

THE MODE LOCALIZATION PHENOMENON IN TURBINES BLADES

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Abstract. We present a numerical study of vibration modes localization phenomenon in blades of aeronautical turbines. This kind of equipment is an example of a class of structures called periodic, that are composed of a sequence of a large number of nominally identical substructures, the blades themselves, lightly coupled by their hub. In the case they are really equal, the vibration modes will extend to the whole set of substructures. If, as is to be expected of real machinery, there are very small differences between the dynamic characteristics of the blades (stiffness, mass etc.), the mode localization phenomenon may occur.

For localized modes, energy may get to be restricted to very few or even a single one of the substructures, the turbine blades. This unexpected behavior may lead to catastrophic failure of the affected part due to excessive vibration amplitude or accelerated fatigue considerations.

Our 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.

Keywords: Turbines blades, Modal analysis, Mode localization, Geometric stiffness, Centrifugal forces.

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, turboprops 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

$$M\ddot{\mathbf{u}} + C\dot{\mathbf{u}} + K\mathbf{u} = \mathbf{p}, \quad (1)$$

where M is the $n \times n$ mass matrix, C the $n \times n$ damping matrix, \mathbf{u} the $n \times 1$ generalized displacements vector, superposed dots representing successive time derivatives, \mathbf{p} the $n \times 1$ load vector and

$$K = K_0 + K_G, \quad (2)$$

is the $n \times n$ 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

$$(\mathbf{K} - \omega^2 \mathbf{M})\boldsymbol{\phi} = \mathbf{0}, \quad (3)$$

where $\boldsymbol{\phi}$ is one of the $n \times 1$ vibration mode vectors and ω 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.

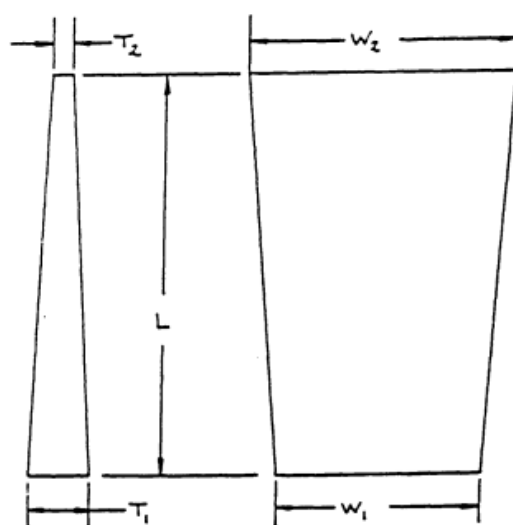
After inputting the parameters and running the program, the outputs can be chosen by the user as any of the matrices or values described initially in this section and also graphs showing each vibrational mode.

3 Case Study: CFM56

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 first step for this case was to retrieve the geometric profile of the turbine blade as shown in Fig. 1.

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.



MODEL NUMBER	NUMBER OF BLADES	WEIGHT (LB)	K.E. (IN-LB)	L (IN)	w_1 (IN)	w_2 (IN)	T_1 (IN)	T_2 (IN)	THRUST (LB)
JT9D-7	46	9.39	$(1.6)(10^6)$	31.30	5.79	7.34	.376	.202	45600
CFM56-2	44	4.41	$(7.5)(10^5)$	23.62	4.57	5.79	.297	.159	24000

Figure 1. N2 turbine blade dimensions for the CFM56 engine. Source [6].

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.

