

# EVALUATION OF TWO UNSTEADY NUMERICAL APPROACHES FOR THE SIMULATION OF MULTI-FREQUENCY TURBOMACHINERY FLOWS

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## ABSTRACT

This paper presents two numerical methods allowing unsteady blade row simulations with a reduction of the computational domain to one blade passage per row: the multiple frequency phase-lagged approach and the harmonic balance time approach implemented in *elsA* CFD code. The first part of the paper reminds the principle of the two methods, their main hypothesis and their theoretical limitations. The second part of the paper presents the application of these two methods on the 3.5 stage axial experimental compressor CREATE investigated at Ecole Centrale de Lyon in LMFA laboratory. The results obtained with the simplified unsteady models are analyzed and compared to an unsteady reference multiple passage computation and with a steady mixing plane approach. The comparison of these results enables to highlight the interests of these two unsteady numerical approaches and also to underline their limits.

## NOMENCLATURE

MFPL	Multiple Frequency Phase Lagged approach
HBT	Harmonic Balance Time approach
REF	Reference multiple passage calculation
MXPL	Mixing plane calculation
(U)RANS	(Unsteady) Reynolds Averaged Navier-Stokes
IGV	Inlet Guide Vane
S <sub>1</sub> , S <sub>2</sub> , S <sub>3</sub>	Stator 1, 2, 3
R <sub>1</sub> , R <sub>2</sub> , R <sub>3</sub>	Rotor 1, 2, 3
x, r, $\theta$	Axial, radial and azimuthal coordinates
T	1/16 <sup>th</sup> of the rotation period
H/H <sub>0</sub>	Relative span height
Pt <sub>a</sub>	Normalized absolute total pressure
Tt <sub>a</sub>	Normalized absolute total temperature
Pt'	Normalized absolute total pressure fluctuation
$\phi$ , $\psi$ , $\eta$	Normalized mass flow rate, total pressure ratio and isentropic efficiency
N <sub>harm</sub>	Fourier series harmonic number
$\rho V_x$	Axial momentum quantity
BPF	Blade passing frequency

## 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, potential effects, hot streak migrations, shock wave propagations, or unsteady transitional flows. 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 (Denton, 1979), 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 ( $360^\circ$ ) 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 (Gourdain, 2010). It is therefore important to have access to numerical methods which reduce the computational domain (ideally 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" (Arnone, 1996) 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 (choke, mass flow). To alleviate this problem, Fourmaux (1994) 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.

This paper presents two alternative numerical methods allowing unsteady blade row simulations with a reduction of the computational domain to one blade passage per row. The first approach is the multiple frequency phase-lagged (MFPL) approach, based on the work of He (1992, 2002) and Neubauer (2004) and implemented in *elsA* CFD code (Castillon, 2012). This method generalizes the classical phase-lagged approach (Erdos 1977, Gerolymos 2002), which is limited to single periodic flow, in order to tackle multiple frequency flows. The second method is the harmonic balance technique (HBT) described in (Sicot, 2013). This method uses the periodicity property of the flow (as induced by rotor/stator interactions) to cast the unsteady governing equations in a set of coupled steady equations, corresponding to a sampling of the periodic flow. HBT has been successfully applied to turbomachinery configurations, including for transonic flows (Ekici, 2010).

The first part of the article shortly recalls the main principles of these two numerical methods, insisting on the advantages and limitations of each approach. The application of these two unsteady models on an axial compressor configuration is then presented. The results obtained with the simplified unsteady models are then analyzed and compared to an unsteady reference multiple passage computation and also with a standard mixing plane approach.

## INVESTIGATED UNSTEADY NUMERICAL METHODS

One shortly reminds in this part the main principles of the two investigated numerical methods : MFPL and HBT.

### **The multiple frequency phase lagged method (MFPL)**

The multiple frequency phase-lagged method has been described in detail in (Castillon, 2012, 2015). It relies on the hypothesis that the flow field can be decomposed as a combination of spinning modes, each mode being characterized by a spatial wavelength and a rotation speed. This assumption enables reducing the computational domain to a single blade passage for each row, using specific multiple phase-lagged boundary conditions both at azimuthal frontiers and at the rotor/stator interfaces. A multiple frequency phase lagged calculation consists in using a classical time-marching solver (as for example Runge-Kutta, Dual-Time stepping, or Newton methods) with specified boundary conditions at the periodic boundaries and at rotor/stator interfaces where the following treatment is done:

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.

