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A NUMERICAL APPROACH FOR THE PREDICTION OF SOUND GENERATED BY A MISTUNED ROTOR CASCADE

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Parole chiave: Aeroelasticità, cascate rotoriche, vibrazioni, emissione sonora.

Abstract. *A numerical investigation on the effects of blade frequency mistuning on the acoustic emission of a rotor cascade in subsonic flow is shown. A numerical method has been developed and implementd to obtain the mistuned rotor aeroelastic response and the associated acoustic waves. Both the aeroelastic and acoustic models are based on a linear unsteady small perturbations theory. The dynamic aeroelastic coupling between bending and torsional responses of each blade and the aerodynamic coupling among the blades are included in the formulation.*

Sommario. *Viene presentata una investigazione numerica degli effetti di "mistuning" sulle frequenze palari e sull'emissione acustica di una cascata rotorica in flusso subsonico. Uno specifico metodo numerico è stato sviluppato e implementato per ottenere la risposta aeroelastica del rotore "mistunizzato" insieme alle associate ampiezze acustiche. Entrambi i modelli aeroelastico ed aeroacustico sono basati sulla teoria lineare delle piccole perturbazioni. Anche l'accoppiamento dinamico aeroelastico tra flessione e torsione viene incluso nel modello insieme a quello aerodinamico tra le palette.*

1 INTRODUCTION

The sound generated by blade rows is generally found to consist of two components: a white noise background of relatively low amplitude (having its origins in random turbulence, non-periodic force fluctuations and non-periodic interactions with external perturbations) and a number of large amplitude tones at certain discrete frequencies (generated by periodic displacement of fluid, fluctuating forces caused by vibration or regular flow disturbances and periodic interactions between perturbed quantities in the flow field). In the development of modern aircraft powerplant, the study of the aeroelastic and acoustic responses of bladed-disk setup is complicated by the presence of small differences between the individual blades, known as mistuning. In the present paper, the proposed numerical technique is capable to compute the acoustic waves scattered from an unsteady rotor cascade and shows that frequency mistuning can also obtain a relevant beneficial effect on both free and forced acoustic response. Furthermore, this work highlights how frequency mistuning is able to introduce multiple acoustic resonant peaks for a given aeroelastic mode and different behaviours of the rotor system corresponding to even and odd blades number in the assembly.

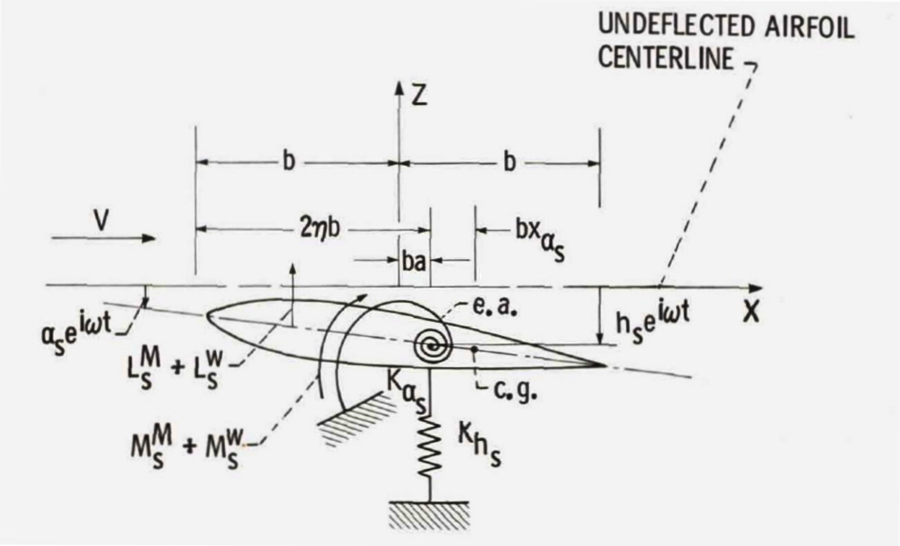


Figure 1: Blade scheme with acting forces and parameters

2 PRINCIPLES AND MODELIZATION

The structural model of the j -th blade of a mistuned cascade is illustrated in Figure 1. Each airfoil is suspended by bending and torsional springs, k_{hj} and $k_{\alpha j}$, respectively. The airfoil is assumed to be rigid along the chordwise and this motion is here neglected. The inertial-elastic coupling between bending and torsion due to pretwist, shrouds, and rotation of the rotor is included in the formulation through the offset distance between the center of gravity and elastic axis. The centrifugal stiffening effects due to rotation could be included in the bending and torsional spring constants. The elastic and dynamic properties of the blades are represented by their respective values at a defined station of the blade span.

