EVALUATION OF A MULTIPLE FREQUENCY PHASE LAGGED METHOD FOR UNSTEADY NUMERICAL SIMULATIONS OF MULTISTAGE TURBOMACHINERY

L. Castillon

ONERA – The French Aerospace Lab, F-92190 Meudon - France

Lionel.Castillon@onera.fr

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Abstract

This paper presents the multiple frequency phase-lagged approach which has been implemented in ONERA's CFD software elsA. This method enables to perform unsteady simulations on multistage turbomachinery configurations including multiple frequency flows, with a reduction of the computational domain composed of one single blade passage for each row. The implementation of this approach is presented, followed by its application on two quasi three dimensional multistage turbomachinery applications in order to evaluate the advantages and drawbacks of such an approach.

Nomenclature

Ω	Rotation speed
N_{stat}	Number of stator blades
N_{rot}	Number of rotor blades
m	Circumferential wavelength
f_m	Spinning mode frequency
ω_m	Spinning mode pulsation
φ	Phase-lag
θ	Azimuth
N_{pt}	Number of perturbations
rpm	Revolutions per minute
S	Curvilinear abscissa
SS	Suction side
PS	Pressure side
LE	Leading edge
MFPL	Multiple frequency phase-lagged method

1 Introduction

The relative motion between adjacent rotor and stator blade rows in turbomachinery configurations gives rise to a wide range of unsteady flow mechanisms such as: wake interactions [1], potential effects [2], hot streak migrations [3], shock wave propagations [4], or unsteady transitional flows [5]. All these phenomena, which can have a crucial impact on the performance of gas turbines, can not be captured accurately with a steady "mixing plane" approach, since the averaging treatment at the rotor/stator interface filters all unsteady effects. It is therefore important for aeroengine designers to take into account these unsteady effects in the design process, at a reasonable cost. Yet the computational cost of a time-accurate full-annulus computation remains very high, despite the increase of computer resources and the availability of parallel computing. Indeed, a direct unsteady Reynolds-averaged Navier-Stokes (URANS) calculation in a three-dimensional multistage whole annulus configuration requires by 3 orders of magnitude more computing time compared to a steady isolated blade row mixing plane simulation [6]. It is therefore important to have access to numerical methods which reduce the computational domain (idealy one blade passage for each row) and at the same time are efficient enough to simulate accurately the main unsteady effects.

Many numerical methods have been developed in the past in order to model the unsteady blade row interaction with reduced computational domains. A first method is the "domain scaling approach" [7] which consists in modifying the blade count of the blade rows in order to reduce the computational domain to a few blade channels for each row. The blade count modification is done in such a way that the rotor/stator interfaces have the same azimuthal pitch in order to use a sliding interface join condition. The drawback of such an approach is that by rescaling the geometry (blade pitch) one modifies the main characteristics of the flow (blockage, mass flow). To alleviate this problem, Fourmaux [8] developed a boundary condition allowing a reduction of the computational domain to a few channels for each row, without modifying the blade counts. An approximation is done in the rotor/stator boundary treatment which performs a join treatment between two boundaries which do not have the same pitch. This join condition implies contraction/dilatation effects which can modify the frequencies of the flow.

Frequency domain approaches, developed and evaluated in the last few years [9][10], are very interesting alternatives to time integration methods for unsteady blade row simulation. Following a Fourier modelling principle, these methods consist in solving steady flow equations for time mean flow and time harmonics. If very promising results can be obtained in terms of CPU, recent validations [11][12] also tend to highlight the weaknesses of such approaches in terms of stability, memory cost, or harmonic number limitation.

An alternative to spectral approaches which is commonly used is the phase-lagged method, also called "chorochronic" approach. This time marching method enables to reduce computing resources without changing the blade count. Developped initially by Erdos and He [13-14], it has then been widely used and improved by many authors [15-19]. The method enables to compute the flow around one blade per row, using appropriate phase-shifted boundary conditions at the pitchwise boundaries.

Unfortunately the phase-lagged method, which assumes the temporal periodicity of the flow field, is in the general case limited to single stage configuration. Indeed on multiple row turbomachinery configurations (more than one stage) several unsteady perturbations with their own periodicities coexist, and such a calculation can only be dealt with a whole annulus computation. To face this problem, He [20-21], followed by Neubauer [22] proposed to generalize the phase-lagged method using multiple frequency phase-lagged boundary conditions, which allows a single blade passage solution for unsteady turbomachinery flows with multiple perturbations. Since their work, very few attempts have been performed to evaluate such a method on multiple stage configurations.

The first part of the paper presents the multiple frequency phase-lagged method implemented in ONERA's CFD code *elsA*, based on the work of He and Neubauer. Two quasi-3D applications, a turbine and a compressor test case, will then be discussed in order to evaluate the approach. For each case the multiple frequency phase-lagged calculation is compared with a reference computation. This comparison enables to quantify the errors induced by the method, and assess the advantages and drawbacks of such an approach.

2 About *elsA* software features

The *elsA* solver, developed at ONERA since 1997, is a multi-application aerodynamic code based on a cell-centered finite volume method for structured meshes [23-24]. Solving the compressible URANS Navier-Stokes equations, *elsA* allows to simulate a wide range of aerospace configurations such as aircrafts, space launchers, missiles, helicopters and turbomachines. Therefore a wide range of numerical tools, turbulence models and boundary conditions are available. In the present calculations the Spalart-Allmaras model [25] is used for turbulence modeling, the 2^{nd} order Jameson scheme for space discretisation [26], and a backward-Euler time integration scheme associated to an LU implicit phase.