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

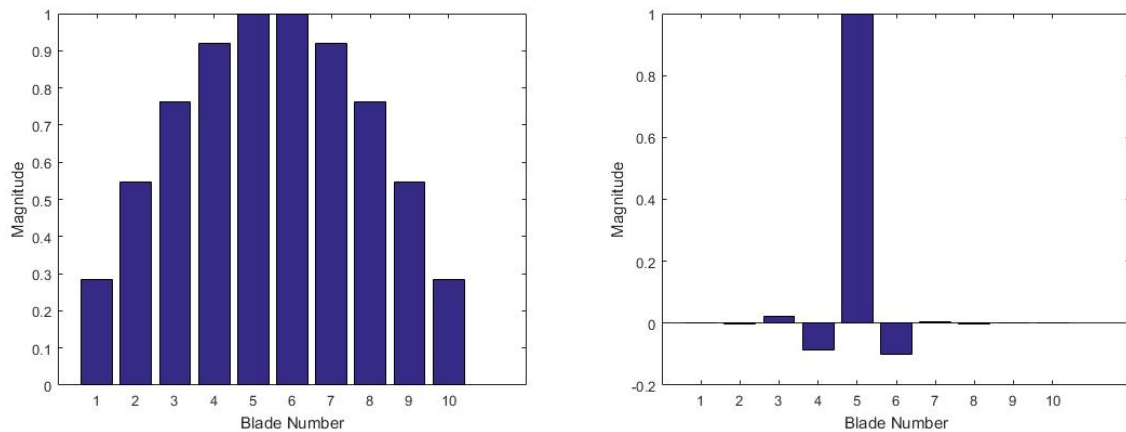


Figure 2. Vibrational mode 1 for both non localization (left) and localization phenomenon (right).

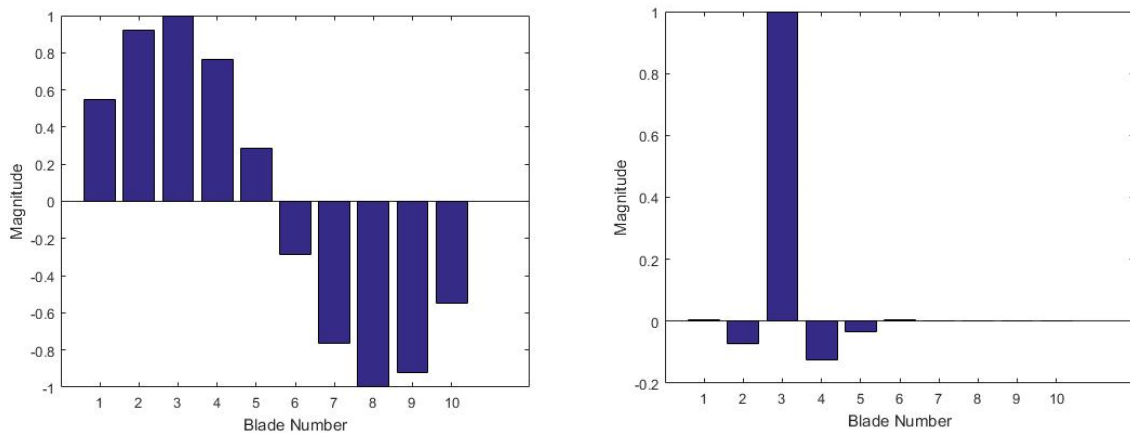


Figure 3. Vibrational mode 2 for both non localization (left) and localization phenomenon (right).

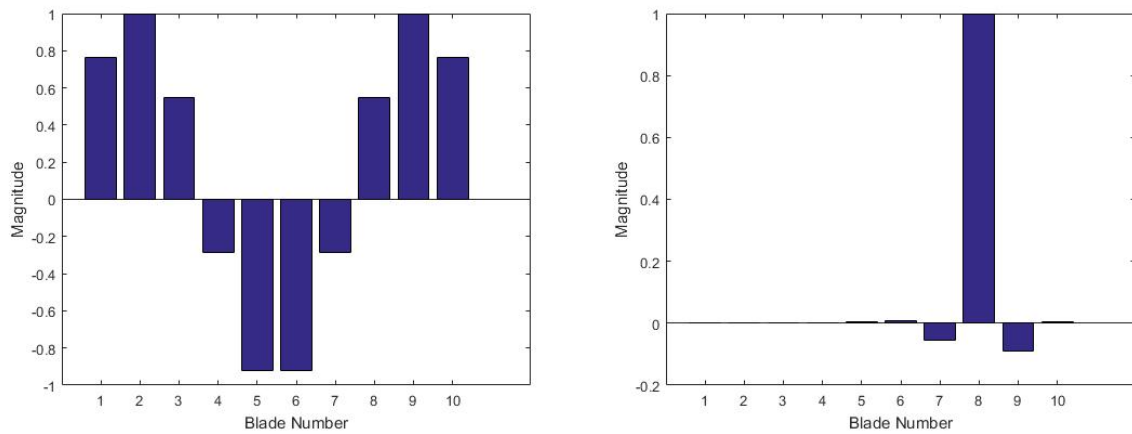


Figure 4. Vibrational mode 3 for both non localization (left) and localization phenomenon (right).