In this study the effects of frequency mistuning on the rotor acoustic response is examined through the use of two mistuning patterns. Without loss of generality, here we consider the alternated and random patterns Figure 2. In the first one, the odd and even numbered blades have different torsional frequencies: in the case of 1% mistuning, the frequency ratio is 1.005 for all the even blades and 0.995 for all the odd blades. The reference frequency is equal to the arithmetic mean of the uncoupled

torsional frequencies of all the blades. In the second pattern, individual blade frequencies are chosen from a normally distributed population about the frequency of the nominal blade (zero index j = 0) with a standard deviation of 0.005. This mistuning is achieved by altering the torsional stiffness of the blades, the bending one also varying through a fixed bending/torsion stiffness ratio of 0.357.

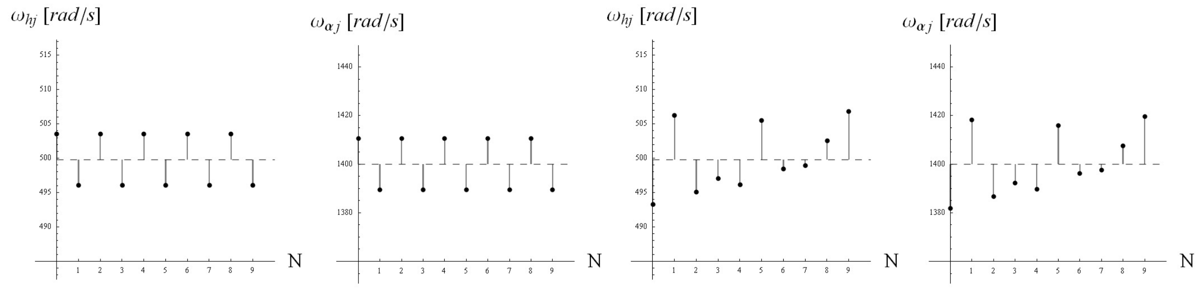


Figure 2: Bending-torsional frequencies alternated (left) and random (right) mistuning patterns.

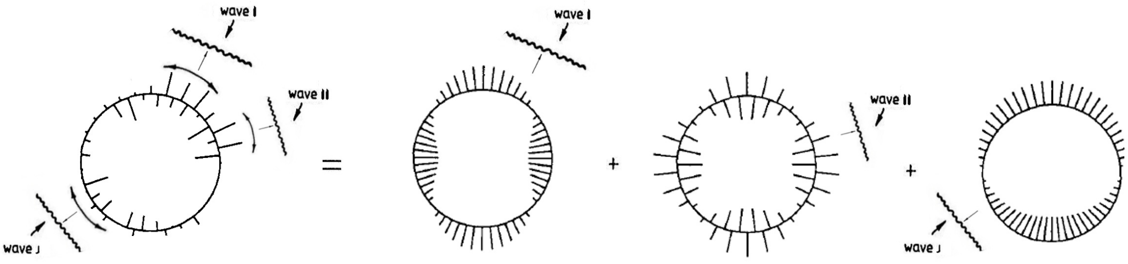
As previously mentioned, the unsteady aerodynamic coefficients have been calculated by using Smith's subsonic flow cascade theory, which is briefly discussed to underline several aspects of the acoustic model adopted in the present paper. Strictly speaking, aerodynamic loads, generated acoustic waves and shed vortex wakes can be calculated when the blades are subjected to bending or torsional vibration, incoming acoustic waves, or convected wake velocity perturbations. In agreement with Kielb et al., in the calculation of subsonic aerodynamic loads, some numerical convergence problems are encountered when $\beta r = 0$ or 2π. This numerical problem has been resolved by setting $\beta r = 0{:}001$ whenever its value should be 0 or 2π. Unlikely, the Smith's theory is inadequate to deal with the extra sound sources introduced by blade steady loading, thus results are restricted
to blades in unloaded condition only.

3 FAR FIELD ACOUSTIC WAVES

A particular cascade wave excites acoustic perturbations in the flow which may propagate unattenuated or exponentially decay away from the cascade, depending on its value of _ and therefore of the acoustic mode with index j, The alternative applied in a given case will be defined by the condition previously imposed for the wave number α. If decaying perturbations are produced, the mode will be in a cut-off condition. For a particular set of cascade parameters, there is a definite value of $|j|$ above which all modes are cut off exciting perturbations with increasing decay rates as $|j|$ increases. As Mach number approaches unity, this limiting value of $|j|$ becomes infinite. Each value of j gives a propagating mode and thus a pair of waves is formed, one travelling upstream and downstream the other one.