### **Time-domain harmonic balance technique (HBT)**

The present harmonic balance approach is a time-integration scheme based on Fourier analysis that turns a periodic or almost-periodic flow problem into the coupled resolution of several steady computations at different time samples of the period of interest. The coupling is performed by a spectral time-derivative operator that appears as a source term of all the steady problems. These are converged simultaneously making the method parallel in time. When solving for a single stage, one only has to consider the blade passing frequency of the opposite row and its harmonics. Therefore a uniform time sampling leads to an orthogonal and invertible discrete Fourier matrix. In multi-stage turbomachinery, a row has to take into account a set of frequencies that depends on its neighbors blade passing frequencies and possible linear combinations. The Fourier matrix can be ill-conditioned leading to a divergence of the computations. A non-uniform time sampling is used to improve the robustness and accuracy regardless of the considered frequency set (see Guédeney *et al.*, 2013). Thanks to the simultaneous knowledge of several time instants in the time period, the flow spectrum can be computed on the fly to apply the corresponding multiple frequency phase lags in a similar fashion as in MFPL.

### **Advantages and limitations of the two unsteady approaches**

Table 1 aims at giving an overview of the advantages and limitations of the two investigated unsteady models (MFPL, HBT) compared to a classical unsteady full annulus (360°) passage reference computation, and also with a standard mixing plane approach (MXPL).

#### CPU cost

In terms of CPU cost, the HBT approach is extremely cheap since the problem of solving a set of unsteady flow equations is transformed to a problem where one solves a set of time-independent steady flow equations. Therefore, in terms of CPU, an HBT computation is quite comparable to a standard mixing plane computation (RANS). The MFPL approach is more expensive since it is a URANS computation, but remains cheaper than a multiple passage computation since one only computes one blade passage per row. To give rough orders of magnitude, based on the following presented case, the MFPL is one order of magnitude more expensive than a HBT or mixing plane computation, and two orders of magnitude less than a 360° full annulus computation (the gain is more or less proportional to the blade counts, which in the following computation is around 100).

### Memory cost

Concerning memory cost, HBT and MFPL approaches are much cheaper than a  $360^\circ$  computation since one only computes a single blade passage per row. Therefore the gain is all the more important as the blade counts increases. The HBT is slightly more memory consuming than the MFPL, since one computes  $2N_{\text{harm}}+1$  coupled problems,  $N_{\text{harm}}$  being the number of harmonics used in the Fourier decomposition. This means that the grids and flow fields used are multiplied by  $2N_{\text{harm}}+1$  compared to a single passage calculation type.

### Harmonic number dependency

Since MFPL and HBT approaches rely on Fourier series decomposition, the user must choose the number of harmonics ( $N_{\text{harm}}$ ) used for the Fourier decomposition. In the MFPL approach adding more harmonics in the flow field decomposition does not induce a significant over cost in terms of CPU or memory, since the flow decomposition treatment is only performed at periodic boundaries and interfaces. On the contrary in HBT, raising the harmonic number leads to a decrease of CPU performance, an increase of memory cost (Guédeney, 2012), since the flow field decomposition in Fourier series concerns all of the cells of the computational domain. Moreover it can also lead to a lack of robustness (Guédeney, 2012). For example, in the presented computation  $N_{\text{harm}}$  could not exceed 4.

### Unsteady effects and clocking modeling

As reminded in (Castillon 2012), many unsteady effects, which are naturally captured by a multiple passage  $360^\circ$  computation, can not be captured with MFPL/HBT approaches:

- these two methods are not valid for unsteady flow configurations including frequencies which are uncorrelated with the blade passing frequency (for example rotating stall, vortex shedding),
- deterministic frequencies must be given by the user as an input for each domains. Some are easy to guess in advance, others not, like linear combinations of upstream and downstream rows ( $f_1+f_2$ ,  $2f_1-f_2$ , etc ...), which are therefore usually neglected in the flow decomposition,
- the MFPL and HBT approaches are not able to take into account non rotating modes (rotor/rotor or stator/stator interference effects, referred as “clocking” hereafter). Interactions between blade rows  $N$  and  $N+2$  are therefore not correctly modeled. This can lead to errors of continuity at the rotor/stator interfaces and conservation losses which need to be checked. In the following presented calculation, for the MFPL approach, the relative error between the upstream and downstream mass flow did not exceed 0.08% (which is less than errors obtained in mixing plane calculations).

### Method implementation

One can finally mention that in terms of code development, HBT requires a bigger effort than the MFPL approach, since the MFPL is a boundary condition, whereas in HBT all the solver is impacted (additional source terms must be implemented in order to couple the steady flow equations).