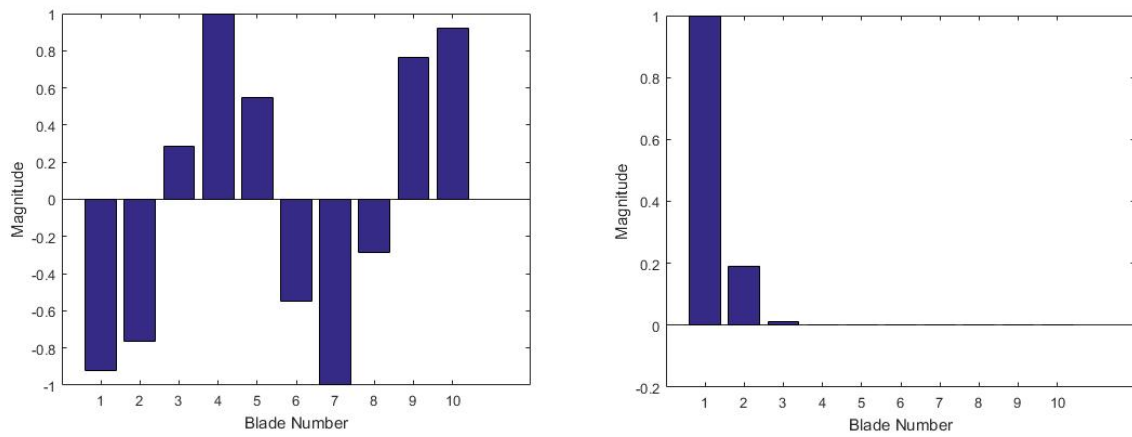


Figure 5. Vibrational mode 4 for both non localization (left) and localization phenomenon (right).

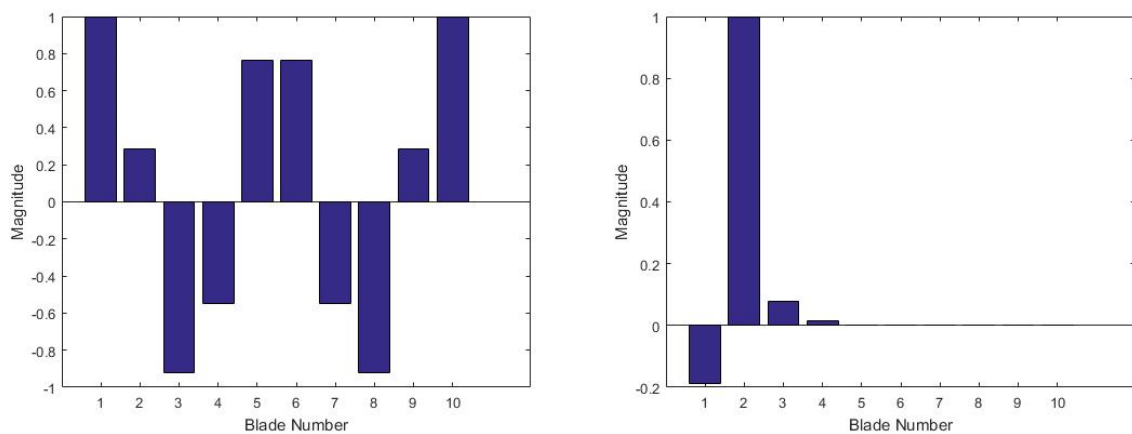


Figure 6. Vibrational mode 5 for both non localization (left) and localization phenomenon (right).