An application of Lagrange's equation to the mathematical model of the j -th blade in Figure 1 leads to the well-known coupled bending-torsion equations; meanwhile the aerodynamic forces due to the motion and the excitation from sinusoidal wakes are expressed in terms of nondimensional coefficients.

In the Kielb's et al. mechanical model for a generally mistuned rotor system, the motion of the airfoils in each mode of the tuned cascade is assumed to be simple harmonic with a constant phase angle (βr between adjacent blades). Also, this interblade phase angle is restricted by Lane's assumption to the N discrete values. Consequently, there are N aeroelastic modes for the cascade with each blade having the same amplitude. When mistuning is introduced, the general motion of a blade is a combination of the motions in all possible interblade phase angle modes of the corresponding tuned cascade. The acoustic model presented in this paper is based on a similar approach: from an acoustic point of view, the general acoustic response of a mistuned rotor may be seen as a superposition of those of the all possible tuned cascade sectors with the associated interblade phase angle. The reader can follow Figure 3 showing a schematic view of the proposed concept.



Mistuned Mode r   Tuned Mode I   Tuned Mode II   Tuned Mode j

Figure 3: Approach scheme for calculating noise

Each of these constant interblade phase angle sector contributes to the overall generated noise of the mistuned cascade scattering two acoustic waves for an acoustic mode j, whose amplitudes can be calculated. In this way, N distinct aeroelastic modes of the mistuned cascade (being themselves combination of the N modes of the associated tuned rotor), can be taken from the aeroelastic solution. Consequently, one also obtains NxN acoustic modes. The numerical code scheme implemented in the present work starts with calculating all of the pressure wave coeffcients amplitudes. At this step, the calculated critical Mach number has been adopted as a numerical filter for all the cut-off acoustic modes, which, for their intrinsic acoustic nature, cannot be present in the far-field. For the calculation of all these remaining cut-off acoustic modes, which decay very rapidly in the near-field, Marretta et al. showed a general method for predicting far-field and near-field noise generated by the unsteady loading induced on a tuned propeller. The aerodynamic model of this method is based on a combination of free wake analysis and a three-dimensional boundary element method, while the acoustic one is based on the Lighthill equation and on a full-surface, moving medium form of the Ffowcs Williams-Hawkings equation. However, this work has been restricted to the cut-on acoustic modes, only.

4 RESULTS AND DISCUSSIONS

The reliability of the numerical analysis proposed in the present paper has been checked for the following special cases:

- The unsteady aerodynamic coefficients for both incompressible and subsonic flow regime have been checked by comparison
of the present results to those presented in (see Figure 4).
- The eigenvalues obtained for the aeroelastic free response case in both incompressible and subsonic flow regimes (not shown)
for the tuned and mistuned systems have been checked by comparison with those presented in literature (see Fig. 5).

- The response amplitudes in the frequency domain obtained for the aeroelastic forced response case in both incompressible and subsonic flow regimes for the tuned and mistuned systems have been checked with those presented in literature (see Fig. 6);

