Vibration Modes Localization in Aircraft Engines Turbine Blades

Reyolando M.L.R.F. Brasil[1]

[1]*CECS, Federal University of ABC*
Bairro Anchieta, Sala 386 - Bloco delta - Campus SBC, 09606-045, São Paulo, Brazil
reyolando.brasil@ufabc.edu.br

Abstract. The present work refers to the identification and analysis of structural issues in aeronautical engine blades referring to the possible occurrence of the Phenomenon of Vibration Modes Localization. We study the distribution of vibrational energy in turbine models in which a large number of nominally identical subsystems (the blades) are coupled by the rotor to which they are attached. Thus, an analysis was adopted considering, first, an ideal model, where we have characteristics, such as length, stiffness, angle of the blades etc., given as identical for all subsystems. In this case, the vibration modes extend to the entire set of blades. Next, the model is considered for a more real consideration, varying certain structural characteristics of the blades (in this work, the focus was on varying the length of the blades). It is shown that, in this type of more real model, the Phenomenon of Vibration Modes localization in Aeronautical Turbine appears and must be considered. In this phenomenon, the vibration energy ends up being located in only part of the system, sometimes in a single blade. For these analyzes, the Matlab language was used in a program based on the Finite Elements Method to identify the vibration modes of a cyclic system such as turbine, generating graphs to allow a better visualization of the presence of this phenomenon and the comparison between the models, real and ideal. This work is carried out using matrix structural analysis and we consider real geometric characteristics of jet turbine motors for a more accurate modelling. Geometric stiffness due to traction centrifugal forces are also taken into account, as such turbines rotate at very high frequencies. A case study of a N2 turbine of the CFM56 engine is presented. Failure to monitor this phenomenon by manufacturers and maintenance companies can result in serious incidents related to overload or fatigue, of one or more blades in the system.

Keywords: mode localization, turbine blades, computational methods.

1 Introduction

Turbines are the propulsion system of choice for most modern commercial aircrafts, they present a high power to weight ratio and small size when compared to piston engines, and also can come in many forms (turboprops, turbojets, turbofans etc.) to attend the requirements of the mission profile for the aircraft. A big concern involving turbines, however, is the large dynamic loads applied to the structure due to vibrations and large high rotational speeds. These loads can lead to the deterioration of the system with time, resulting in cracks due to fatigue as well as possible catastrophic failure if corrective measures are not taken.

The symmetry of a turbine is a characteristic that defines it as a periodic structure, due to its composition of nominally identical (same stiffness, mass and loads) modules coupled by the turbine shaft. These modules, which in the case of the turbine are the blades, may not be identical structures due to manufacturing imperfections, FOD (Foreign Object Debris) collisions, among other conditions that may change one or more dynamic characteristics of these blades.

These small differences in the blade's properties can cause a phenomenon known as mode localization, where the free vibrational modes are shifted from the ideal model. Whereas the ideal model distributes the vibrational energy through all the components of the system, in the model where mode localization occurs, the vibrational energy is confined to just a few or even one component. This phenomenon was first described by Anderson [1] in 1958, in the context of Solid Physics, a work that earned him a Nobel Prize. Dye and Henry [2] developed an approximated equation for the turbine blades response, using a discrete parameter model.

Valero and Bendiksen [3,4] investigated the case of the mode localization phenomena for unsynchronized cyclical symmetrical structures. The mode localization phenomenon in periodic structures of linear behavior was extensively discussed by Brasil [5], showing that the mode localization can constrain important structural movements to a small region of the system, sometimes even to only one component, while the others suffer almost no motions.

In this work, an algorithm to evaluate mode localization phenomena in turbines was developed and implemented as a computational program that takes into consideration both geometric and elastic stiffness.

A case study of the N2 turbine of the CFM56 engine is shown as an example of application of the developed scheme.