3 Multiple frequency phase-lagged method description

3.1 Classical phase-lagged approach

In order to introduce the multiple frequency phase-lagged (MFPL) approach, we remind very briefly in this paragraph the principle of the "classical" phase-lagged approach used for single stage configuration. The blade to blade phase shift periodicity, also called "chorochronic" periodicity, has been described by many authors and more details can be found in [15-19].

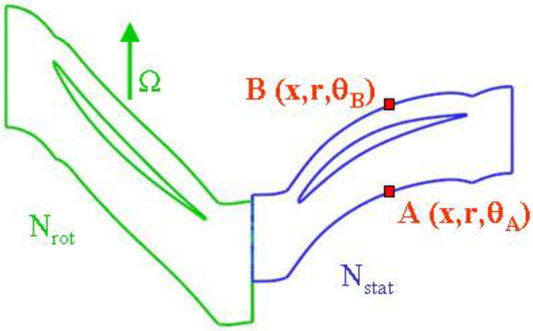

Fig. 1: Phase-lagged configuration (periodic flow)

Figure 1 represents a blade to blade view of a rotor/stator configuration. Let us consider two points A and B having the same axial and radial position, located at the upper and lower boundaries of the stator domain. With the hypothesis that the sources of unsteadiness are only due to the rotation of the wheel, the flow field in each blade row can be assumed to be time periodic (with a different period in each row). For example at point A, any aerodynamic variable represented in the cylindrical frame of reference is supposed to be a periodic function:

$$g(x,r,\theta_A,t) = F_{x,r,\theta_A}(t) = F_{x,r,\theta_A}(t + f_{stat}^{-1}) \quad (1)$$

with $f_{stat} = N_{rot}|\Omega|/2\pi$ its associated frequency.

Moreover, the previous hypothesis enables to link the flow field at points A and B which experience the same flow field but with a phase lag :

$$g(x,r,\theta_A,t_1) = g(x,r,\theta_B,t_1+\varphi) \qquad (2)$$

with $\varphi = (\theta_B - \theta_A)/\Omega$ being the phase-lag

Analogous relationships can be written in the rotor frame of reference. The previous formulas enable to reduce the computational domain to a single blade passage for each row, using specific boundary conditions at the azimuthal boundaries and at the interface, using equations (1) and (2). During the computation the flow field in A and B, time periodic according to (1) is approximated by Fourier series whose coefficients are updated at each time step using a sliding average technique. Equation (2) is used to perform the join condition between A and B. The boundary treatment at the rotor/stator interface relies on the same principle. At each time step, taking into account the rotation, the two sliding interfaces are positioned one with respect to the other. The field for each computing cells of the donor interface, approximated by a Fourier series, is then reconstructed using time and the phase lag information, before being used for the join treatment.

Let's consider now the general case of a configuration composed of 3 or more blade rows, with independent blade counts and different rotating speeds such as represented in figure 2. As mentioned in the introduction, on such a configuration the classical phase-lagged approach is not valid any more since each blade row experiences at least two blade passing frequencies corresponding to the upstream and downstream row, which are different in the general case. Therefore each blade row experiences multiple disturbances with unrelated frequencies. Now the question is the following: in order to reduce the computational domain to one blade passage for each row, which numerical treatment should be done at the upper and lower azimuthal boundaries, in other words which link can be assumed between the flow field in A (x,r,θ_A) and B (x,r,θ_B)?

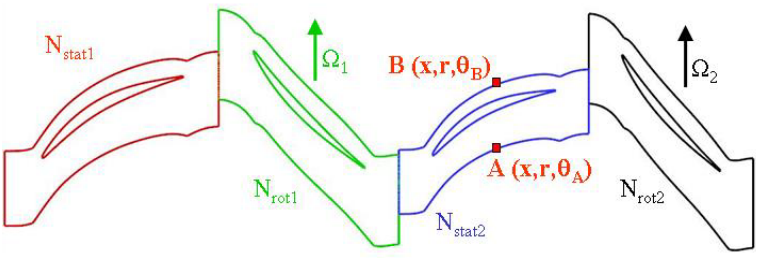

Fig. 2: Muliple frequency phase-lagged configuration (multiple perturbation flow)

3.2 Spinning mode hypothesis

The main hypothesis of the multiple frequency phase-lagged method is to assume that the flow field can be decomposed in a linear combination of spinning modes, each mode being characterized by a spatial wavelength m and a rotation speed Ω_m as proposed by Tyler & Sofrin [27]. Each aerodynamic variable written in the relative frame of reference can be decomposed in a sum of disturbances corresponding to circumferential traveling waves, for which a phase-shift periodicity can be defined:

$$g(x,r,\theta,t) = \sum_{m=0}^{N} g_m^{x,r}(\theta,t) \qquad (3)$$

$$g_m^{x,r}(\theta,t) = a_m^{x,r}\cos(m[\theta-\Omega_m t]) + b_m^{x,r}\sin(m[\theta-\Omega_m t])$$

In the following formulas, we decide to drop the subscript (x,r) and consider once again two gauges A and B, located at the same axial and radial position, but at different azimuth θ_A and θ_B. Figure 3 represents the evolution of a spinning mode g_m in a time-azimuth diagram.