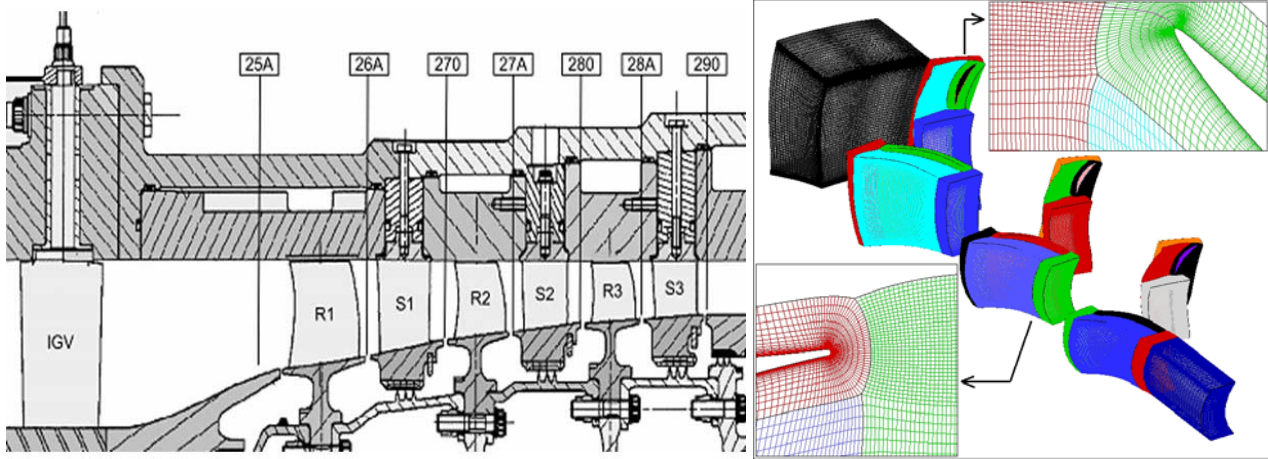
	360°	MFPL	HBT	MXPL
CPU cost	High	Medium	Low	Low
Memory cost	High	Low	Medium	Low
Harmonic number dependency	-	Low	Medium	-
Captured unsteady effects	All	Adjacent BPFs	Adjacent BPFs	Not modeled
Clocking effects	Captured	Not modeled	Not modeled	Not modeled
Implementation complexity	Low	Medium	High	Low

**Table 1: Summary of the main advantages and limitations of 2 unsteady models (MFPL/HBT) compared to a standard mixing plane (MXPL) and unsteady full annulus multiple passage computations ( $360^\circ$ ).**

## COMPUTATIONAL PROCEDURE

### Investigated configuration and computational grid

The studied configuration is the experimental compressor CREATE (Ottavy, 2012), which is located at the Laboratory of Fluid Mechanics and Acoustics (LMFA) in Lyon, France. This axial compressor from SNECMA comprises 3.5 stages presented in Fig. 1 (left) and is representative of the median stages of modern high pressure compressors. Table 2 details the blade numbers for each row, which are multiple numbers of 16.



**Fig. 1: Meridian view of CREATE (left) and computational grid (right).**

Row	IGV	R1	S1	R2	S2	R3	S3
Number of blades per row ( $2\pi$ )	32	64	96	80	112	80	128
Number of blades for $2\pi/16$	2	4	6	5	7	5	8

**Table 2: Blade numbers of the compressor rows.**

A view of the computational grid is presented in figure 1 (right). The numerical domain is meshed with a multi block approach, using an O-H grid strategy for each passage of the compressor. The total number of nodes to represent the three compressor stages is 6.5 million points (32 blocks) when only one passage per blade row is meshed, and 36 million points (178 blocks) to reach a  $2\pi/16$  sector to perform the reference multiple passage computation. The blade of the IGv is not meshed, yet its influence is modeled in the calculation by applying at the inlet boundary a map corresponding to flow conditions downstream the IGv (such as total pressure deficit).

### Compared calculations

As mentioned in table 1 the blade numbers allow a reduction of the computational domain to  $1/16^{\text{th}}$  ( $22.5^\circ$ ) of the machine. As a consequence, instead of performing a whole annulus calculation, one can reduce the computational domain to  $1/16^{\text{th}}$  of the circumference. Therefore in this study, four types of calculations have been performed in order to be compared:

- a multiple frequency phase-lagged calculation (MFPL), performed by ONERA,
- a harmonic balance time computation (HBT), performed by CERFACS,
- a RANS mixing plane calculation (MXPL),
- a reference multi-passage unsteady calculation (REF), performed by CERFACS (Gourdain, 2012) on the same grid as the MFPL/HBT/MXPL approaches, but with each blade passages being duplicated in order to reach a  $22.5^\circ$  sector.