2 Methodology

2.1 Mathematical formulation

The equations of motion of a n-degree-of-freedom linear mechanical discrete system, as those we analyze in this paper, can be put in matrix form as

$$\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{C}\dot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} = \boldsymbol{p}, \tag{1}$$

where $\boldsymbol{M}$ is the nxn mass matric, $\boldsymbol{C}$ the nxn damping matrix, $\boldsymbol{u}$ the nx1generalized displacements vector, superposed dots representing successive time derivatives, p the nx1 load vector and

$$\boldsymbol{K} = \boldsymbol{K_0} + \boldsymbol{K_G}, \tag{2}$$

is the nxn stiffness matrix, composed, respectively, by the constant initial elastic stiffness matrix and the geometric stiffness matrix, the latter a function of the applied load, centrifugal forces in our case.

Here we are interested on the computation of frequencies and modes of free undamped vibrations given by the eigen problem

$$(\boldsymbol{K} - \omega^2\boldsymbol{M})\emptyset = \boldsymbol{0}, \tag{3}$$

where $\emptyset$ is one of the nx1 vibration mode vectors and □ one of the n vibration frequencies.

For periodic structures, composed of a large number of nominally identical substructures these modes extend to whole set. But if light coupling between these modules and small imperfections are present, inevitable in real structures, these modes may get to be localized, that is, motions and vibration energy may become restricted to a few or even to only one of the substructures. This is the mode localization phenomenon, that may occur in such linear systems.

2.2 Algorithm implementation

We implemented an algorithm to solve Eq. (3) for jet engines turbines systems displaying the mode localization phenomenon in MATLAB (Matrix Laboratory). This dedicated program takes the information inputted by the user and applies the resident MATLAB eig function to compute frequencies and vibration modes for this kind of structure, composed of a large number of lightly coupled nominally identical substructures, allowing for the artificial introduction of small imperfections.

The required information is as follows.

- Blade length
- The desired analysis type, either for a perfect or an imperfect system.
- The Young modulus of the blade material.
- The moment of inertia of the blade.
- The mass per unit length of the blade.
- Turbine angular velocity.
- Number of blades.

- Percentage of blade imperfection.
- Coupling stiffness percentage.

After inputting the parameters and running the program, the outputs can be chosen by the user as any of the matrices or values described initially in this section and also graphs showing each vibrational mode.

3 Case study

Next, a N2 turbine of the CFM56 engine was chosen to be analyzed both in an ideal situation and in a situation where the mode localization phenomenon occurs. The turbine and turbine blade data were retrieved from Lane [6].

The next step was to use a CAE (Computer Aided Engineering) software to retrieve more information about the blade. The blade was modeled in MSC Patran, a finite element analysis software, with the data from the literature, in order to obtain the moment of inertia and the volume of the blades

Table 1. Values used in the MATLAB program.

Blade	Nominal Length	Real Length	% Difference
1	0.6	0.633	5.50%
2	0.6	0.615	2.50%
3	0.6	0.576	-4.00%
4	0.6	0.596	-0.60%
5	0.6	0.567	-5.50%
6	0.6	0.592	-1.40%
7	0.6	0.624	4.00%
8	0.6	0.572	-4.70%
9	0.6	0.601	0.20%
10	0.6	0.639	6.50%

Table 1 shows the nominal length of each blade, used when the program is run without the mode localization phenomenon. However, for mode localization to occur, a difference in the dimensions are required and this difference are shown in the same Table.

We also note that only 10 blades were used in this analysis, even though that turbine has 44 blades. This was purposefully chosen due to the fact that we have plotted 2 modes for each blade, yielding a total of 20 figures. If all 44 blades were used in this case study, we would have 88 graphs that would make this paper unduly lengthy. Also, the turbine was considered to be under a 14000 RPM working condition.

The computed vibration frequencies for both cases are shown in Table 2 and the graphs for each mode behavior is shown in Figures 2 through 11.