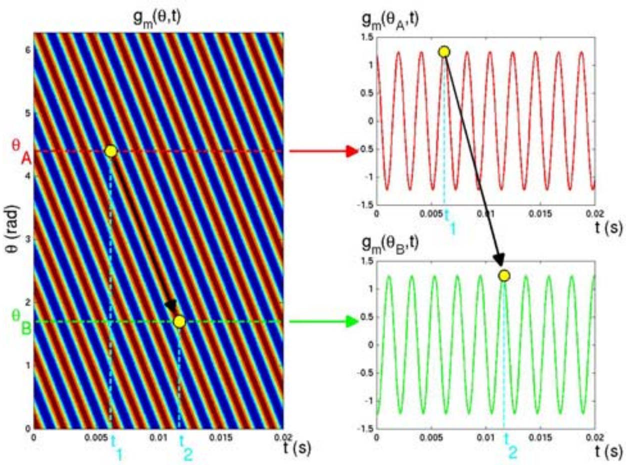

Fig. 3: Spinning mode function presented in a time - azimuth diagram

One can observe from figure 3 that gauges A and B experience the same signal, characterized by the following frequency and pulsation:

$$f_m = \frac{m\Omega_m}{2\pi} = \frac{\omega_m}{2\pi}$$

but with a phase lag:

$$g_m(\theta_A,t_1) = g_m(\theta_B,t_2),\ t_2 = t_1 + \frac{\theta_B-\theta_A}{\Omega_m}$$

Let us assume now that the aerodynamic field at point $A(x,r,\theta_A)$ is a linear combination of spinning modes, each disturbance being time periodic and having its own phase shift periodicity :

$$g(\theta_A,t) = \sum_{m=0}^{N} g_m(\theta_A,t) \qquad (4)$$

with $g_m(\theta_A,t) = a_m\cos(2\pi f_m t) + b_m\sin(2\pi f_m t)$, then we can obtain the value of the aerodynamic field in θ_B by phase shifting each mode:

$$g(\theta_B,t) = \sum_{m=0}^{N} g_m(\theta_B,t)$$

$$g_m(\theta_B,t) = g_m(\theta_A, t - \frac{\theta_B-\theta_A}{\Omega_m})$$

Fundamentally, this approach is the same as for the classical phase-lagged approach. It is just more general, as it enables to take into account more than one fundamental frequency. Indeed, for a classical phase-lagged configuration (rotor/stator) the values of m correspond to the multiple integers of the blade counts of the adjacent row, and Ω_m is the adjacent blade row rotation speed. The multiple frequency phase-lagged approach is more general in the sense that one allows to use any values of m and Ω_m. For example m can take the value of the upstream and downstream blade row numbers (which can be different), associated to a value of Ω_m corresponding to the opposite blade row rotation speed (which can be different). m (and Ω_m) can also be a linear combination of the upstream and downstream blade numbers (blade rotation speed). Any kind of deterministic modes can be selected for the spinning mode decomposition.

3.3 Boundary condition treatment

The previous assumption enables reducing the computational domain to a single blade passage for each row, using specific multiple frequency phase-lagged conditions both at azimuthal boundaries and at the rotor/stator interfaces. The boundary condition treatment is performed in two steps:

1) the flow variables are first approximated by a sum of Fourier series, whose coefficients are updated at each time step,
2) a time shift is performed on the Fourier series, in order to determine time shifted variables which are used in ghost cells at the opposite adjacent boundaries.

Once again we consider a pair of mesh points A and B located at upper and lower azimuthal boundaries. At the periodic boundaries of a single passage computational domain, one approximates the flow field as a sum of periodic functions corresponding to multiple periodic disturbances. By gathering all of the modes associated to a common perturbation (or a common frequency), equation (4) can be rewritten as a sum of N_{pt} periodic functions, as proposed by He [20]:

$$g(\theta_A,t)=\sum_{i=1}^{N_{pt}}F_i(t) \text{ with } F_i(t)=F_i(t+f_i^{-1})$$

Each periodic function F_i, of frequency f_i, is approximated by its Fourier series truncated to $N_{harm(i)}$ harmonics :

$$F_i(t)=\sum_{n=0}^{N_{harm(i)}}a_{ni}\cos(2\pi n f_i t)+b_{ni}\sin(2\pi n f_i t)$$

The flow field in B can then be deduced by phase-shifting each periodic perturbation:

$$g(\theta_B,t)=\sum_{i=1}^{N_{pt}}F_i(t-\sigma_i) \qquad (5)$$

with $\sigma_i=\dfrac{\theta_A-\theta_B}{\Omega_i}$ being the phase lag corresponding to the i[th] perturbation. During the time marching integration, the boundary conditions are applied at both upper and lower boundaries, a similar treatment being done at B.

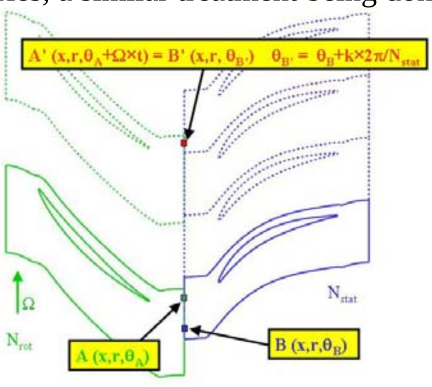

Fig. 4: Treatment of the rotor/stator interface

At any rotor/stator interface, a similar treatment is done, but taking into account the relative motion between each blade row. At each time step, the interfaces are positioned one with respect to the other. The flow field for each computing cells located at the donor interface is reconstructed using Fourier series and the phase lag information. It is summarized in figure 4 (only one interface is represented): considering point A located in the rotor domain on the rotor/stator interface, it is located at A' at time t and its value is equal to the flow field in B', located in a "ghost" stator domain, which can be deduced from B by phase shifting its periodic functions following equation 5:

$$\text{If } g(\theta_B,t)=\sum_{i=1}^{N_{pt}}F_i(t) \text{ then } g(\theta_{B'},t)=\sum_{i=1}^{N_{pt}}F_i(t-\sigma_i)$$

$$\text{with } \sigma_i=\frac{\theta_B-\theta_{B'}}{\Omega_i}=-\frac{k\times 2\pi}{N_{stat}\Omega_i}$$

