

# **UNSTEADY BLADE FORCES IN A TURBOMACHINE**

**BY**

**VADDADI VENKATA RAMANA RAO**

**Mechanical Engineering Department**

**Submitted**

**in fulfilment of the requirements of the degree of**

**DOCTOR OF PHILOSOPHY**

**To the**

**INDIAN INSTITUTE OF TECHNOLOGY, DELHI**

**September 1982**

CERTIFICATE

We are satisfied that the thesis presented by Sri V.V.RAMANA RAO is worthy of consideration for the award of the degree of Doctor of Philosophy and is a record of the original bonafide research work carried out by him under our guidance and supervision and that the results contained in it have not been submitted in part or full to any other University or Institute for award of any degree/diploma.

*J.S.Rao*

(J.S.Rao)  
Professor & Head,  
Mechanical Engg. Department,  
Indian Institute of Tech.,  
New Delhi-110016

*V. Seshadri*

( V. Seshadri) <sup>10/9/82</sup>  
Professor,  
Applied Mechanics Department  
Indian Institute of Technology,  
New Delhi-110016

## ACKNOWLEDGEMENTS

The author is grateful to the authorities of Sri Venkateswara University, Tirupati, for sponsoring him to do Ph.D under Quality Improvement Program and the authorities of Indian Institute of Technology, Delhi for extending all facilities to carry out this work.

The author wishes to express his sincere thanks and deep sense of gratitude to Prof. J.S.Rao of Mechanical Engineering Department and Prof. V.Seshadri of Applied Mechanics Department, I.I.T.Delhi, for the continuous guidance and sustained encouragement given by them during the execution of this work and the keen interest they have evinced in the progress of this work.

Sri Arun K. Agarwala, young and dynamic Design Engineer from IDDC, deserves thanks from the author for helping him in designing filter circuits and in solving instrumentation problems.

The author thanks Sri Sitaram Bhogal and his fine team of workers consisting of S/Shri Onkar Singh, Ram Sarup, Rakshpal Bhogal, Dewan Singh, Roop Ram and Rameshwar Dayal, from the Fluid Mechanics Laboratory but for whose help and cooperation the experimental work mentioned in this thesis would have been difficult.

The author's thanks are due to the staff of IDDC, Gas Dynamics Laboratory, Mechanical Engineering Workshop

and Applied Mechanics Workshop, who have extended their cooperation in developing and fabricating the experimental set-ups.

The discussions with Dr. P.N.Rao from Mechanical Engineering Department, Dr.J.V.Rao from Computer Centre, Dr. B.B.Madan from CARE and Shri Ratan Moolchandani from IDDC have helped the author considerably in carrying out this work. He expresses his thanks to them.

The help extended by Dr. A.J.Chapgar from N.P.I. in sparing the services of the real time analyser is very much appreciated.

The author thanks his wife, Ratna, for having faced cheerfully all the difficulties that were encountered during their three years stay at Delhi.

Sri C.M.Manocha deserves appreciation from the author for the care he has taken and the patience he has exhibited in typing this thesis.

Finally, the author wishes to thank Prof.J.S.Rao and Smt. Indira J.S.Rao for the affection they have shown towards him and his family during their stay at Delhi.

(V.V. Ramana Rao)

## ABSTRACT

An attempt is made to evaluate the unsteady aerodynamic forces in a turbomachine stage analytically and verify them by an analogy. The quantitative assessment of these unsteady forces which arise due to potential and wake interactions in a turbomachine stage is of utmost importance, since these forces lead to dangerous vibrations which may cause in-service failures of the machine.

The interaction model considered for theoretical investigations consists of a turbomachine stage with an upstream and downstream blade rows. The blade rows are considered as two-dimensional infinite cascades. The aerodynamic quantities of interest are unsteady lift and unsteady moment on a particular blade. Flow is assumed to be inviscid, except that the viscous wakes behind upstream blades are considered as regions of velocity defect. Successive approximation scheme is used in that while calculating the unsteady quantities at a particular blade, the entire unsteady effect on the circulation of any blade is taken to be small compared to the steady circulation carried by the blade. The flow is assumed to be compressible and subsonic. The analysis is made for a general camber airfoil having incidence to the flow. The effects of interactions were ultimately brought in the forms of upwash and downwash distributions over the

blades, and from these upwash and downwash components the unsteady lifts and moments due to various interactions are obtained through the application of basic isolated airfoil theories. A computer program is developed which calculates the unsteady lifts and moments due to the above interactions, for a general camber airfoil. Computations have been made over a wide range of geometric parameters and Mach number.

The theory developed for the determination of unsteady forces has been substantiated by experimentation through the use of hydraulic analogy which utilizes the fact that the governing equations for a two-dimensional isentropic compressible gas flow are similar to the equations for a free surface incompressible water flow. A modified analogy which is suitable for simulating real gas flows on water table is used to simulate a simple flat plate stage on a rotating water table. As a first step in this direction, the validity of hydraulic analogy and in particular that of modified analogy has been established by considering compressible gas flow through an axisymmetric rocket nozzle. Isentropic, both subsonic and supersonic, and flows with shocks in the divergent section of the nozzle have been studied analytically and are simulated on the water table. From these studies, it is shown that, within the experimental errors, the modified analogy can be effectively used for the study

of two-dimensional isentropic flow of gases, and flows with weak shocks. The experimental results obtained from the simulation of flat plate stage on rotating water table, through thus established modified analogy are compared with the computed results obtained for the stage geometry under consideration.