## Numerical and model parameters

The flow solver used for this study is the *elsA* software that considers a cell centered approach on structured multiblock meshes. General information about this flow solver can be found in (Cambier, 2013). For this application, convective fluxes are computed with a third-order scheme, based on the flux splitting method of Roe. Diffusive fluxes are calculated with a classical second order centered scheme. To obtain a time consistent solution (for the two URANS simulations: REF and MFPL), the time marching method is based on the second order Dual Time Stepping technique. All unsteady RANS simulations are performed with a time step equal to the rotor-passing period divided by 6400 (100 time steps are used to describe the blade passing frequency of the first blade row). The size of this time step has been validated by previous works on the same configuration (Gourdain, 2013). The turbulent viscosity is computed with the two equations model of Wilcox based on a  $k-\omega$  formulation. Boundary conditions are detailed in (Ottavy and Gourdain, 2012). The inlet of the calculation domain is located at position 25A (see Fig. 1) where experimental pressure probe measurements are available to define the inlet conditions. The outlet duct behaviour is modelled using a throttle condition, coupled with a simplified radial equilibrium law. The treatment of periodic boundaries and rotor/stator interfaces is different for the 4 calculations. Spatial pitch wise periodic boundaries are applied at the periodic boundaries for the MXPL and REF computations, while multiple frequency phase lagged conditions are applied in MFPL and HBT. At rotor/stator interface a mixing plane condition is applied for the MXPL, sliding mesh join conditions for the REF, and a sliding join condition using a Fourier reconstructed (and phase lagged) field for HBT/MFPL methods. Concerning the convergence criteria described in (Castillon, 2015), URANS calculation (REF and MFPL) are considered converged when time flow periodicity is obtained ( $1/16^{\text{th}}$  of the rotation period), while for the steady type calculations (MXPL/HBT), classical steady criteria are used, such as mass flow convergence, or residual decrease. Regarding the number of harmonics, in the MFPL calculations the flow field is approximated as a sum of two periodic functions associated to the upstream and downstream blade passing frequency. Each periodic function is approximated by a Fourier series composed of  $N_{\text{harm}}=16$  harmonics. A lower number of harmonics is used in the HBT approach (4 harmonics). Indeed, for robustness issues  $N_{\text{harm}}$  could not be increased in the HBT computations.

## RESULTS

In the following paragraph, one analyzes results (compressor maps, circumferentially and time-averaged radial distributions, flow field snapshots, and finally time fluctuations) obtained with the two unsteady reduced models (MFPL, HBT) comparing them to the reference multiple passage unsteady computation (REF) and a standard mixing plane computation (MXPL). The following comparisons aim at answering the following questions:

- 1) Compared to the reference multiple passage computation, are the MFPL/HBT methods capable of reproducing the main unsteady effects?
- 2) Compared to the reference multiple passage computation, which effects are not captured by the MFPL/HBT methods?
- 3) In terms of time averaged global quantities, is there a significant improvement compared to a standard mixing plane approach?

In the following paragraphs, for clarity purpose, only numerical results are compared. Indeed, a deliberate choice has been made not to present experimental values, since the main objective of the present paper is to quantify the errors between the reduced models and their reference which is the multiple passage computation. Comparisons between calculations and experiments on the CREATE compressor have already been presented and discussed (Marty 2012, Gourdain 2012, Castillon 2015, Guédeney 2012).

## Compressor map

The comparison of the compressor maps (pressure ratio and isentropic efficiency as function of mass flow) obtained for the four types of computation is presented in figure 2. Calculations plotted are those which converge, numerical stall is considered when computations diverged. In terms of pressure ratio, one observes that the four calculations give close results (less than 1% difference) for all of the operating points from choke ( $Q \sim 1.08$ ) to nominal points ( $Q \sim 1.02$ ). Discrepancies begin to appear for operating points close to stall. Both the HBT and the MFPL computations underestimate the stall margin obtained by the reference computation. Indeed, the reference computation exhibits a last stable point around  $Q \sim 0.97$ , while the last stabilized computation for the MFPL is around  $Q \sim 0.99$  and  $Q \sim 1.02$  for the HBT. Even if the MFPL computation is more stable than the HBT simulation in the sense that it is capable of obtaining stabilized solutions near surge zone  $[0.99; 1.00; 1.01]$ , the compression ratio for these points are underestimated of about 3% compared to the reference computations. This difficulty for the simplified unsteady models (MFPL, HBT) to obtain accurate results for such operating points can be explained by the fact that these models rely on hypothesis which are no longer valid near stall, like the spinning mode hypothesis, or the assumption that the main encountered flow frequencies are the adjacent blade passing frequencies. Concerning the mixing plane results, the stall margin is a bit overestimated (last stabilized computation is around  $Q \sim 0.95$ ), and also the isentropic efficiency. In the following analysis, the computations close to the operating point  $Q \sim 1.05$  are compared.