3.4 Computation of Fourier coefficients

The coefficients of the previously mentioned Fourier series are computed with the moving average technique adapted to multiple frequency flows proposed by He [20]. At the first iteration all of the Fourier coefficients (a_{ni},b_{ni}) are set to 0, except for the mean value a_{oi} of each periodic function F_i, chosen in such a way that their sum corresponds to the initial flow field value. Then at each time step, Fourier coefficients are updated with a moving average technique adapted to multiple frequency flows. As mentioned by He [20], during the time marching integration, the Fourier shapes continuously correct each other according to the phase shift. The correction carries on until a "converged" state is obtained, this means when the Fourier coefficients reach a constant value.

A key point to mention concerning the stability of the method is to apply an under relaxation of the Fourier coefficients when they are being updated as proposed by He [21]:

$$a_{ni(stored)}=(1-\alpha)a_{ni(stored)}+\alpha a_{ni(new)}$$

with a similar treatment for b_{ni}. In the presented calculation the parameter was set to 0.1, ensuring a good stability of the method.

3.5 Theoritical limits of the multiple frequency phase-lagged approach

If the advantages of the multiple frequency phase-lagged approach are easy to understand (unsteady effects are modeled with a reduction of the computational domain to one blade passage for each row), it is important to keep in mind the limits of this method. The first limit is that the spinning mode hypothesis (Eq. 3) assumes that the sources of unsteadiness are linked to the wheel rotation and that the unsteady phenomena can be modeled by spinning modes (supposing that information travels in the azimuthal direction). The method assumes that the flow field is governed by deterministic frequencies, therefore it is not valid for flow configurations including non deterministic frequencies such as rotating stall [6] or vortex shedding.

A second limitation of the MFPL approach is that the user needs to select which spinning modes will be used for the mode decomposition (Eq. 3), in other words which modes exist in the flow field. If spinning modes corresponding to adjacent blade row motion are easy to determine (m is a multiple integer of the adjacent blade count, and Ω_m is the adjacent blade row rotation speed), there can also exist modes whose wavelength and rotation speed are linear combination of the previous modes [28]. It is possible to take into account perturbations due to interaction between the upstream and downstream frequency (f_1+f_2 , f_1-f_2 , $2f_1+f_2$, etc …) but it is difficult to guess *a priori* which modes will be dominant. In fact they are difficult to guess in advance unless one performs a full annulus calculation (which is precisely what is trying to be avoided). Therefore a simple rule to apply for the computations is to take into account only the modes associated to the disturbances from the neighbouring blade rows (N_{pt} = 2): the modes wave length will correspond to multiple numbers of both the upstream and downstream number of blades, and their associated rotation speed. This choice was done in the calculations presented hereafter (Vega3 turbine and Create compressor configurations).

Last but not least, the most important limitation of the method is it relies on formula which are not valid anymore for non spinning modes, i.e. if $\Omega_m = 0$. The behaviour of such a mode in a time-azimuth diagram can be presented in figure 5. One sees that two gauges A and B located at two different azimuthal positions θ_A and θ_B will experience a different constant value. There is no way, knowing the flow field at A to evaluate it at B and vice versa. Such a particular mode can be encountered for example on a stator/rotor/stator configuration with independent blade counts for the two stator rows. In the 2nd stator, two adjacent stators will not experience the same flow field. Indeed, wakes of the upstream stator, after being convected in the rotor, impact the downstream stator, but with a different position with respect to the 2nd stator. There is no easy way to take into account this effect and to link the upper and lower boundaries. This phenomenon has been described by Chen and Van Zante [28].

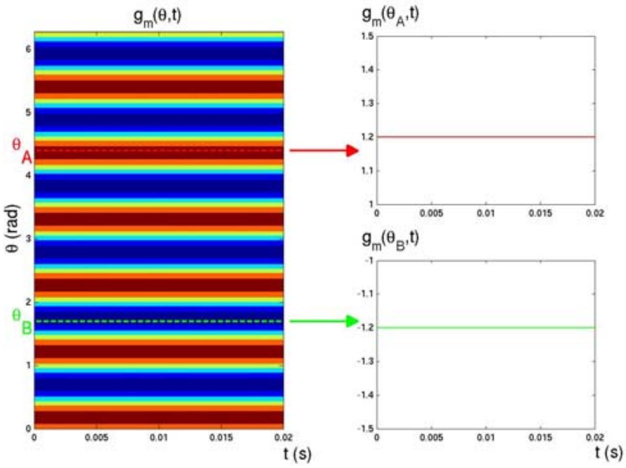

Fig. 5: Non spinning mode function presented in a time-azimuth diagram.

Therefore the MFPL approach is not able to take into account non rotating modes, ie rotor/rotor or stator/stator clocking effects. It represents an important limitation of this numerical approach, meaning that the impact of blade rows N-2 and N+2 on blade row N are not correctly modeled. This modeling error leads to errors of continuity and conservation losses which need to be checked. In the following presented calculation, the relative error between the upstream and downstream mass flow did not exceed 0.4% (order of magnitude equivalent to mixing plane calculations).

