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Influence of Spin Softening on Natural Frequencies of A Steam Turbine Rotor Assembly with Interference-fit

Gurudatt B*, Seetharamu S**, Sampathkumaran P*** and Vikram Krishna****

Vibration is the default state of all mechanical systems that causes them to possess a natural frequency. The significance of natural frequency cannot be emphasised enough, considering the fact that its study is essential in averting resonance which causes violent swaying motions and catastrophic failures in improperly constructed structures. In case of rotating structures, the study of natural frequency is incomplete without the understanding of spin softening. *This paper presents an ANSYS based analysis to study natural frequency variation due to spin softening, but in a faster and more accurate way than conventional GUI-based ANSYS analysis. The conventional GUI based ANSYS procedure is a laborious time consuming process, with the user having to perform multiple iterations of model analysis involving different rotational velocities to examine the variation of natural frequencies of the system. Through this paper, a novel way has been suggested to bring down the time and effort involved in such a study by using an advanced ANSYS feature called ANSYS Parametric Design Language(APDL). The results obtained have been found to validate spin softening.*

Keywords: *Finite Element Method, ANSYS Parametric Design Language, Natural Frequency, Spin Softening, Vibrations, Nelson Rotor*

1.0 INTRODUCTION

Vibration in rotating structures causes relative circumferential motions, which change the direction of the centrifugal load which, in turn, tends to destabilize the structure. As a small deflection analysis cannot directly account for changes in geometry, the effect can be accounted for by an adjustment of the stiffness matrix. This adjustment of stiffness matrix is called *spin softening*[1]. The effect that this adjustment of stiffness matrix, i.e. spin softening, tends to have on the natural frequency of a rotating structure has been explored in this paper through model analysis (which produces accurate natural frequencies) and with the help of ANSYS Parametric Design Language, a scripting language that has been used here to build the model in terms of parameters and automate tasks which would otherwise have consumed a great deal of time and effort.

2.0 METHODOLOGY

Model considered: A steam turbine rotor assembly with a hollow shaft of outer diameter 30mm and inner diameter 10mm is taken as the model. A disc of diameter 600mm[2] is attached

*Professor, Dept of Mechanical Engg, Bangalore Institute of Technology, Bangalore-560004, INDIA. email: gurudatt_bgd@yahoo.co.in
**Additional Director, MTD, Central Power Research Institute, Bangalore-560080, INDIA. email: ssramu@cpri.in
***Joint Director, MTD, Central Power Research Institute, Bangalore-560080, INDIA. email: sampath@cpri.in
****Research Associate, RSOP Project of CPRI (Govt. of India), Bangalore-560004, INDIA. email: vkrm_krishna@yahoo.co.in

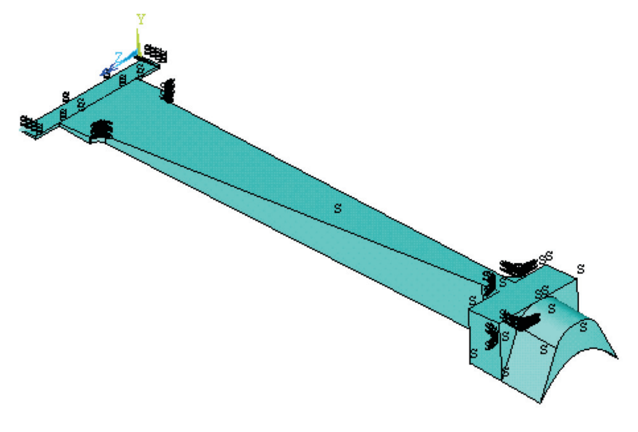

FIG. 1 STEAM TURBINE ROTOR ASSEMBLY

to the shaft by interference fit. Since the model possesses cyclic symmetry, only a 6^o sector of the assembly is modeled and care is taken to apply the necessary symmetry boundary conditions on the model.

Geometric modeling and finite element modeling using APDL: The shaft and disc have been modeled in ANSYS using SOLID95 which is a higher order solid element in three dimensions with twenty nodes and three degrees of freedom at each node. This element can assume any spatial orientation and hence facilitates the modeling of shaft and disc. In interference fit[3], contact occurs when the shaft's outer surface penetrates the disc's inner surface. This interference has been modeled using CONTA170 and CONTA174 elements respectively. The nodes, elements, material properties, real constants, boundary conditions and other physical sytem-defining features that constitute the model have been created by exclusively using APDL commands.

Solution and postprocessing: Once the finite element model has been prepared, boundary conditions are applied. These include locking displacement of the shaft, applying symmetry boundary conditions on top and bottom surfaces of the model to ensure cyclic symmetry. By entering the solution module, modal analysis is performed, also with spin softening activated using *KSPIN* command. First eight modes are expanded and reviewed in the post processor. Thus obtained results containing natural frequencies of the system are recorded. A value of 10rpm is assigned to angular velocity of shaft using *OMEGA* command and the above explained procedure is repeated to obtain natural frequencies. Similarly natural frequencies are obtained for different angular velocities ranging from 10rpm to 1000rpm in steps of 10rpm, which amounts to 100 iterations.

APDL Program Algorithm: A two-dimensional array with 9 columns and 100 rows is defined using the APDL command '**DIM*' [4].'**GET*' is an APDL command which has been used to retrieve the natural frequency results of the first eight modes that were extracted through modal analysis, for a particular angular velocity value, and to store these results in the recently created array at the appropriate row and column. As can be learnt from the methodology, modal analysis can prove to be a laborious process, especially when 100 iterations are involved. By placing the whole set of commands that were used for solution, analysis and result retrieval inside the '**DO*' loop of APDL, generation of the required results of ten iterations was possible with minimal effort and time consumed on part of the user. The program algorithm is as below-

1. Setup the model and impose boundary conditions.
2. Create a two dimensional array with 9 rows and 100 columns using '**DIM*' command.
3. Assign value of 10rpm to parameter 'j' which represents angular velocity.
4. Perform modal analysis.
5. Retrieve frequency of first eight modes; store these in array at appropriate cell using '**GET*'.
6. Increment parameter 'j' by 10 to increase angular velocity by 10rpm.
7. If parameter 'j' is more than 1000rpm, continue to next step. Otherwise go back to step 4.
8. Save array with '*.prn*' extension to export results to MS Excel. End of program.

