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Report on A. Gomar's Ph.D Thesis *(L. He , 21 March, 2014)*

"Multi-Frequential Harmonic Balance Approach for the Simulation of Contra-Rotating Open Rotors: Application to Aeroelasticity"

1 General

1.1 Relevance of the Work

There are two major aspects to which the present work is regarded as closely relevant and important.

Firstly the development of open rotor technology with strongly revived recent interest in aero-engine industry and R&D community presents considerable opportunity and potential for next generation aircraft propulsion systems. Advanced design and analysis methods are needed to deal with the two major technical challenges in open rotor development: noises and structural vibrations generated in un-ducted rotors. The work documented in this thesis would enhance the capabilities in analysing both types of problems for open rotors.

Secondly unsteady flow solution methodologies are at the forefront of advanced design method developments for turbomachinery in general. Prediction of blades aeroelasticity (flutter and forced response as flow-induced vibrational pheonomana) problems remains among the most challenging in new gas turbine/engine development. The need for fast and accurate CFD methods for unsteady flow around vibrating blades has been increasingly highlighted by the multi-disciplinary constraints (which increasingly dictate the outcome of a new gas turbine development) in a design environment.

As the originator of the Fourier-based approach to turbomachinery unsteady flow simulations and analyses, the present reporter has a declared interest (in addition to extensive experience) in any new development and applications of the kind for the last 25 years or so. A particular issue of interest to all main developers and users involved in the Fourier methods is the capability in capturing and resolving multiple disturbances of distinctive frequencies. Although the general formulations and relatively simple demonstration cases of the Fourier methods' capability for multi-disturbances in turbomachinery unsteady flows were introduced in early 1990's, there have been hardly attempts for realistic 3D multistage configurations with arbitrary blade counts. Also, the stiffness issue of the problems with disparate multi-frequencies has not been effectively addressed at all.

Overall, the present reporter has no doubt that the work performed under this Ph.D is of close engineering relevance and practical importance, addressing significant technical challenges presented in the state of the art in the field.

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1.2 Main Technical Contributions

There are two major original technical contributions arisen from this Ph.D work.

Firstly the candidate should be commended for the development, verification and demonstration of the gradient optimization algorithm for selecting the non-uniform temporal samplings. It is recognised that the direction of the effort and the problem statement owes to a previous PhD project of the same group. But still, it is clear that the particular algorithm developed as part of the present Ph.D project is simple and effective (hence very useful in an engineering sense) in controlling otherwise very disparate conditioning numbers. The framework seems rigorous and systematic (hence scientifically sound) and the improvement as demonstrated the case studies is quite remarkable.

Secondly the analysis of the harmonic spectral convergence has been quite thoroughly carried out. The error analysis has thrown some useful light on the aliasing behaviour for a typically turbomachinery blade wake (albeit a rather idealised wake profile). The harmonic convergence is a common issue and source of uncertainty bothering people using the Fourier methods. The proposed priori estimator/guidance based on the steady mixing place solution, as a guidance of this kind, should provide a comparable platform using a harmonic solver more consistently for ranking different designs (although it may be argued that the treatment might look to be on a more conservative side - as a wake convected further downstream tends to be much thicker than that when it is measured at an intra-row interface).

The test case studies and analyses conducted as documented are all useful to various extents, some are more telling than others in terms of serving the central themes of the thesis. The results and discussions give confidence in the quality of the work.

The overall outcomes of the work as presented in the thesis are good. The development has enhanced the predictive capability of the CFD method significantly, forming a good basis for further development, enhancement and applications.

1.3 Thesis Presentation

The thesis is very well structured and written in good English. The documentation provides some useful guidance for future development and application of the approach. The reporter has picked up some typos, which can be easily rectified to improve the presentation quality of the thesis (the list of typos is given after the specific comments).

The following are some specific points, some of which may sound critical, but are meant to be constructive, striving for future improvement (or simply taken as points of view).

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2 Specific Comments

Chapter 1: A good introduction to the general background and brief justification of the thesis work are presented. The general case for pursuit of open rotor is well made and the main challenges faced in the technology development for open rotor are well articulated. The relevance and importance of the rotor blade aeroelasticity is particularly emphasized, rightly so.

Chapter 2: Introduction to Aeroleasticity is brief but adequate. The reporter would be happy with the blade aeroelasticity problems being divided into flutter and forced response. He is less sure of the labelling of Fig.2.4 (b) amplified (flutter) and (c), which might be taken as implying that (c) is not flutter - better to label (b) as 'linear flutter instability'. LCO is a balanced (still unstable) state dictated by nonlinearity (aerodynamic or structural damping wise).

The modal description is adequate. However, the term 'weak-coupling approach' may be more suitably called 'decoupled approach'. In fact, there has been some previous work to link the decoupled to fully coupled approach in frequency domain (Moffatt and He, 2005). At least it should be clearer that the basis of the energy method (i.e. work-sum ➔ aero-damping for stability) is based on the assumption that the eigen mode shapes and frequency are only negligibly affected by blade oscillations induced unsteady aerodynamics (thus decoupled approach is justified).

Chapter 3: The Fourier based time methods are introduced. While this is done quite comprehensively with most major works being cited, the literature review is still more confined to the frequency domain formulations - otherwise the Fourier method as firstly introduced in 1990 (the shape correction) should be recognised. As a matter of fact, the multi-frequency formulation (3.21) had been introduced, used and published about 10 years earlier than [50].