4 Evaluation of the MFPL approach on two quasi-3D multistage configurations

4.1 Test case 1: Vega3 turbine

The first investigated configuration is the 1.5 turbine stage Vega3 [29] composed of 23 stators, 37 rotors and 31 stators. The rotation speed of the rotor is 13000 rpm. Two quasi-3D calculations have been performed: a multiple frequency phase-lagged calculation, taking into account one single blade passage for each row, and a full annulus reference calculation, performed on the same grid as the multiple frequency phase-lagged approach, but with each blade passages being duplicated in order to reach a 360° sector. For the reference calculation a sliding interface join condition is imposed at the rotor/stator interface. For the MFPL calculation, the MFPL boundary conditions previously described are imposed both at the periodic boundaries and at the rotor/stator interfaces. Both calculations are performed with identical numerical parameters and turbulence model in order to quantify the errors due to the boundary condition. As summarised in table 1 below, the multiple phase-lagged calculation enables to obtain a significant reduction in terms of number of blocks, number of points, around 30 which corresponds approximately to the average blade count. This leads to a CPU gain of the same order of magnitude.

	Blocks	Points	HCPU
Reference (360°)	478	3.10^6	86
Multiple phase-lagged	16	10^5	3

Table 1: Mesh characteristics (number of blocks and points) and calculation time (CPU hours to perform one revolution).

On this configuration both stator rows experience a single frequency phenomena corresponding to the rotor blade passage (f_{rot}=8017 Hz), while the rotor blades experience the passing frequencies of the two adjacent stator rows (f_{stat1} = 4983 Hz, f_{stat2} = 6717 Hz) which are different since the blade counts of the two stator rows are not the same. On the rotor boundaries concerned by the multiple frequency phase-lagged treatment (interfaces, lower and upper azimuthal boundaries), the flow field is approximated by a sum of two Fourier series associated to the two frequencies (each Fourier series are truncated at 16 harmonics). In the stator domains the flow field is approximated by a single Fourier series corresponding to f_{rot}. Therefore in the stator the boundary condition will phase lag in time the flow field without taking into account clocking effects due to the relative position of the two stator rows.

Results obtained after one revolution are compared hereafter. Figure 6 represents a turbulent viscosity snapshot for the two calculations. One notices that the main flow features existing in the reference computation are well reproduced by the MFPL approach which enables simulating the migration effects of the wakes through the stage.

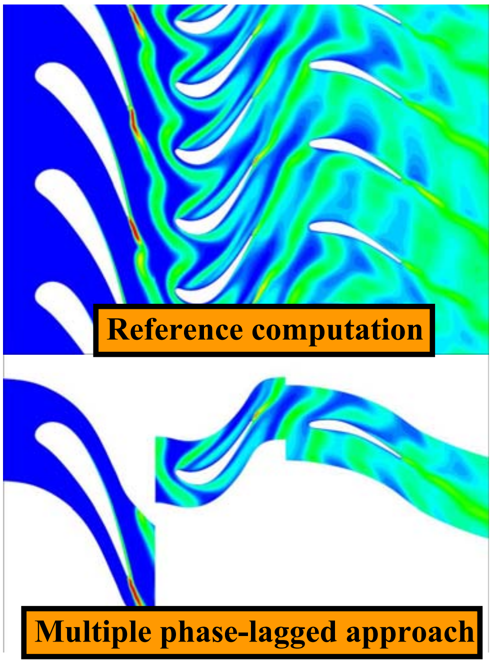

Fig. 6: Vega3 turbine - Comparison of the turbulent viscosity snapshot for the reference (full annulus) computation and the multiple phase-lagged approach.

The blade time averaged static pressure and the min-max envelopes are plotted in figure 7 for the 3 blades: stator1 and 2 and rotor. On the first stator the unsteady effects are mainly located on the rear part of the suction side, while on the rotor and on the second stator unsteady effects concern all the blade chord. One can observe a satisfactory agreement between the two calculations, despite the fact that the amplitudes of the unsteadiness are slightly underestimated for the MFPL approach.

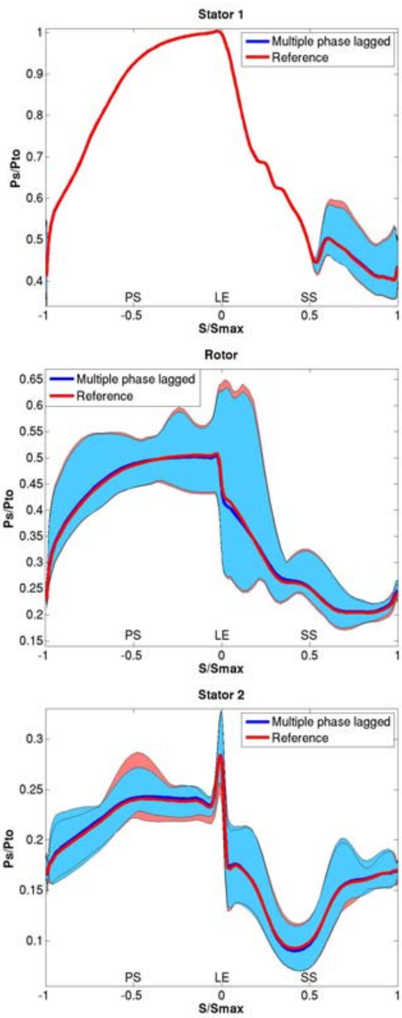

Fig. 7: Vega3 turbine - Time-averaged and min-max envelopes of the blades static pressure as a function of curvilinear abscissa (S/S_{max}=0→leading edge, S/S_{max}=[0-1] →suction side, S/S_{max}=[-1,0] →pressure side).