Figures 2 through 11 clearly show the effects of the mode localization phenomenon for each vibrational mode. The vibrational energy is confined mostly to one blade of the set, while in the ideal case, the energy is distributed a lot more homogeneously. It is also interesting to note how the small changes in the blade’s dimensions change the mode frequency, as seen in Table 2.

4 Conclusions

A mathematical model was implemented as a computer algorithm to evaluate the mode localization phenomenon in turbine blades, taking in consideration both elastic and geometric stiffness, due to large centrifugal forces. The method was successfully implemented in MATLAB environment that can be used for any kind of turbine blades, given that all the required information is available. The results from the calculations are presented to the user in graphs and matrices that can show the behavior of the engine blades at different conditions (considering the mode localization phenomenon or not).

Potentially dangerous conditions due to the mode localization phenomenon was clearly detected.

Table 2. Frequencies for each mode and each case

Mode	Frequency without mode localization (Hz)	Frequency with mode localization (Hz)
1	25258	32399
2	25371	30554
3	25550	31373
4	25780	21439
5	26043	23961
6	26316	27575
7	26578	26659
8	26808	22603
9	26987	25984
10	27101	20763

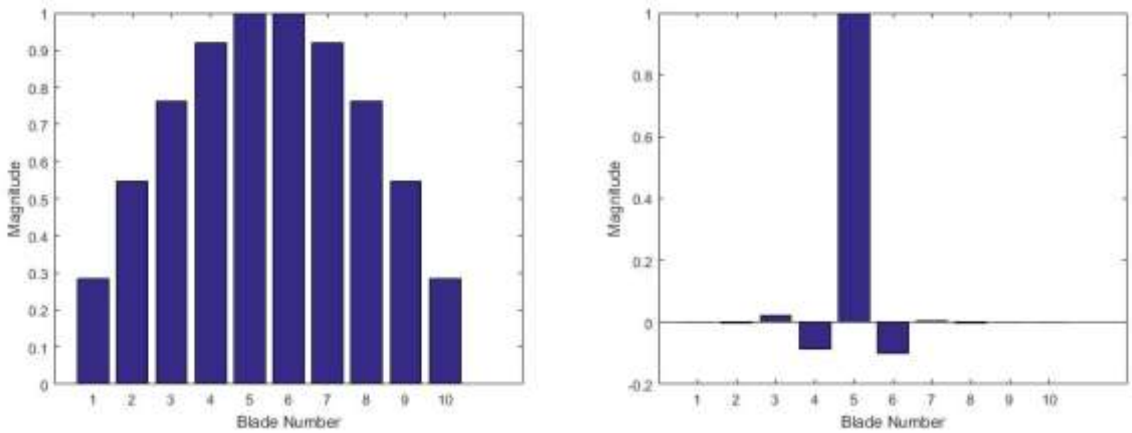

Figure 2. Vibrational mode 1 for both non localization (left) and localization phenomenon (right).

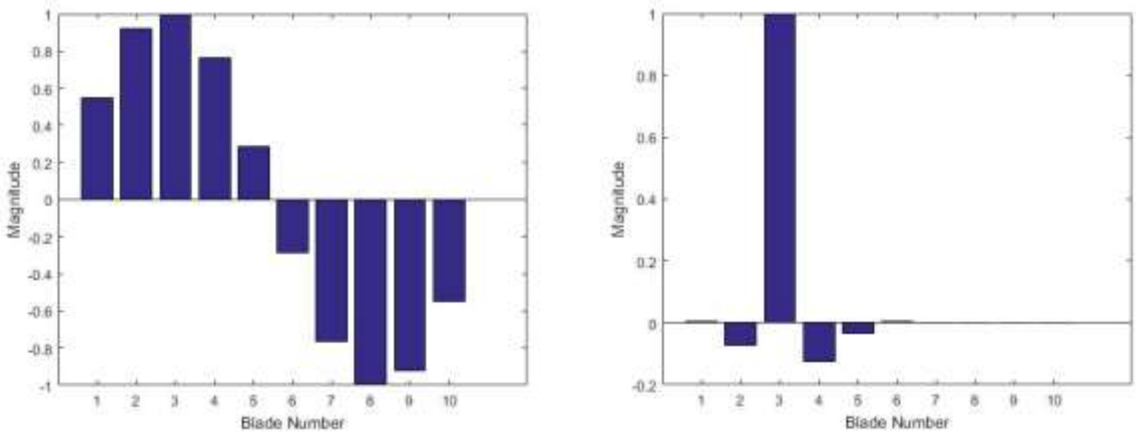

Figure 3. Vibrational mode 2 for both non localization (left) and localization phenomenon (right).

