CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

A hybrid method has been developed and validated for unsteady and forward flight applications. The hybrid methodology is a combination of Navier-Stokes, potential flow and free wake methods and can be used to model rotors in forward flight. The entire wake is modeled from first principles as an integrated part of the hybrid solution. The blade dynamics module can handle blade pitching and flapping motions and the complex blade deformation due to aeroelastic effects. An appropriate interface for coupling the solver to a computational structure dynamics code (CSD) has been developed. The trim module implemented in the potential flow solver, which serves as a preprocessor to the hybrid code, provides the capability for adjusting the collective pitch and cyclic pitch to obtain the desired thrust coefficient, tip path plane angle, and pitching and rolling moments based on the values input by the user. The hybrid method, in conjunction with a CSD code, thus covers all the important disciplines in rotor forward flight: aerodynamics, aeroelasticity, blade dynamics and trim. It provides a way of comprehensive modeling of rotorcraft in forward flight.

In this chapter, some concluding remarks on the hybrid technique and its application are given. Recommendations for future work to improve and extend this methodology are subsequently made.

6.1 Conclusions

The major conclusions from this research are summarized as follows:

1. The hybrid method integrates the most appropriate models in different flow regions, aimed at capturing all the important aerodynamic phenomena such as transonic flow, dynamic stall and blade vortex interaction. The results indicate that this approach is an efficient and accurate way of modeling rotors in forward flight.

2. Compared to a conventional Navier-Stokes analysis, for a four-bladed rotor, the present method is nearly 6 times as efficient. In other words, a four bladed forward flight analysis using 310,000 nodes per blade will require over 80 CPU seconds per time step with a full Navier-Stokes method. The present hybrid method will require only 13 CPU seconds per time step. The hybrid method, in its present form, requires 50 CPU hours for two rotor revolutions on a Silicon Graphics O2 system. With faster processors or distributed/parallel computing, overnight simulations are certainly feasible with this approach.

3. The validation studies in rotor forward flight show that inclusion of tortional deformations is extremely important. In the UH-60A high speed forward flight calculation, the agreement with the experimental data was improved dramatically with the inclusion of the elastic effects. The negative lift due to the rotor deformation can be captured only using the elastic information from the experimental data. In the AH-1G descent calculations, where information on elastic deformation was not available, the hybrid calculation gave less satisfactory results.

4. The AH-1G results demonstrate the method's ability to predict the three-dimensional unsteady flow about a rotor which generates and interacts with its wake system, without need for wake information from an external comprehensive analysis code. The wake is modeled as an integral part of the hybrid analysis using either a prescribed wake model or a free wake model. At the advance ratios considered (μ>0.16), the free wake and prescribed wake based inflow models gave comparable results, even though the vortex geometry was entirely different for these two methods, and the blade vortex interaction phenomena were present. This is because the loads were affected mainly by the downwash. The distortion of the wake geometry from the basic helical shape can be captured by the free wake model.

5. Measured data regarding blade dynamics is often inaccurate, or simply not available. A trim analysis should always be done as part of any forward flight analysis, based on user supplied thrust level C_T/σ, α_{tpp} and desired pitching and rolling moments. The supplied tip path plane angle is used to set blade flapping motion. In this work, a consistent way to trim the rotor has been developed and gives good results. The desired C_T/σ, α_{tpp} and moments are achieved through the adjustment of the collective and cyclic pitch.

6.2 Recommendations

The hybrid methodology has been validated in rotor forward flight against experimental data. Based on the results of the present work, it is recommended that the following improvements be considered:

1. In the calculation of the induced velocity by the embedded wake, Biot-Savart law occasionally produces velocity spikes when wake markers are very close to a computational node. This can lead to unrealistically high velocity, and low density values. Alternate approaches for computing the rotational component of velocity in potential flow zone need to be explored.

2. In descent flight at low advance ratio, the variations of dynamic loads due to blade-vortex interactions lead to abrupt changes in loads. The present approach captures these variations well. In some instances, a secondary post

BVI blip in the computed loads occurs. This high secondary peak may be due to the use of a fixed vortex core size in the hybrid analysis before and after the BVI phenomena. Johnson [6] has stated that vortex size may increase following a BVI encounter. Further studies are needed that include a vortex core dissipation model [6] and eliminate the unrealistic secondary peaks.

3. The hybrid solver uses a third or fifth order upwind scheme in space. To reduce the numerical dissipation in capturing the tip vortex in viscous zone, spatially higher order schemes such as 7th order ENO scheme [48] need to be implemented. This will allow the grid size in the tip vortex region to be small.

4. The transpiration boundary condition approach used in this work is not suitable in forward flight cases, involving complex blade dynamics and large blade deformation. An exact approach needs to be used. Improved grid deformation algorithms and Newton sub-iteration scheme should be explored to solve the stiffness problem encountered in the current exact approach.

5. In high speed rotor forward flight, dynamic stall may occur on the inboard section of the retreating side due to the reversed flow and high angle of attack. The accurate prediction of dynamic stall is dependent on an appropriate turbulence model and transition model. In the current hybrid method, a zero equation (Baldmin-Lomax) algebraic turbulence model was used. More advanced turbulence models and transition models such as the one equation

Spalart-Allmaras model [115], k-ε model and Michelle's transition model [116] should be studied to assess the benefits of these models.

In conclusion, an efficient, first principles based approach for modeling rotors in forward flight has been developed and validated. It is hoped that this work will provide a useful step in the development of first principles based modeling of complete rotorcraft configurations.