In order to evaluate the ability of the MFPL method to capture the perturbations existing in the flow, Fourier transforms of 4 pressure signals obtained after one revolution are plotted in figure 8. A good agreement between the two methods is obtained for gauges 1 (downstream stator 1) and 2 (upstream rotor) for which the unsteady effects are mainly due to the adjacent blade row rotation: rotor passing frequency (N_{rot}=37) for gauge 1, stator passing frequency (N_{stat1}=23) for gauge 2. Gauge 3, located downstream of the rotor, experiences two perturbations, due to stator 1 (N_{stat1}=23) and stator 2 (N_{stat2}=31). Frequencies corresponding to linear combination of stator 1 and 2, which can be observed in the reference computation as (N_{stat2}-N_{stat1}=8), are not captured by the MFPL method. Finally gauge 4, located in stator 2, experiences a flow with a single perturbation, due to the rotor motion (37). Yet discrepencies on the amplitude of these perturbations are observed. This gap is due to the fact that clocking effects between the two stator rows are not modeled in the MFPL approach. Two adjacent stators are supposed to experience the same periodic flow, with a phase lag, which is not true due to the relative position of stator 1 and 2.

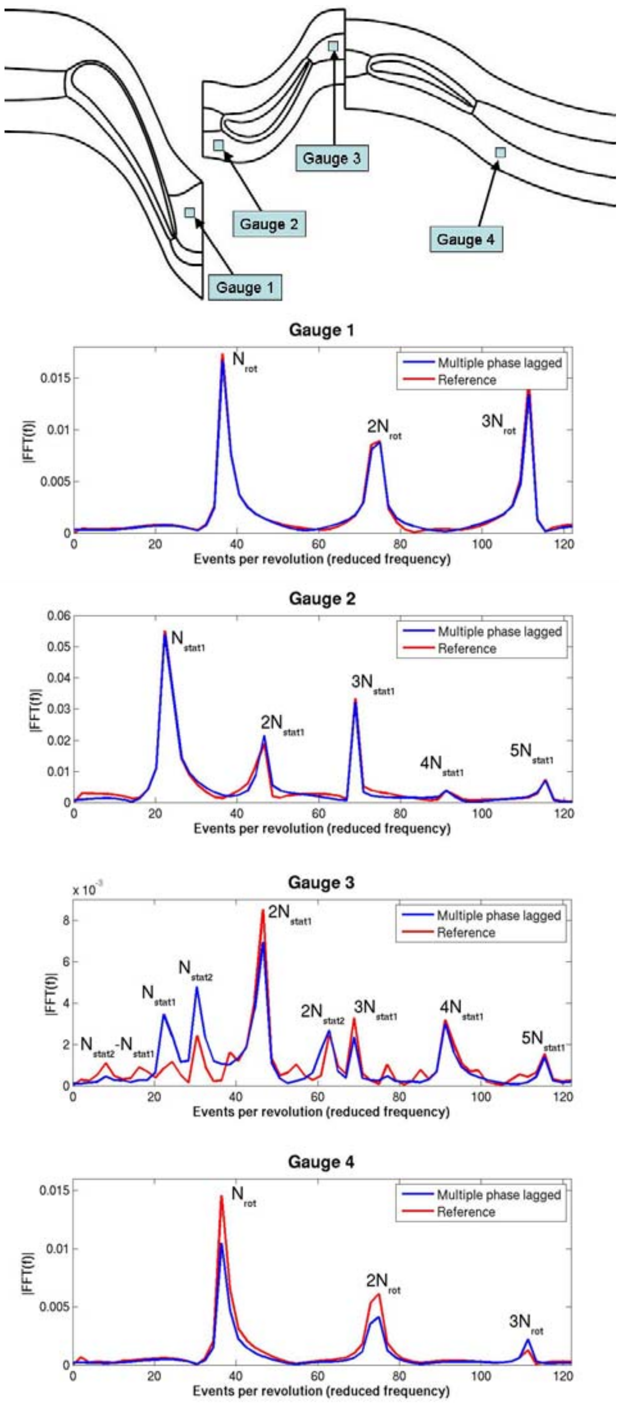

Fig. 8: Vega3 configuration: numerical gauges position and Fourier analysis of pressure signals.

4.2 Test case 2 : Create compressor

The second quasi-3D simulations concern the 3 stage axial compressor CREATE [30]. The blade numbers (64/96/80/112/80/128) allow a reduction of the computational domain to 1/16 (22.5°) of the machine. Therefore, a reference computation, corresponding to 1/16 of the compressor is performed on a grid composed of 10^6 points divided in 175 blocks. It is compared to a MFPL simulation, performed using only one blade passage per row. As mentioned in table 2, the use of the MFPL approach enables reducing the computational domain to 30 blocks and 1.8 10^5 points, and a reduction of CPU cost of a factor 4.4. Yet it is important to recall on this configuration that the reference calculation is performed on 1/16 of the machine. Therefore, compared to a 360° calculation the CPU gain would be 16 times higher.

	Blocks	Points	HCPU
Reference (22.5°)	175	10^6	25
Multiple phase-lagged	30	1.8 10^5	5.7

Table 2: Mesh characteristics (number of blocks and points) and calculation time (hours CPU to perform one revolution).