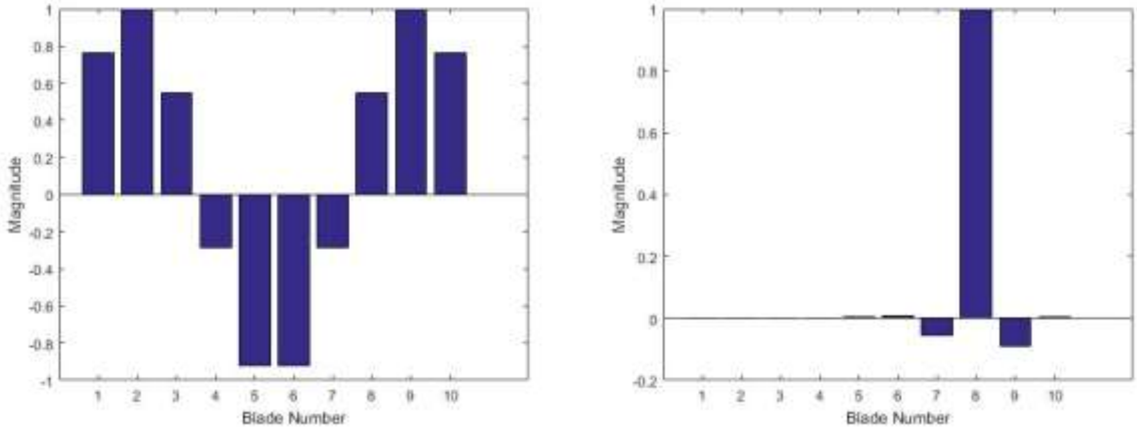

Figure 4. Vibrational mode 3 for both non localization (left) and localization phenomenon (right).

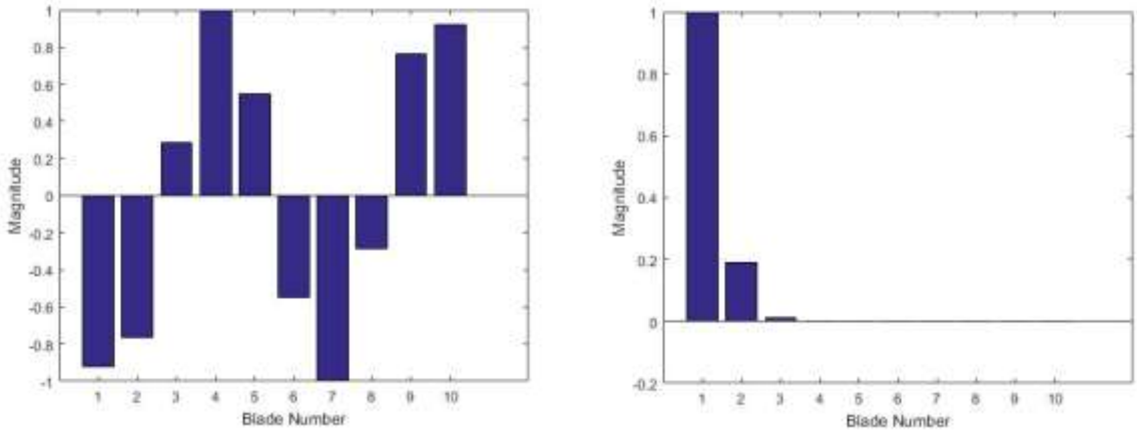

Figure 5. Vibrational mode 4 for both non localization (left) and localization phenomenon (right).