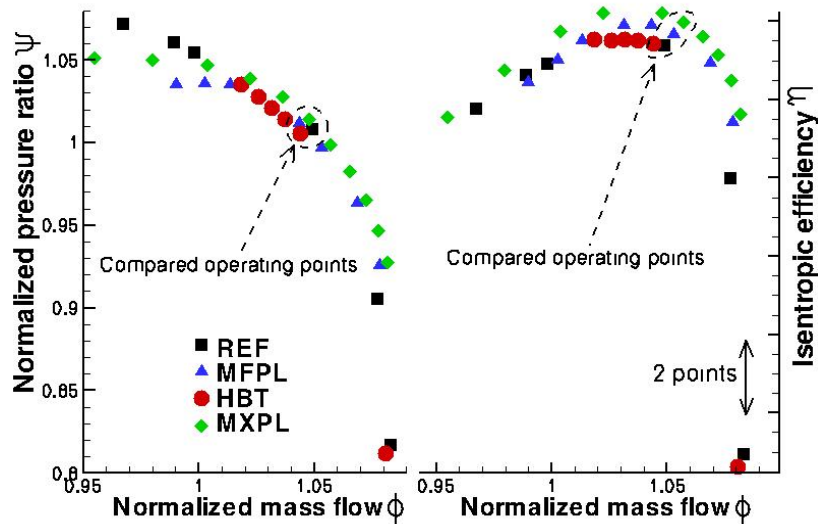
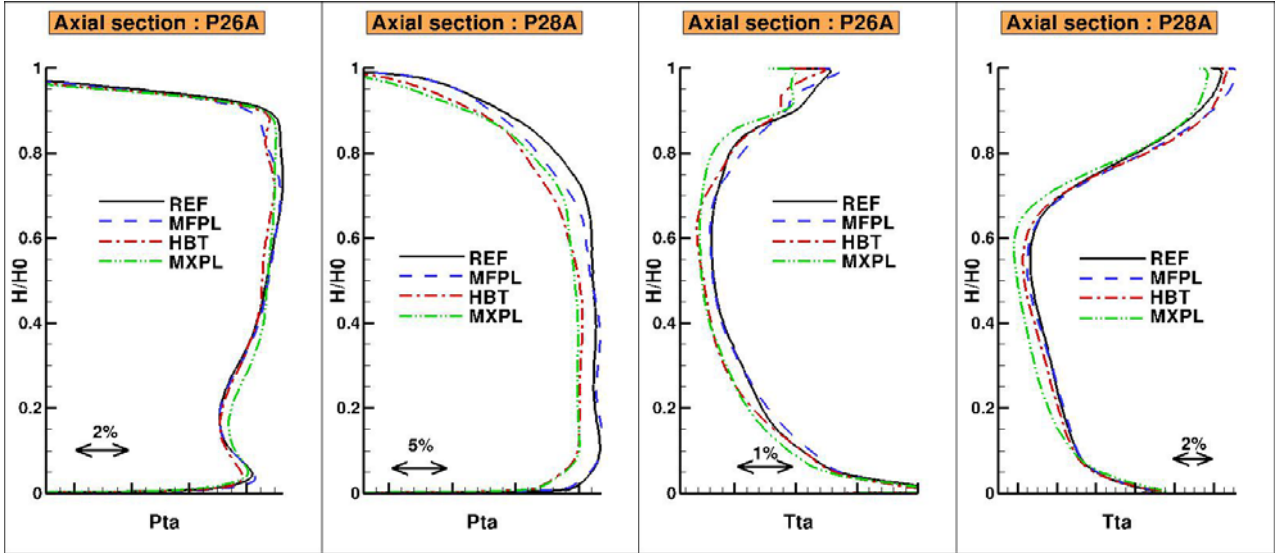


Fig. 2: Compressor map : compression ratio (left), isentropic efficiency (right).

## Radial distribution

Radial distributions of circumferentially and time averaged total pressure and total temperature are presented in figure 3 at two experimental axial planes : plane 26A (downstream rotor 1) and plane 28A (downstream rotor 3). The position of the experimental planes is reminded in figure 1. One can notice that the results are quite close for the four methods (maximum 2% difference for total pressure and 1% for total temperature). The slight discrepancies between the four computations are due to the fact that the computations are not located exactly at the same position in the compressor map. The HBT and MFPL computations both manage to capture the shapes of the radial evolutions obtained in the reference computation. It is also worth noting that there is no significant improvement of these radial distribution predictions with the three CFD approaches (REF and MFPL) compared to the steady (MXPL) approach. Therefore, if in an industrial design context one is only interested in global values prediction as radial distributions of time-averaged results, the mixing plane model is well adapted. For this investigated configuration, the estimation of these time-averaged quantities will not be significantly improved with the two reduced unsteady approaches.