The rotation speed of the rotors is 11543 rpm. For each blade row the flow field is approximated as a sum of two periodic functions which frequencies are the upstream and downstream blade passing frequency. Each periodic function is approximated by a Fourier series composed of 16 harmonics. Figure 9 represents the sliding average evolutions of mass-flow and blade static pressure through the stage for the MFPL approach. 5 revolutions are necessary to reach a satisfactory convergence.

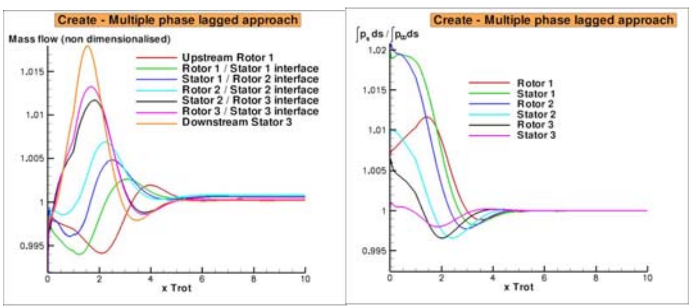

Fig. 9: Create configuration: Sliding average evolutions of mass flow and blade integrated pressure

Results obtained after ten revolutions are compared hereafter. The comparison of the entropy snapshot presented in figure 10 indicates that the MFPL approach reproduces the main flow patterns observed in the reference computation: wake convection and segregation effects within the stage, which would not be possible with a mixing plane approach. Figure 11 represents the time averaged blades static pressure and the min/max envelopes. If a good agreement is obtained on the 3 first rows (rotor 1, stator1, rotor 2), discrepancies appear in stators 2 and 3, where the min-max enveloppes are significantly underestimated.

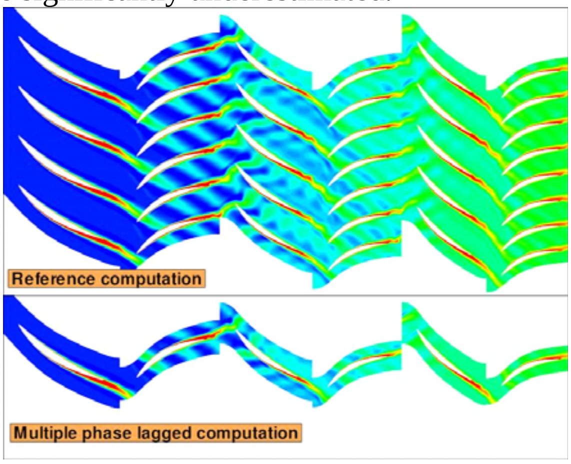

Fig. 10: Entropy field snapshot comparison of reference and multiple phase-lagged computation.

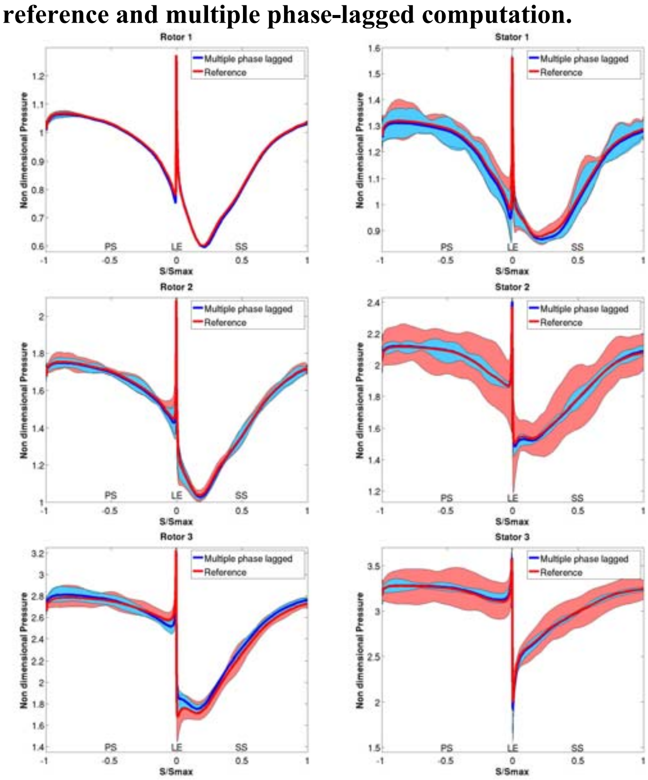

Fig. 11: Create configuration: time-averaged and min-max envelopes of the blades static pressure.