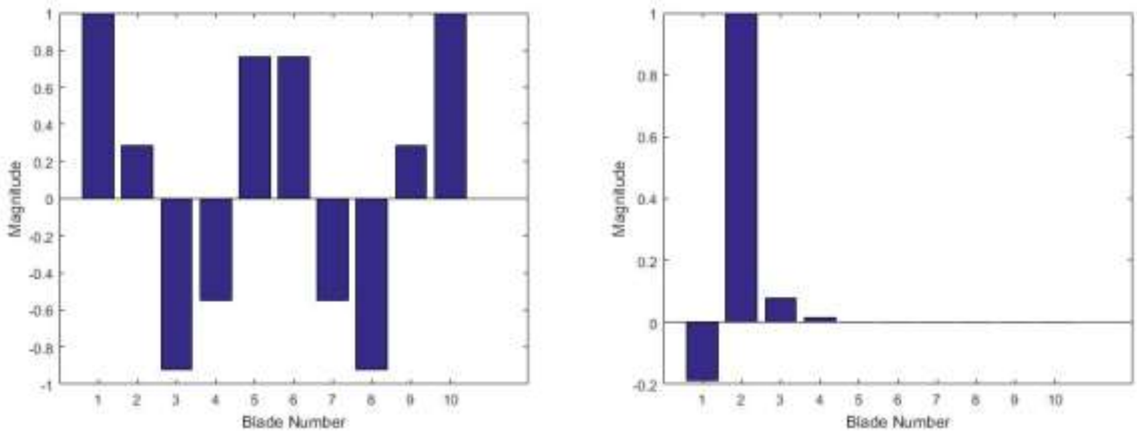

Figure 6. Vibrational mode 5 for both non localization (left) and localization phenomenon (right).

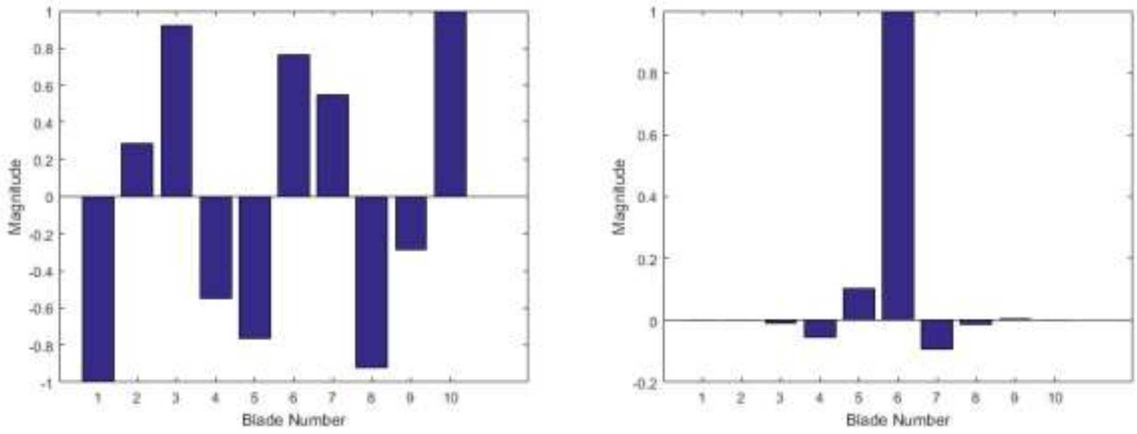

Figure 7. Vibrational mode 6 for both non localization (left) and localization phenomenon (right).