While the description of the nonlinear harmonic method is comprehensive, a point for clarification may be worth noting: For N harmonics, the NLH model would only need to solve N *complex-number* harmonic equations (e.g Eq.3.20) plus a real number time-averaged flow equation. Thus for Eq.3.20 and others, the range of index should be, $k \in (1,N)$. Each complex harmonic equation is equivalent to 2 real number equations in terms of the amount of computations needed due to the need of balancing both real and imaginary parts. Hence in total, the computational effort of one NLH model retaining N harmonics is indeed equivalent to that of 2N+1 steady-like solutions. Once the real and imaginary parts of the +N harmonics are solved, their conjugate counterparts can be directly constructed.

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The HB method has been well covered. Both the history and methodology essences are comprehensively described. In the context of contrasting different Fourier formulations, it might be helpful if the name 'harmonic balance' can be interpreted/explained in the formulations and embodiment of the method – e.g. where is 'balancing'? ('Fourier time spectral method' may be more appropriate, but this is out of the remit of the thesis understandably).

Another point worth noting in this chapter is the choice of the frequencies to be retained. It looks to be much of an ad hoc treatment at this stage, but its importance as well as uncertainty may be problem dependent.

Chapter 4: The baseline verifications of the HB method have been carried out quite comprehensively for the linear advection problem. The problem with non-negligible nonlinearity is interestingly illustrative. There are two primary harmonic disturbances (specified with their frequencies and amplitudes) at the channel exit, but a large number of induced 'sub-harmonics' exist, as identified in the spectrum. Hence the harmonic spectral convergence can only be achieved with a relatively large number of harmonics (N=9). A good agreement with the direct time domain nonlinear solution is obtained.

It is taken (assumed) that the exit boundary condition is non-reflective (so that none of the 'sub-harmonics' should be induced by the way the BC is treated). Some clarification/examination re the dependence of the induced harmonics on the exit BC might be more instructive.

Chapter 5: This is probably the most interesting and original chapter. The problem statement regarding the relevance and importance of the matrix condition number is well made. Its significance in solution accuracy and convergence stability is clearly illustrated in the test results. Built on the previous APFT technique, quite useful in its own right, the present thesis work has progressed to develop a clearly better and more effective method in overcoming the problem. The sample results of the OPT algorithm are impressive, confirming the effectiveness of the new method. This chapter is very well structured and written.

Chapter 6: This is also a substantial chapter, dealing with the harmonic spectral convergence in relation to a well-established (though idealised) wake model. A systematic analysis has been carried out on the spectral errors. The examination in terms of the wake width is of practical significance, and the results of the errors-harmonic dependence are helpful, though qualitatively as expected. Detailed examination and explanation of the plateau in the error spectral and the dependence on number of harmonics are made to give some insight.

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The rather systematic analyses are followed by a proposal for a priori error estimator based on the initial steady mixing-plane solution for intra row interfaces. This is a practically convenient option.

The chapter is reasonably well written. It is felt however that clarity may be improved if a distinction in the spectral errors between the spatial Fourier representation (on upstream side of an interface) and the temporal harmonics (as used in a HB solution). A point which may not be readily appreciated by readers not working on implementing the Fourier methods is that one can take as many harmonics as one likes in the spatial FT without paying much price at all. This (the spatial FT and harmonic truncation in generating suitable harmonic inlet/interface boundary conditions) should be clearly separated from the harmonic dependence (i.e. the number of harmonics retained) in the HB solution. For instance, Fig.6.5 shows that N=2 is almost completely useless, as it cannot pick up any unsteadiness, whilst the results in Fig.6.10 show a very different behaviour for N=2. It could be assumed that for the former, only 5 sampling points of the spatial distribution were taken, which might easily miss the wake profile altogether.

Related to the above, some more details should perhaps be given in relation to the interface treatment (either in this section or in the previous section when the HB method is first introduced) – to help to clarify what are missed /truncated when passing data from one side of the intra-row interface to another.

Chapter 7: Validation of the HB method for oscillating blades. The results look sensible. The mesh dependence is addressed briefly, so is the dependence on the discretization schemes. Both subsonic and transonic conditions are considered. Although some nonlinearity is expected for the transonic case, the response still seems to be quite linear and single harmonic looks to be more than adequate. The reporter is a bit unsure of the discussion re the nonlinearity based on a steady shock argument. The nonlinear behaviour may not sufficiently show itself up for the current mesh with the relatively coarse resolution in the shock foot. A finer local resolution and a slightly larger blade oscillating amplitude may lead to a different outcome.

A general observation to make re the aeroelaticity validation cases is that they are all still mainly confined to 2D.

Chapter 8 describes a low speed open rotor case. Aerodynamics analyses are conducted for the coupled rotor-rotor configuration. The results look sensible, but no experimental data were available for comparisons. The aeroelastic analysis is carried out for the frontal rotor, the results look sensible,

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Chapter 9 presents the results at a high speed condition for the same open rotor configuration. Again, the aerodynamics analyses are conducted for the coupled rotor-rotor configuration. The aeroelastic analysis is carried out for the frontal rotor, the results look sensible.

Finally the conclusions summarizing the major findings and achievements of the present thesis and some recommendations for the future work are presented. While recommended future works include all the main thrusts to the future applications, one extra point should be considered: aeroelastic multi-row effects. The damping of the first rotor can be quite considerably affected by the acoustical reflection from the second one, and vice versa.

Some Typos

p30 'shown to exists' ➔'shown to exist'

p33, 'has then be' ➔ 'has then been'

p72, 'time instances'➔ time instants (a few places)

p74, 'Baring' ➔ 'Bearing'

p110, 'bare' ➔ 'bear'

p127, 'baring' ➔ 'bearing'

p137, ' bellow'➔ 'below'

p138, 'bare' ➔ 'bear'

On the whole, the present reporter very much appreciates the challenges faced, the efforts put in and the useful and valuable outcomes of the project. The work as presented should be of a standard for a PhD degree. As such, the reporter would like to recommend it for the viva defence.

Professor L He, FASME, FRAeS