3.0 RESULTS AND DISCUSSIONS

As explained earlier, a detailed modal analysis has been carried out on the considered model to study the effect of spin softening on natural frequencies of first eight modes of vibration of the system at angular velocities ranging from 10rpm to 1000rpm in steps of 10rpm which amounts to 100 iterations of modal analysis. Consolidated results containing 10 of these iterations are presented in Table 1. These results were generated by the APDL program whose algorithm has been decribed in the previous section.

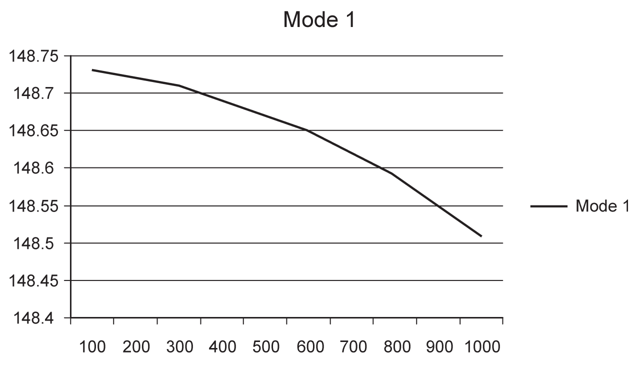

FIG. 2 VARIATION OF FIRST MODE NATURAL FREQUENCY(Hz)(ON Y AXIS) WITH ROTATIONAL VELOCITY(rpm)(ON X AXIS)

TABLE 1

SAMPLE RESULTS SHOWING NATURAL FREQUENCIES AT 21 DIFFERENT ANGULAR VELOCITY(ω) VALUES

ω rpm	Mode 1(Hz)	Mode 2(Hz)	Mode 3(Hz)	Mode 4(Hz)	Mode 5(Hz)	Mode 6(Hz)	Mode 7(Hz)	Mode 8(Hz)
100	148.73	508.62	1100.2	2056.5	2744.3	3524.4	5476.8	6380.9
200	148.72	508.58	1100.2	2056.4	2744.1	3524.4	5476.9	6380.7
300	148.71	508.53	1100.1	5056.3	2743.7	3524.4	5476.8	6380.6
400	148.69	508.47	1100	2056.2	2743.3	3524.3	5476.8	6380.4
500	148.67	508.39	1099.8	2056.1	2742.8	3524.3	5476.8	6380.2
600	148.65	508.3	1099.6	2056	2742.2	3524.2	5476.8	6380
700	148.62	508.2	1099.4	2055.9	2741.5	3524.2	5476.7	6379.6
800	148.59	508.08	1099.2	2055.7	2740.8	3524.1	5476.7	6379.3
900	148.55	507.95	1099	2055.5	2739.9	3524	5476.7	6379
1000	148.51	507.8	1098.7	2055.3	2738.9	3523.9	5476.6	6378.5

Interpretation of results. In order to provide validation for the behaviour of natural frequency, a simple spring-mass system as in Fig. 3, with the spring oriented radially with respect to the axis of rotation, is considered.

Equilibrium of the spring and centrifugal forces on the mass using large deflection logic requires

$$Ku=\omega^2M(r+u) \quad (1)$$

Rearranging terms,we get

$$(K-\omega^2M)u=\omega^2Mr \quad (2)$$

Defining effective stiffness matrix as

$$K'=K-\omega^2M \quad (3)$$

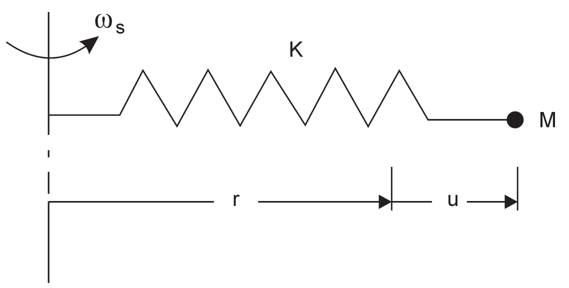

FIG. 3 A SIMPLE SPRING MASS SYSTEM WHERE u = RADIAL DISPLACEMENT OF THE MASS FROM THE REST POSITION, r = RADIAL REST POSITION OF THE MASS WITH RESPECT TO THE AXIS OF ROTATION AND ω = ANGULAR VELOCITY OF ROTATION

This decrease in the effective stiffness matrix is called spin softening. As angular velocity of rotation ω increases, stiffness K' decreases(see Eq 3) and natural frequency, being directly proportional to stiffness[5], also reduces. Fig. 2 which displays graphically the variation of natural frequency of the considered system with angular velocity, confirms that natural frequency keeps on decreasing as the angular velocity increases. This behavior can therefore be attributed to spin softening effect.

4.0 CONCLUSION

Modal analysis was performed on the considered model at different angular velocities to study the effect of spin softening on natural frequencies of the model. It was observed that natural frequency decreases with increase in angular velocity. It has been reasonably shown that this behaviour could be attributed to *spin softening*. A novel way to reduce time and effort involved in performing multiple iterations of prestressed modal analysis has been suggested through adept use of APDL, an advanced feature of ANSYS. The process of exporting the results into MS Excel has also been touched upon.

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