Passage-Spectral Method for Fluid Instabilities
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Abstract
The non-axisymmetric nature of the flow into a rotor-stator cavity with a number of counter-rotating vortex pairs presents a computational challenge as a full 360 circumferential domain will be needed, requiring a significant amount of computational resource. The goal is to be able to run a certain number of sectors (few lower order Fourier harmonics) of the circumferential domain in order to capture the large scale structures. We propose a spatial Fourier approach filtering to capture the long length-scale unsteady flow features of interest. The purpose of using a Fourier modeling is to reduce the computing resource required by a direct calculation of the whole domain of 360 circumference. The circumferential domain can be truncated to such an extent as long as it can provide sufficient information to carry on the Fourier transform in the circumferential direction. For more engineering applications, only a few lower order harmonics will be sufficient.

Introduction
Fluctuating pressure structures which are previously shown to form inside the disc cavity can influence the gas ingestion from the main flow stream. These rotating low pressure regions can reduce the lifetime of the turbine by overheating the components, induced by ingestion of hot gas, and influencing the mechanical integrity of the device. With the demands of further aerothermal performance enhancement, there is an increasingly need not only for better understanding of the dominant interaction mechanisms and influencing parameters, but also adequate analysis tools for rotating flows in a design process, which presents a computational challenge as a full circumferential domain will be needed. The method of using the Fourier series in computing nonlinear time-domain unsteady flows has been first proposed by He [1], who extend the Fourier modeling methodology to nonaxisymmetrical steady and unsteady flows, in conjunction with the technique of a simultaneous Fourier transform, using a simple spatial Fourier spectrum over the whole domain to capture the unsteadiness with one or more unknown frequencies. Stapelfeldt [2] modelled a whole annulus multi-stage using a time-domain Fourier method, which can be used do general non-axisymmetric flows across multiple blade rows. In this work, we apply the spatial Fourier method to other purposes, filtering to capture the long length-scale unsteady flow features of interest.

Main Objectives
Once we will be able to solve efficiently 3D rotating flows in a open rotor-stator cavity, we will be capable to study the behaviour of this unsteady and non-axisymmetric kind of flow. The reduction factor \( R \) in computational mesh points in the circumferential direction for 3D non-axisymmetric domain geometry in comparison with a direct whole annulus solution will be
\[
R = \frac{\text{total number of mesh points in direct solution}}{N + 1}
\]

Materials and Methods
The work to be carried out in this thesis is partly funded by FEP and so this work has a markedly industrial focus. Passage-Spectral method has been implemented into the in house code called MesoTurb (MultiRow Unsteady Unstructured Specific Solver for Turbomachinery) in order to run CFD simulations.

Mathematical Section
At any time instant \( t \), the flow variable is decomposed by \( N \)th order Fourier series, thus at any given \((x, r)\)
\[
U(x, r, \theta, t) = \sum_{n=1}^{N} \left[ A_n(x, r, t) \sin(n\theta) + B_n(x, r, t) \cos(n\theta) \right]
\]
(2)
The Fourier coefficients in Eqn 1 are time-dependent and need to be evaluated at every time step to approximate the instantaneous distribution. For given flow variables \( U \) at 2N + 1 mesh points
\[
\sum_{x=1}^{2N+1} \frac{1}{2N+1} U_i
\]
(3)
\[
A_n(x, r, t) = \frac{2}{2N+1} \sum_{i=1}^{2N+1} U(i \sin(n\theta_i))
\]
(4)
\[
B_n(x, r, t) = \frac{2}{2N+1} \sum_{i=1}^{2N+1} U(i \cos(n\theta_i))
\]
(5)
Once Fourier coefficients have been calculated at each mesh cell, we need to evaluate/assign the flow variables at the dummy points to enable fluxes or differences calculations at each time-step iteration. This implementation would have a minimum influence on the flux calculation routine, we only need to modify how the flux calculation is corrected at the periodic patches.

Results
The first case studied is carried out for a model rotor-stator cavity configuration Figure 2. After a few hundred time steps, the 360 direct solution and the reduced passage approach with 4 harmonics (9 samples) produce a pattern with 2 pair of vortices on the radial velocity. It was observed that the vortex core would typically slip relatively to the rotating disk surface at a fraction of rotation speed. The Fourier solutions indicate that a number of harmonics higher than the number of vortex pairs would be enough to resolve with adequate accuracy and a significant reduce in the computational time and memory.

Figure 2: Unsteady radial velocity perturbation within a rotor-stator cavity midplane

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To the authors’ knowledge, this works presents for the first time the application of a reduced-passage method to non-axisymmetric geometries such as rim ingestion or a whole fan stage annulus. The method presented here provides an efficient means of approximating flows with spatial Fourier methods. However, the studies performed are not exhaustive and a wider range of applications must be analysed in the future to build a complete understanding.

Conclusions
• We can achieve a significant reduction in the computing memory and time with a very good approximation leading to a significant computational speed up 10 times over a direct whole annulus solution.
• The method is able to fully capture non-linearities into the whole crown, solving an unsteady time domain and non-axisymmetric solution without any assumed frequency.

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References

Figure 1: Computational mesh cells required for one Fourier harmonic (N=1)

Figure 3: Fan-Stage Under Temperature Inlet Distortion with 2 harmonics (5 passage-samples)

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References