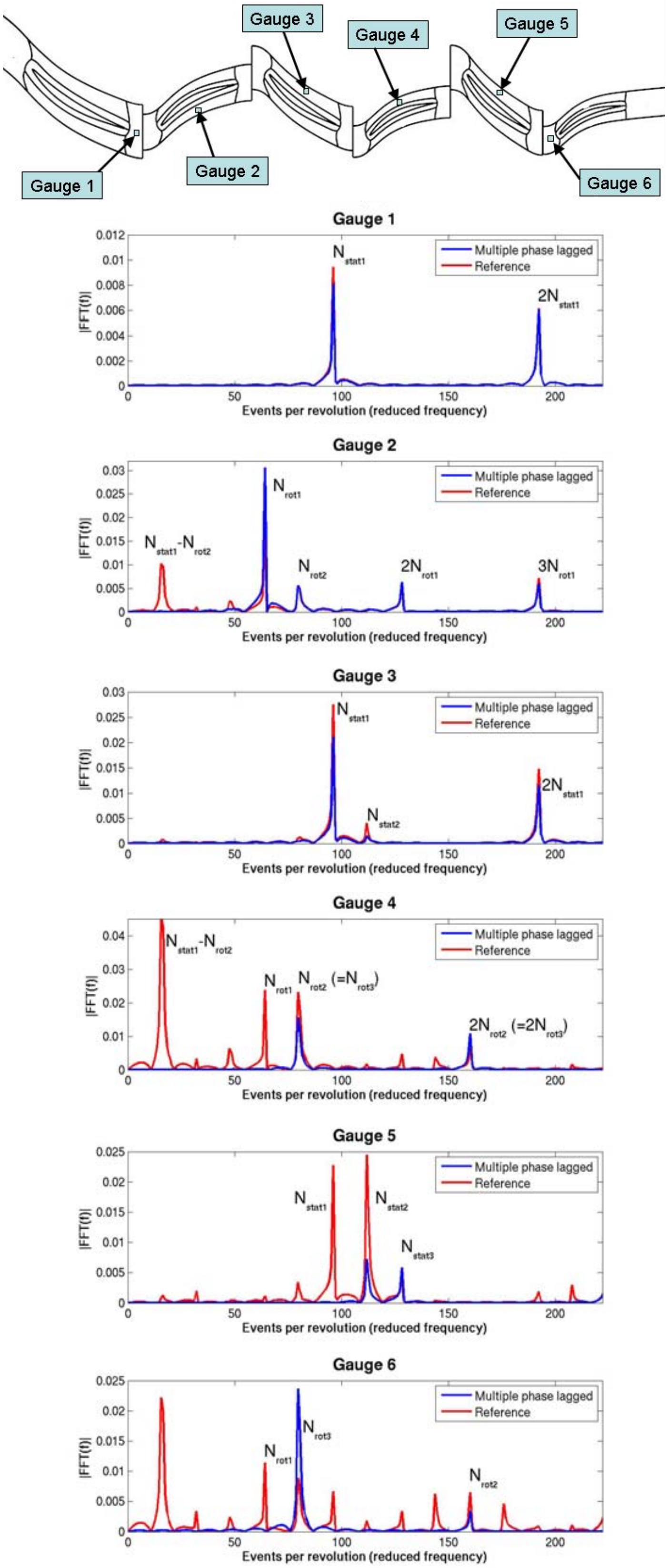

Fig. 12: Create configuration: numerical gauge positions and Fourier analysis of pressure signals.

Once again to evaluate the ability of the MFPL approach to reproduce perturbations existing in the reference flow, Fourier transforms of 6 pressure signals, obtained after ten revolutions, are presented in figure 12. A good agreement between the two calculations is obtained for gauge 1 (downstream rotor 1), where the unsteady effects are mainly dictated by the stator 1 passing frequency (N_{stat1}=96). On gauge 2 (stator 1) the MFPL method captures well the first harmonics of rotor 1 (N_{rot1}=64), and rotor 2 (N_{rot2}=80). Yet one observes that the reference calculation exhibits a reduced frequency of 16 (N_{stat1}-N_{rot2}) which is not seen by the MFPL calculation. A good agreement between the two methods is obtained on gauge 3 (rotor 2) which exhibits reduced frequencies corresponding to the upstream and downstream stator passing frequencies (N_{stat1}=96 and N_{stat2}=112). In gauge 4 (second stator), the MFPL simulation exhibits only the passing frequencies of the upstream and downstream rotors (N_{rot2}=N_{rot3}=80), while the reference calculation observes a richer spectrum, with in particular the reduced frequencies 16 (N_{stat1}-N_{rot2}), and 64 (influence of the first rotor, not taken into account in the MFPL approach). In gauge 5, located in the last rotor, the MFPL approach only exhibits the adjacent stator passing frequencies (N_{stat2}=112 and N_{stat3}=128), with a significant underestimation of the impact of the mode 112, while the full reference observes a much richer spectrum, capturing for exemple the reduced frequency 96, corresponding to the first stator. Finally, on gauge 6 (last stator), only the harmonics of the adjacent rotor passing frequency is obtained in the MFPL approach (80) is captured, while the full reference calculation exhibits much more frequencies.

To conclude, this spectrum analysis indicates that taking into account in the MFPL approach two perturbations corresponding to the adjacent blade passing frequency is enough to obtain a good description of the unsteady perturbations on the three first blade rows. It is not enough on the three downstream blade rows for which the reference simulation exhibits a much richer spectrum.

5 Conclusion

A multiple frequency phase-lagged approach, based on the work of He and Neubauer [20-22] has been implemented in *elsA* CFD software and evaluated on two quasi-3D multistage turbomachinery configurations. The comparisons of the results obtained with the multiple frequency phase-lagged approach and the reference computations enable to highlight the interests of this approach but also to underline its limits.

Concerning the interests of the method, the MFPL approach enables to simulate unsteady effects on a multistage turbomachinery with a reduction of the computational domain to one blade passage per row and to have access to unsteady information which would not be available with a “mixing plane” approach. It generalizes the phase-lagged approach which was limited to single stage configurations. The calculations are obtained with a CPU gain of the order of magnitude corresponding to the reduction of channels. Unsteady effects between adjacent blade rows (N/N+1) are modelled, and sometimes accurately captured. Concerning the drawback of the method, if the MFPL approach is able to model the unsteady effects induced by the adjacent blade rows, it fails modeling clocking effects, i.e. the relative influence between row N and N+2. Therefore, one can not expect from the method to reproduce these effects, which can be important on the downstream blade rows. Finally, the method does not ensure flux conservation, conservation losses need therefore to be checked for the result interpretation.

The method has been tested with success on 3D applications which will be presented in future papers. The method will also be investigated on aero elastic configurations.

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