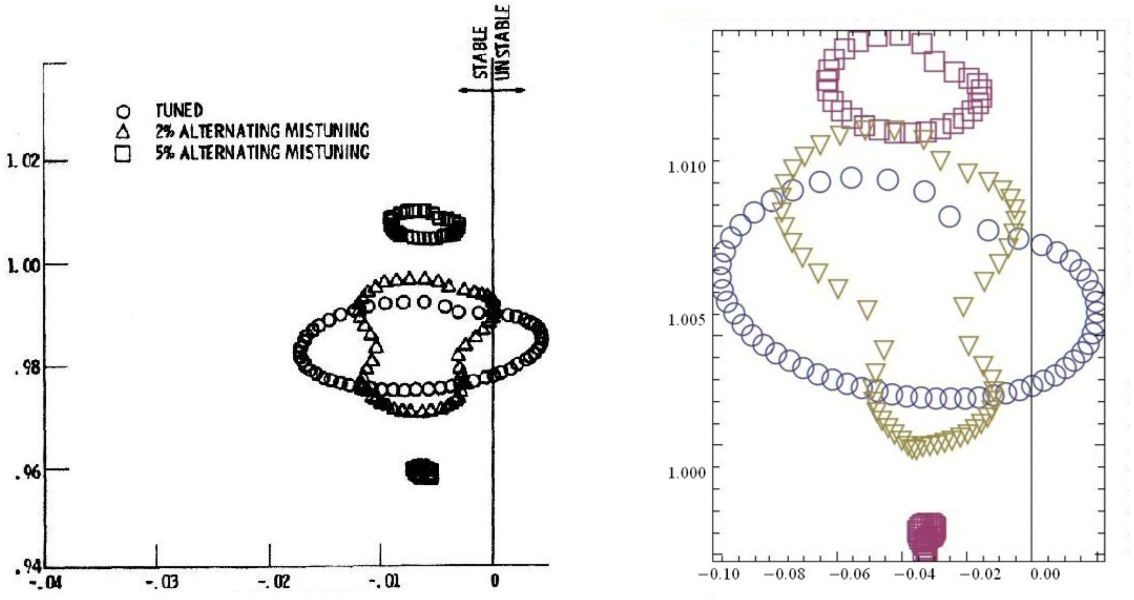


Figure 5: Comparison of aeroelastic eigenvalues (torsional mode only).

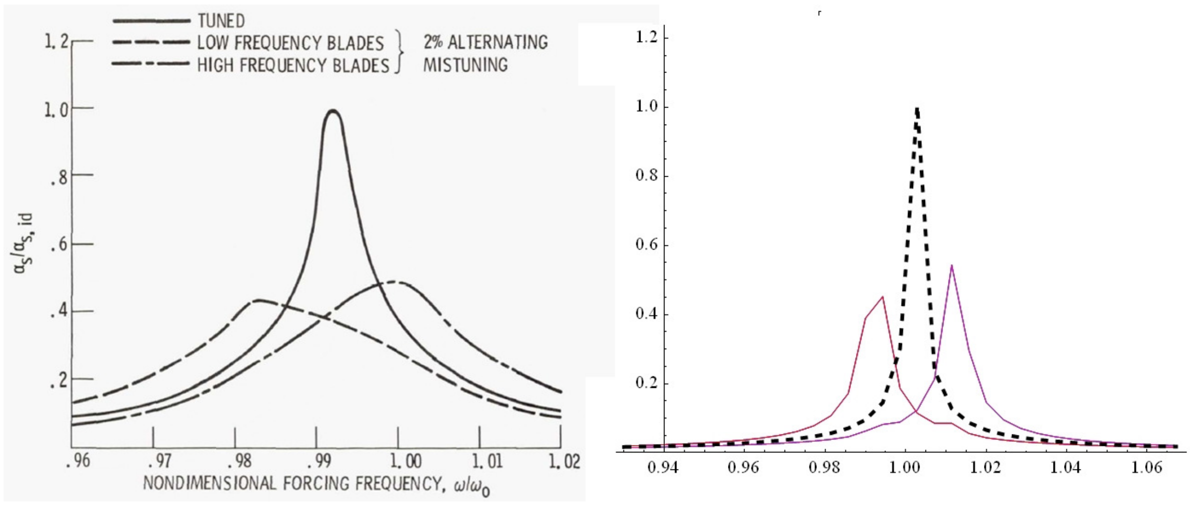


Figure 6: Comparison of forced response amplitudes for torsional mode only.

For all of these cases a good agreement has been achieved.

A digital program was written to calculate the aeroelastic and acoustic responses of a mistuned rotor cascade. In this program, it is possible to consider several types of mistuning such as blade-to-blade variations of the uncoupled bending and torsional frequencies, damping ratios, mass ratios, elastic axis and center of gravity positions, and so on. Here, from a computational point of view, one has to consider and underline that reasonable low cost computational resources are just capable for the involved process (3.60GHz processor). Both tuned and mistuned uncoupled bending and uncoupled torsion cases, in addition to the tuned coupled bending-torsion case, can be treated as special cases by this code, being the test rotor a 10-blades assembly at the specified parametric conditions

When (respectively to the tuned case) other harmonics come from the interaction between the critical Mach number and the interblade phase angle $\beta r;j$, the present code can only give the amplitudes of one harmonic at once: nothing can be said and predicted about the superposing phenomena which come from reflections, transmissions and interactions, in general, between the harmonics themselves when these are locally scattered from the rotor, even though the Smith's theory (for the tuned cascade case) is able to evaluate these phenomena for each tuned sector independently. One way for estimating the overall generated noise of a mistuned rotor in the presence of more than one harmonic consists of performing an overall integration of the all harmonics spectrum for each aeroelastic mode. This has as a consequence that the noise calculated with the present method is the same of that perceived by an observer (located in the far-field) if the N harmonic amplitudes of the (acoustically speaking) worst r-th aeroelastic mistuned mode were totally added together. For an alternated mistuning pattern Figure 7, several aeroelastic mistuned modes have been found in which the odd (or even) harmonics have all the same amplitude (all associated to the same interblade phase angle) and the even (or odd) harmonics amplitudes become zero or relatively small, all together contributing equally to the sound generation. For the same conditions and cascade parameters, it has been found that (for a given normal distribution for the random pattern) either the alternated or random mistuning patterns have a beneficial effect in both free bending/torsion and forced acoustic responses. This particular case shows that a mean noise (in terms of all three pressure coefficients) reduction of -25:9% is achieved by the random mistuning pattern (being the acoustically worst the 1st/2nd aeroelastic tuned/mistuned modes) and - 29:4% by the alternated one (with the 1st/(5th,3rd) aeroelastic tuned/mistuned modes associated).