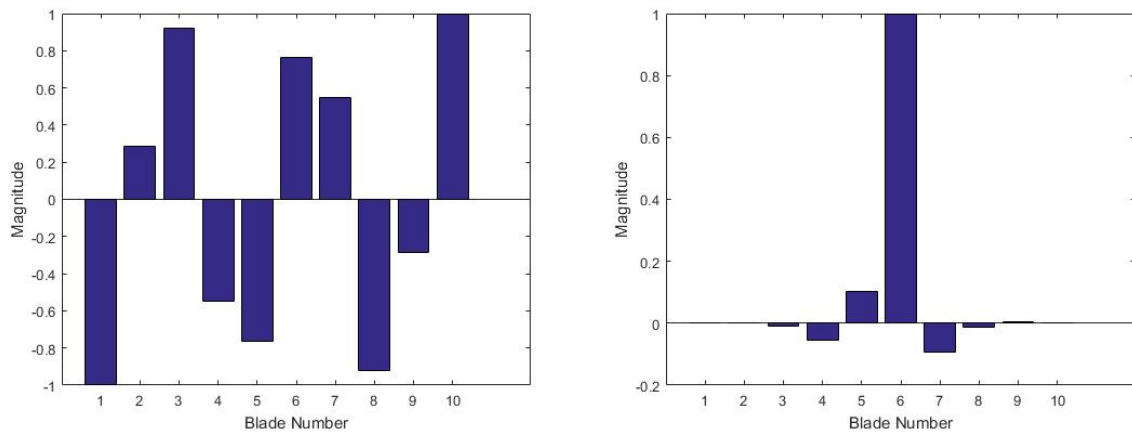


Figure 7. Vibrational mode 6 for both non localization (left) and localization phenomenon (right).

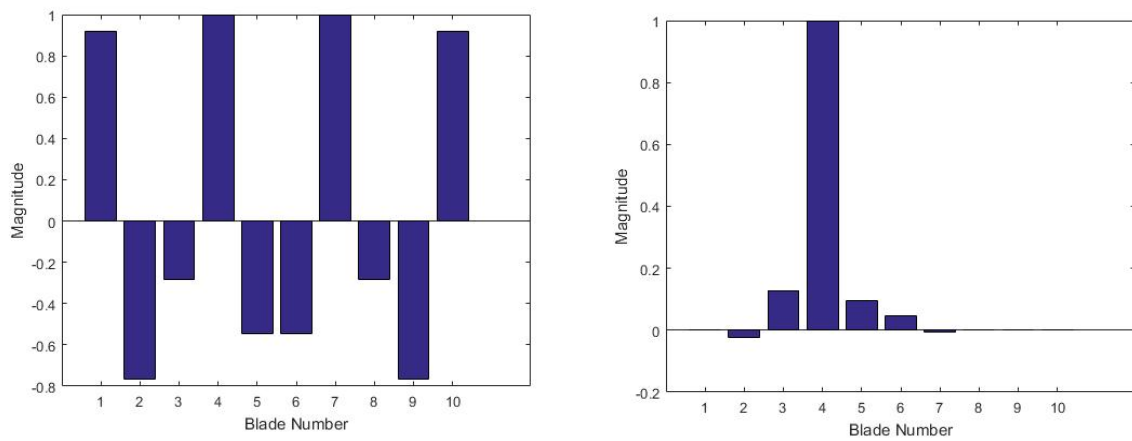


Figure 8. Vibrational mode 7 for both non localization (left) and localization phenomenon (right).