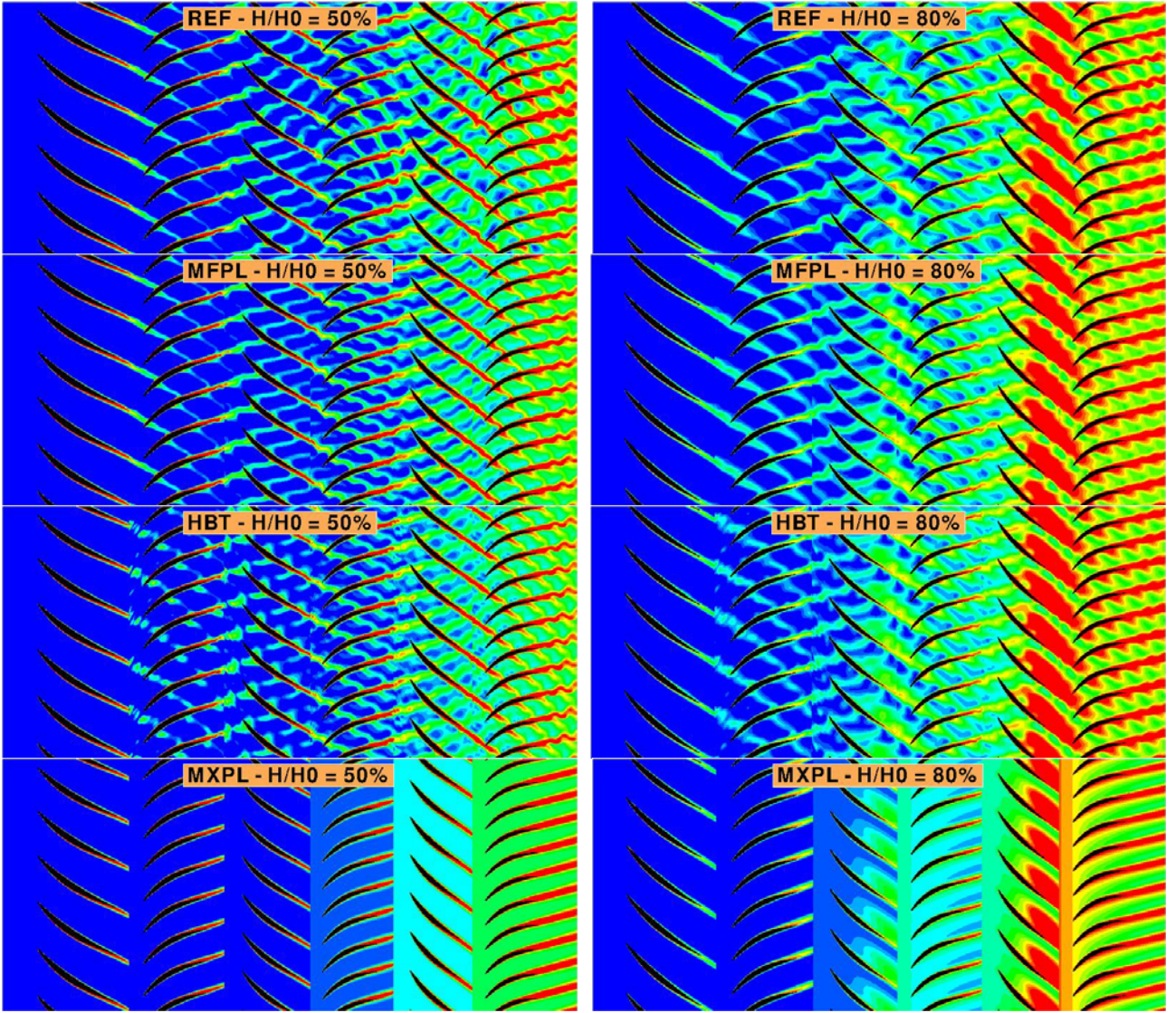
**Fig. 3: Radial distributions of time and circumferentially averaged absolute total pressure and temperature at axial sections P26A and P28A.**

### Snapshots

The MFPL/HBT calculations are performed with only one blade passage per row. Yet, knowing the flow Fourier decomposition in one blade passage, one can reconstruct the flow field on adjacent blade passages from the current blade passage by applying a phase-shift (Castillon, 2015). Such reconstruction is presented in figure 4 where entropy snapshots are plotted at two span heights (50% and 80%). The main flow structures are well captured by the two simplified unsteady models: the main convective effects (wake migration) and segregation effects between low and high entropy zones are well reproduced. In particular at 80% of span height, the high entropy zone which is observed on the pressure side at rotor 3 for the reference computation is well captured by both unsteady models. This figure is also interesting since it enables to highlight the weaknesses of both reduced unsteady models. First of all one can observe that clocking effects are not accurately simulated by MFPL/HBT. Indeed, the wakes emanating from rotor 1, which are convected through stator 1, are not transmitted correctly in stator 2 since the HBT and MFPL models do not take into account any phase lag influence between rotor 1 and rotor 2. Moreover one can observe on this figure that the number of harmonics ( $N_{\text{harm}}=4$ ) used in the HBT computation is insufficient to capture accurately the rotor 1/stator 1 interaction. Indeed, the wakes emanating from rotor 1 are cropped and filtered by the interface treatment at rotor 1/stator 1. This effect is less observed in the MFPL computation for which 16 harmonics are used in the flow decomposition. But as mentioned previously, for robustness issues  $N_{\text{harm}}$  could not be increased in the HBT computations.