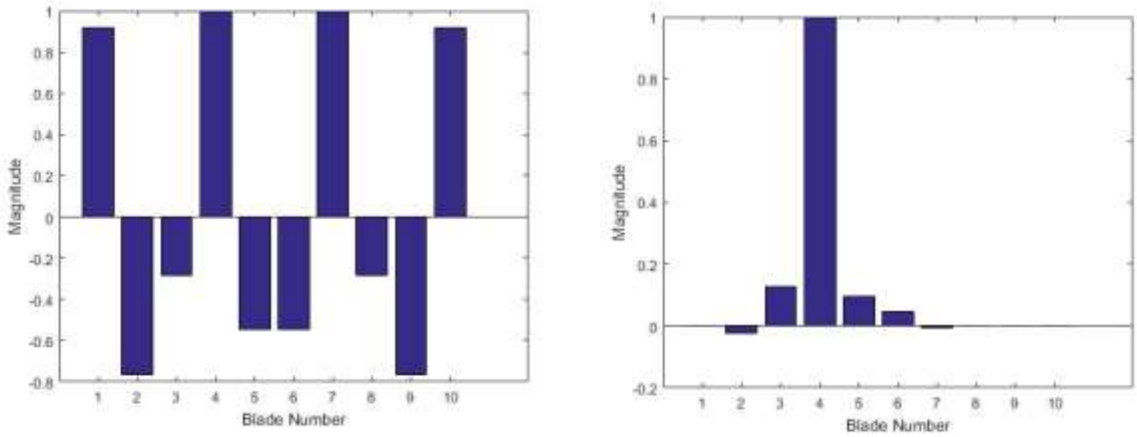

Figure 8. Vibrational mode 7 for both non localization (left) and localization phenomenon (right).

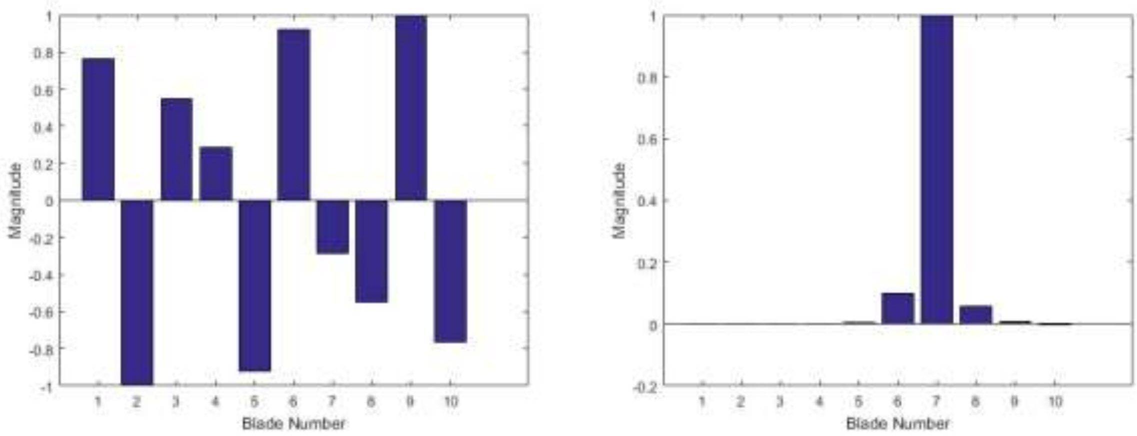

Figure 9. Vibrational mode 8 for both non localization (left) and localization phenomenon (right).