## CONTENTS

|  | <u>PAGE</u> |
|--|-------------|
| CERTIFICATE  |             |
| ACKNOWLEDGEMENTS   |             |
| ABSTRACT   |             |
| TABLE OF CONTENTS  | (i)         |
| LIST OF FIGURES  | (v)         |
| LIST OF TABLES   | (ix)        |
| NOMENCLATURE   | (xiii)      |
| <br>   |             |
| CHAPTER  |             |
| 1. INTRODUCTION  | 1           |
| 2 LITERATURE SURVEY  | 8           |
| 2.1 Basic isolated airfoil theories  | 9           |
| 2.2 Blade cascades and interference phenomena  | 20          |
| 2.3 Hydraulic analogy and its applications   | 33          |
| 3 BASIC ISOLATED AIRFOIL THEORIES  | 46          |
| 3.1 Isolated airfoil in incompressible flow  | 47          |
| 3.1.1 Effect of a gust in the direction perpendicular to the mean flow   | 47          |
| 3.1.2 Effect of a gust in the direction parallel to the mean flow  | 50          |
| 3.1.3 Response of airfoils subjected to both convecting and non-convecting flow perturbations - Extension of analysis to camber profile airfoils | 51          |
| 3.1.4 Effect of incidence and camber   | 56          |
| 3.1.5 Response of general camber airfoil for non-convecting streamwise gust  | 58          |
| 3.2 Isolated airfoil in compressible flow  | 62          |

| CHAPTER |  | <u>PAGE</u> |
|---------|--|-------------|
| 4       | INTERFERENCE EFFECTS IN A TURBOMACHINE<br>STAGE  | 69          |
| 4.1     | Formulation of the problem   | 69          |
| 4.2     | Interference of rotor on stator  | 75          |
| 4.3     | Interference of stator on rotor  | 86          |
| 4.4     | Application of isolated airfoil theories   | 88          |
| 4.4.1   | Unsteady lift and moment on stator   | 89          |
| 4.4.2   | Unsteady lift and moment on rotor  | 93          |
| 4.5     | Unsteady lift and moment on rotor due<br>to vortex wakes interaction                     | 95          |
| 4.6     | Unsteady lift and moment due to viscous<br>wake interaction                              | 99          |
| 4.7     | Results and discussion   | 108         |
| 4.7.1   | Flat plate blades with incidence   | 114         |
| 4.7.2   | Parabolic cambered blades  | 120         |
| 4.7.3   | Blades with skewed mean line   | 125         |
| 5       | HYDRAULIC ANALOGY  | 207         |
| 5.1     | Two-dimensional classical analogy  | 207         |
| 5.2     | Analogy with non-rectangular cross-<br>section for gases with any specific<br>heat ratio | 212         |
| 5.3     | Limitations of hydraulic analogy   | 214         |
| 5.4     | Modified analogy   | 218         |
| 5.5     | Axisymmetric converging-diverging<br>nozzle, nozzle geometry                             | 223         |
| 5.6     | Gas dynamic solution for flow through<br>the nozzle                                      | 226         |
| 5.6.1   | Isentropic subsonic flow   | 226         |
| 5.6.2   | Transonic flow   | 228         |
| 5.6.3   | Isentropic supersonic flow   | 229         |
| 5.6.4   | Non-isentropic flow - Flow with a<br>normal shock  | 229         |

| CHAPTER |   | <u>PAGE</u> |
|---------|---|-------------|
| 5.7     | Equivalent 2-D Nozzle, nozzle geometry  | 233         |
| 5.8     | Analytical water table solutions  | 235         |
| 5.8.1   | Isentropic subsonic flow  | 235         |
| 5.8.2   | Transonic flow  | 237         |
| 5.8.3   | Isentropic supersonic flow  | 237         |
| 5.8.4   | Non-isentropic flow - Flow with a hydraulic jump                                  | 238         |
| 5.9     | Concluding remarks  | 247         |
| <br>6   | <br>SIMULATION OF GAS FLOWS THROUGH CONVERGING<br>DIVERGING NOZZLE ON WATER TABLE | <br>253     |
| 6.1     | Description of water table  | 253         |
| 6.2     | Simulation of isentropic flows  | 255         |
| 6.2.1   | Isentropic subsonic flow  | 255         |
| 6.2.2   | Isentropic low subsonic flow  | 262         |
| 6.2.3   | Transonic flow  | 266         |
| 6.2.4   | Isentropic supersonic flow  | 268         |
| 6.3     | Effect of Reynolds number in the supersonic flow                                  | 277         |
| 6.4     | Simulation of non-isentropic flows  | 280         |
| 6.5     | Effect of Reynolds number in the post shock region                                | 284         |
| 6.6     | Concluding remarks  | 286         |
| <br>7   | <br>SIMULATION OF A FLAT PLATE STAGE<br>ON A ROTATING WATER TABLE                 | <br>298     |
| 7.1     | Modelling aspects   | 299         |
| 7.2     | Description of the rotating water table   | 301         |
| 7.2.1   | Mechanical construction   | 301         |
| 7.2.2   | Flow circuit and measurements   | 306         |
| 7.2.3   | Instrumentation   | 307         |
| 7.3     | Simulation of the stage   | 311         |

| <u>CHAPTER</u> |   | <u>PAGE</u> |
|----------------|---|-------------|
| 7.4            | Test Procedure                                      | 313         |
| 7.5            | Analysis of the test data                           | 314         |
| 8              | CONCLUSIONS AND RECOMMENDATIONS<br>FOR FURTHER WORK | 343         |
| 8.1            | Conclusions   | 343         |
| 8.2            | Recommendations for further work                    | 345         |
|                | REFERENCES  | 346         |
|                | APPENDIX A  | 363         |
|                | APPENDIX B  | 368         |
|                | APPENDIX C  | 372         |
|                | APPENDIX D  | 375         |
|                | APPENDIX E  | 379         |
|                | BIO-DATA OF THE AUTHOR                              |             |