It is also interesting to compare the MFPL and HBT snapshots with the steady flow field obtained by the mixing plane calculation. In the MXPL calculations, due to the averaging treatment at interfaces, the wakes are "lost" at each interface, only the mean level is transmitted uniformly in the downstream rows. Wake migrations and segregation effects between low and high entropy zones can therefore not be captured by the MXPL model. In particular at 80% of span height, the high entropy zone associated to the tip leakage flow observed on the pressure side at R3 for the reference computation is reproduced but it is much more diffused compared to the MFPL and REF computations. Even though rigorously one should compare the steady flow of the MXPL computation with the time-averaged flow of the three unsteady calculations (rather than snapshots, and it has been done previously for the radial distribution), this comparison is interesting in order to highlight the advantages of the MFPL and HBT approaches compared to the MXPL calculations in the sense that they give access to unsteady and local effects which can not be obtained with the standard mixing plane approach.





**Fig. 4: Comparison of entropy snapshots at 50% and 80% of span height.**

### Fluctuation analysis

Figure 5 represents a time-azimuth diagram of the axial momentum and total pressure fluctuations obtained at section P26A (R1/S1 interface) at 50 % of span height. The azimuth is represented at the abscissa of the diagram and corresponds to a  $2\pi/16$  sector, while the time, corresponding to a period of  $1/16^{\text{th}}$  of the rotor revolution, is plotted at the ordinate. The time fluctuation is defined as the instantaneous value minus the time averaged value,  $T$  corresponding to  $1/16^{\text{th}}$  of the rotation period:

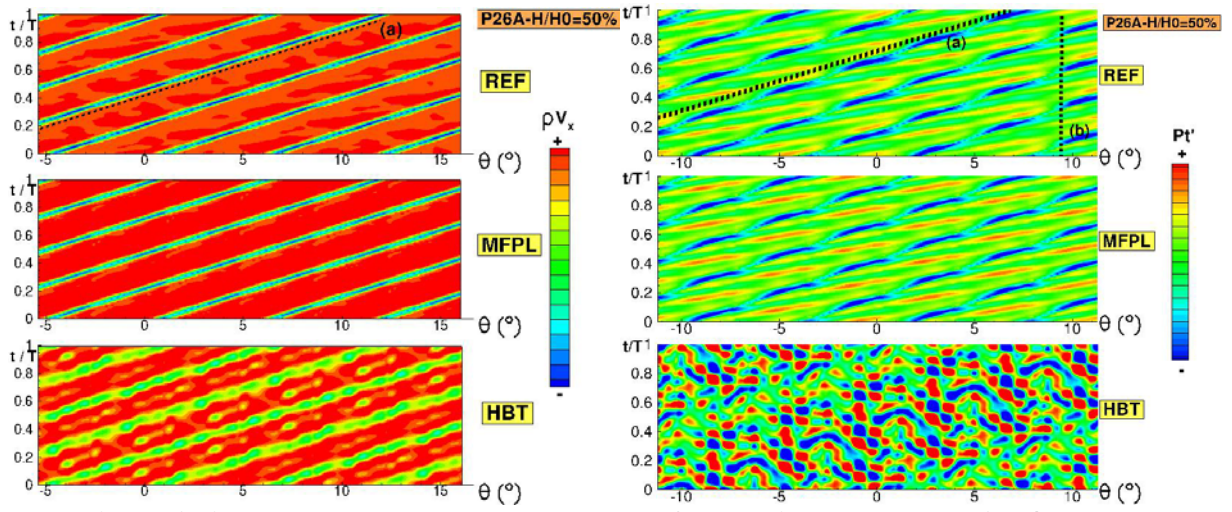
$$F'(x, r, \theta, t) = F(x, r, \theta, t) - \frac{1}{T} \int_0^T F(x, r, \theta, t) dt \quad \text{with } F = \rho V_x \text{ or } F = P_t$$

The values obtained in the REF computation are compared with the two unsteady models (the MXPL calculation, which is a steady approach, can not provide these unsteady fluctuations). The main phenomenon which can be seen on these diagrams is the 4 wakes emanating from R1, represented by the 4 diagonal streaks (a). One can notice a satisfactory agreement between the MFPL approach and the reference computation which captures the wakes emanating from rotor 1 in the frame of reference of stator 1. The HBT method also captures the wake migration, but with less precision due to the low number of harmonics used ( $N_{\text{harm}}=4$ ). In fact the wakes are thicker, as observed previously on the entropy snapshots.

