON CIRCULATION CONTROL

Lewis, M.E. and A.R. Seed, "A Preliminary Investigation into the Use of an Electromagnetic Analogue to Determine the Induced Flow of a Lifting Rotor," Nat. Gas Turbine Est. (England) in-house report (Sep 1962).

Cheeseman, I.C. and A.R. Reed, "The Application of Circulation Control by Blowing to Helicopter Rotors," lecture to the Royal Aeronautical Society (Feb 1966); published J.R.Ae.S., Vol. 71, No. 848 (Jul 1966).

Osborn, A.R., "Critical Mach Number of Circulation-Controlled Circular and Elliptic Section," Nat. Gas Turbine Est. (England) in-house report (Apr 1967).

Cheeseman, I.C., "Circulation Control and Its Application to Stopped Rotor Aircraft," presented at Tenth Anglo-American Conference, Los Angeles (Sep 1967); published as a supplementary paper J.R.Ae.S: (Jul 1968) and as AIAA Paper 67-747.

Seed, A.R., "Rotor Induced Flow," presented to AGARD Conference, Gottinger (Sep 1967); available as Technical Memorandum 915 in AGARD Conference Proceedings 22.

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Kind, R.J., "A Calculation Method for Circulation Control by Tangential Blowing around a Bluff Trailing Edge," Aeron. Quart (Aug 1968).

Seed, A.R., "Detachment of Wall Jets from Curved Surfaces," Paper presented at Eromech 16 Symposium on Turbulent Jets, Wall Jets, and Control Jets, Berlin (14–16 Apr 1969).

Smith, M.C.G., "The Aerodynamics of a Circulation-Controlled Rotor," presented to Third CAL/AVLABS Symposium on Aerodynamics of Rotary Wing Aircraft, Cornell University, Buffalo, New York (18–20 Jun 1969).

Kind, R.J., "Calculation of the Normal-Stress Distribution in a Curved Wall Jet," West Virginia University, Department of Aerospace Engineering, Technical Report TR-18 for ONR Project THEMIS Contract N00014-68-A-0512 (Aug 1969).

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13 ABSTRACT

This report presents a bibliography of technical notes, formal reports, and technical papers by personnel of the Rotary Wing Division of the Aviation and Surface Effects Department, Naval Ship Research and Development Center (NSRDC) from the beginning of calendar year 1969 until the end of fiscal year 1973.

The citations are arranged chronologically and represent the technology of circulation control as it has developed at NSRDC. This report also contains appendixes of selected outside references which are pertinent to circulation control.

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Critical Mach Number						
End Plates						
Elliptic Airfoils						
Fluid Flow						
Finite Wing						
Helicopter Blade Airfoil						
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High Advance Ratios						
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Hover Performance						
Induced Velocity						
Inherent Stability						
Jet Flap Rotor						
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