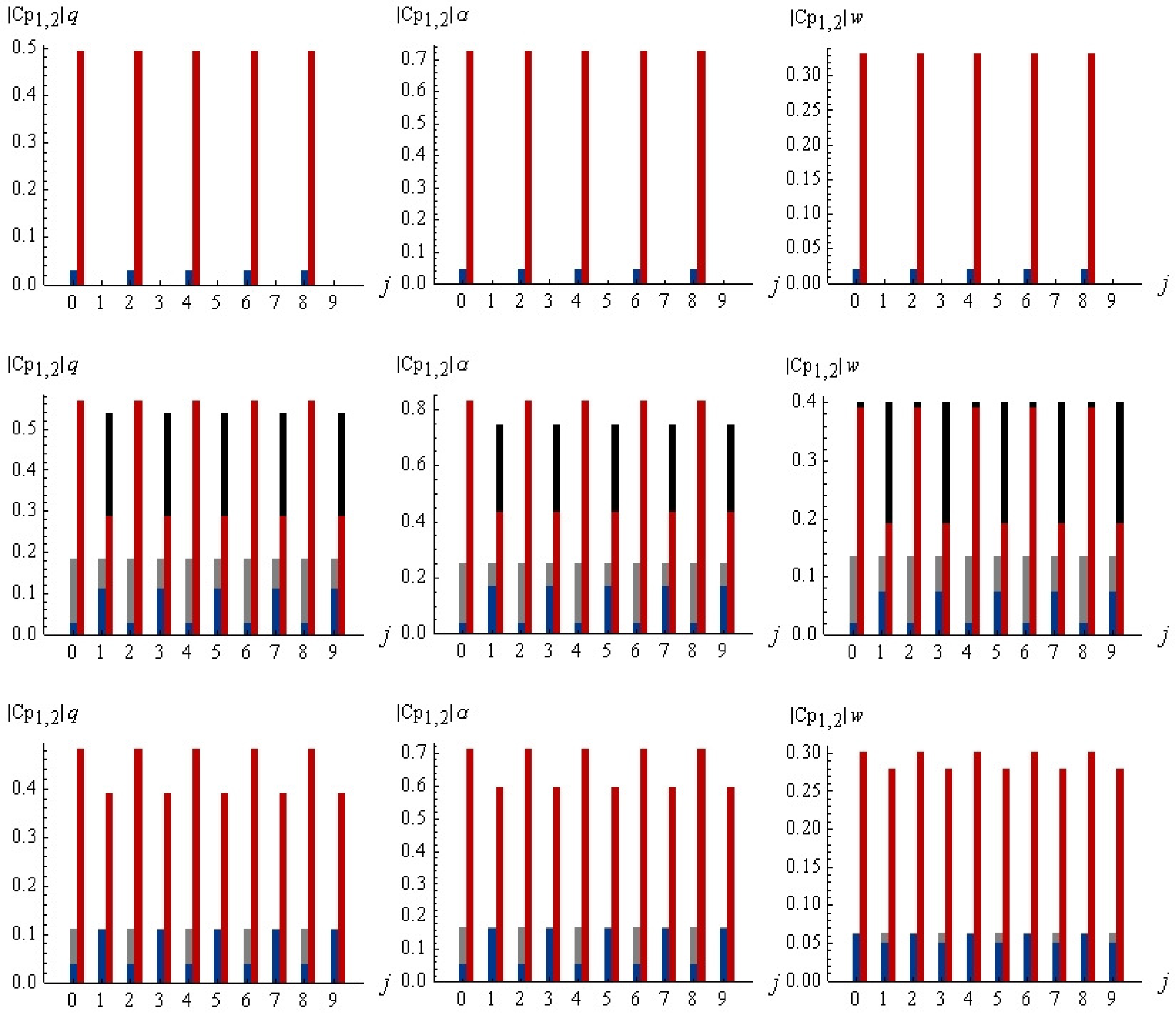


Figure 10: acoustic-aeroelastic modes of a 5% alternated mistuned rotor in free bending/torsional and forced vibrations.

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