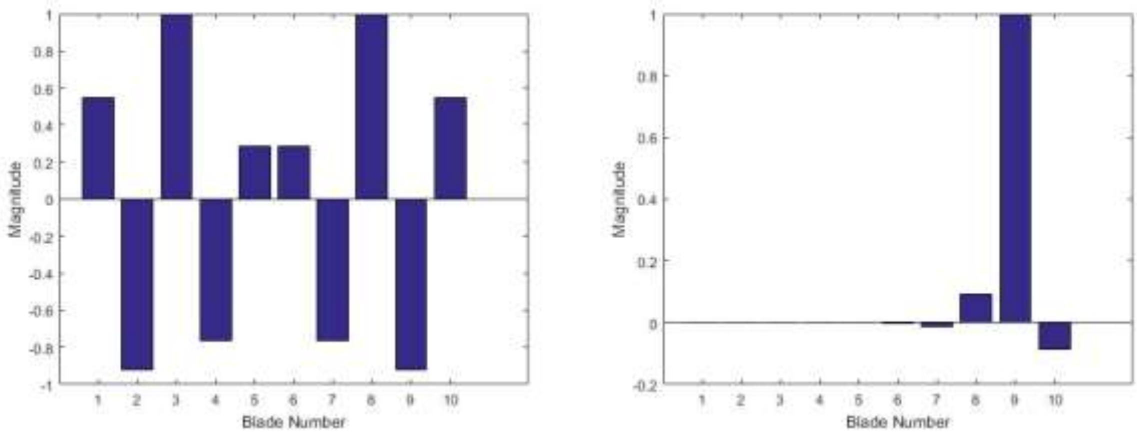

Figure 10. Vibrational mode 9 for both non localization (left) and localization phenomenon (right).

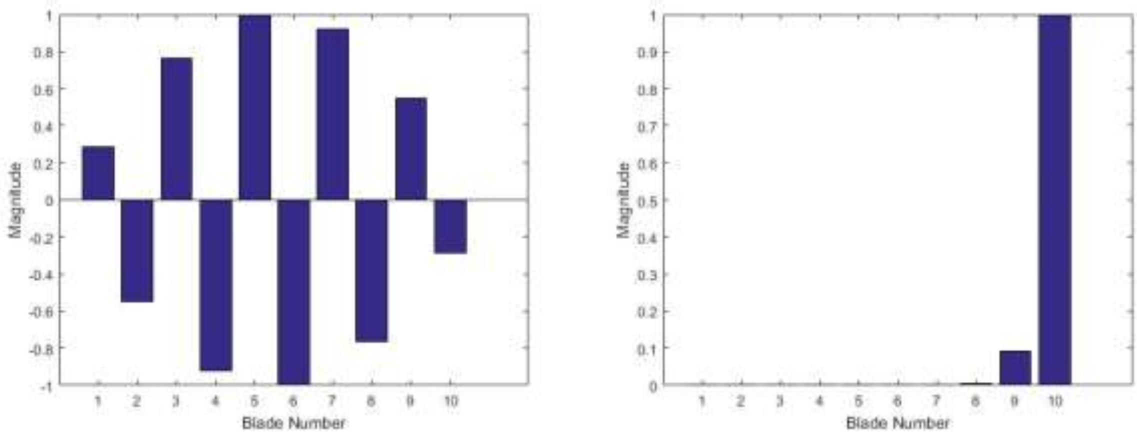

Figure 11. Vibrational mode 10 for both non localization (left) and localization phenomenon (right).

Acknowledgements. The authors acknowledge support by CAPES, CNPq and FAPESP, all Brazilian research funding agencies

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] P. W. Anderson. Absence of diffusion in certain random lattices. Physical Review, vol. 109, pp. 1492–1505, 1958.
[2] R. C. F. Dye and T. A. Henry. Vibration Amplitude of Compressor Blades Resulting from Scatter in Blade Natural Frequencies. ASME Journal of Engineering for Power, vol. 91, pp. 182–188, 1969.
[3] O. O. Bendiksen. Mode Localization Phenomena in Large Space Structures. AIAA Journal, vol. 25, pp. 1241–1248, 1987.
[4] O. O. Bendiksen and N. A. Valero. Localization of Natural Modes of Vibration in Bladed Disks. ASME Paper, n. 87-GT-46, 1987.
[5] R. M. L. R. F. Brasil. O Fenômeno de Localização de Modos em Dinâmica e Estabilidade de Estruturas Moduladas de Comportamento Linear ou Não-Linear, thesis, Universidade de São Paulo, 1995.
[6] A. D. Lane. Development of an Advanced Fan Blade Containment System, US Department of Transport, Federal Aviation Administration, 1989.