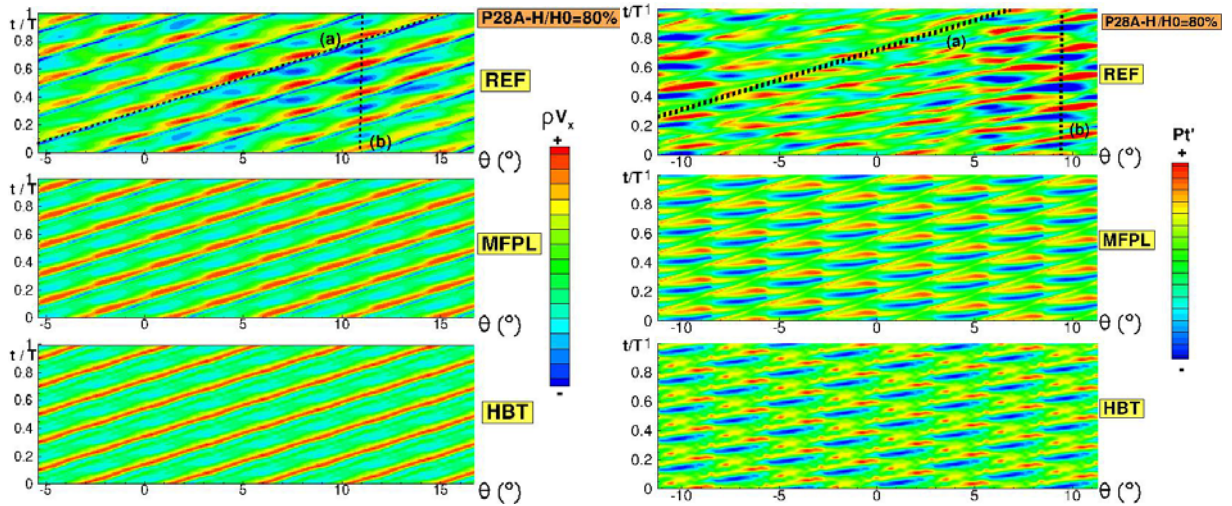


On the total pressure fluctuation diagram, the MFPL calculation captures the potential effects emanating from S1, corresponding to the 6 vertical streaks (b). Once again, due to the low number of harmonics used in the flow decomposition, the HBT does not manage to reproduce this effect.

Figure 6 represents the same time/azimuth diagrams at section P28A (R3/S3 interface) at 80% of span height. Two kinds of streaks can be observed in this diagram: 5 diagonal streaks (a) corresponding to the wake convection of R3 and 8 vertical streaks (b) corresponding to the potential effects of S3. At this section P28A, clocking effects are more important than at the previous section P26A. They are clearly visible for the reference computation, since two azimuthal positions separated by one stator pitch do not experience the same flow field history. A different behaviour is obtained in the MFPL/HBT calculations, since two azimuthal positions separated by a stator pitch experience the same flow field history, with a phase-lag in time. Therefore the clocking effects, which are captured in the reference computation, can not be captured by the MFPL/HBT calculations, since it does not take into account any phase lag effects between rows  $N/N+2$ .



**Fig. 5: Axial momentum and total pressure fluctuation at plane 26A-h/H=50%.**



**Fig. 6: Axial momentum and total pressure fluctuation at plane 28A-h/H=80%.**

## CONCLUSION

This study has enabled to evaluate two unsteady models (MFPL, HBT) for multiple frequency unsteady blade row interaction simulations, which are very interesting alternatives to a full-annulus 360° multiple passage unsteady computations. Both methods enable to reduce the computational domain and therefore to reduce the CPU and memory cost compared to a full-annulus computation, the gain is all the more important as the blade count is large. The comparison with the reference computation shows that the main unsteady effects are well captured by both computations. Unsteady effects between adjacent blade rows (N and N-1) are modelled and captured by the MFPL/HBT approaches. Therefore, the MFPL/HBT approaches seem to be a very interesting compromise between a mixing-plane calculation, which does not model any unsteady effects, and a full-annulus unsteady calculation, which remains very expensive in an industrial context.

Concerning the drawback of the two unsteady methods, if the MFPL/HBT approaches are able to model the unsteady effects induced by the adjacent blade rows, they fail modelling clocking effects, i.e., the relative influence between rows N and N-2. Therefore, at best, these method will only capture unsteady effects linked to the adjacent upstream and downstream blade rows passing frequency. One cannot expect from the method to reproduce clocking effects, which can be important on the downstream blade rows. Moreover, stall margin prediction is underestimated by these approaches compared to a full annulus computation, HBT being worse than the MFPL.

It is now up to aeroengine designers to determine for which configurations these approaches can be relevant. If one is only interested in time-averaged quantities, it was observed on CREATE compressor that mixing plane approach is sufficient. If one needs to have access to unsteady information, for aeroelasticity for example, HBT and MFPL are interesting alternatives. If few harmonics are to be used in the Fourier decomposition, the harmonic balance approach is extremely interesting to reduce CPU, since the computational cost is comparable to a steady computation. If flow situation requires more harmonics (sharp gradients crossing rotor/stator interfaces), the MFPL is a good candidate.

It is important to be careful: the conclusions listed above have been observed on the investigated compressor CREATE. Other tendencies could be observed on other configuration, and these two methods require additional testing on other applications. Concerning future work, it is finally mentioned that the MFPL method will be evaluated on open rotor configurations and that preliminary evaluations have been performed on aeroelastic configurations (Placzek 2014).

## ACKNOWLEDGEMENTS

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