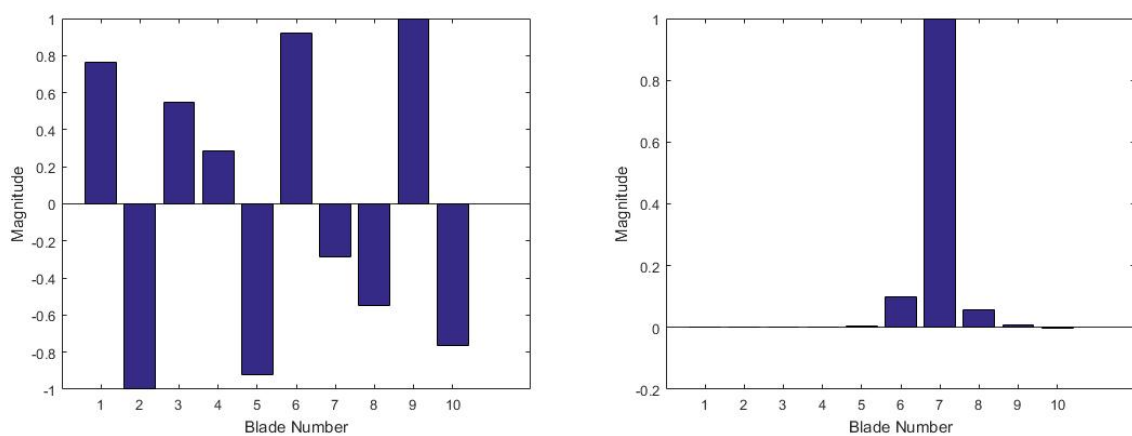


Figure 9. Vibrational mode 8 for both non localization (left) and localization phenomenon (right).

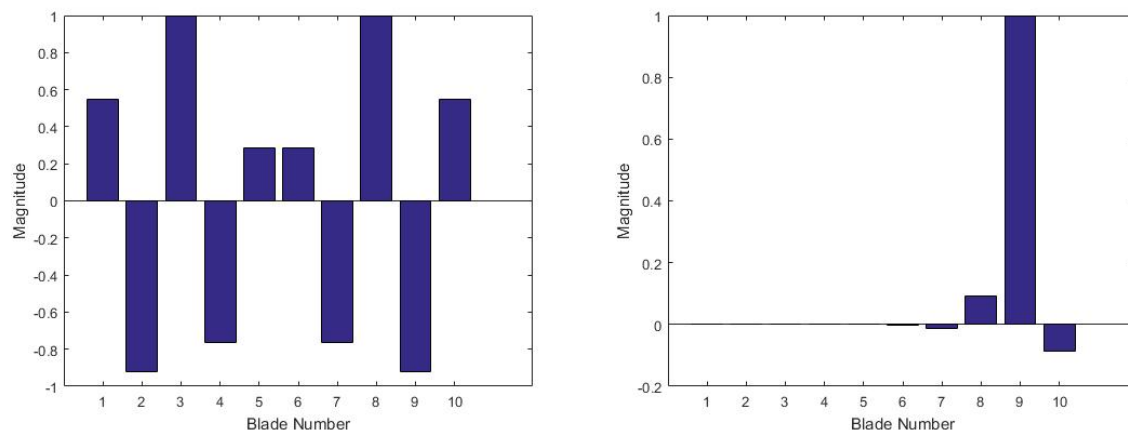


Figure 10. Vibrational mode 9 for both non localization (left) and localization phenomenon (right).

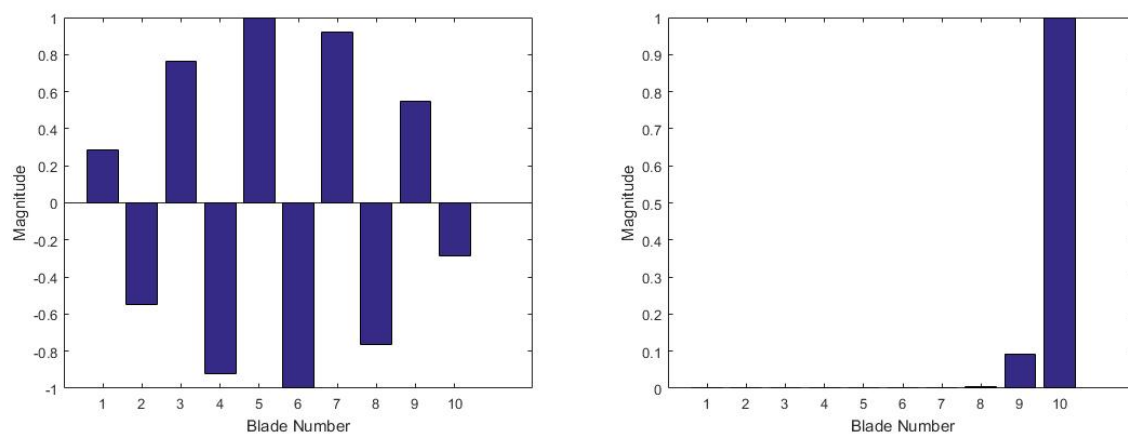


Figure 11. Vibrational mode 10 for both non localization (left) and localization phenomenon (right).

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 Conclusion

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.

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