Abstracts
The size of advanced turbomachines such as turbocharger, turbo compressor and turboexpander is decreasing in size to make it more compact and easy for maintenance. The decreasing size leads to high-speed for better efficiency of the turbomachinery. These high-speed rotors are complex in shape because of presence of turbine, compressor and the collar. These complex shaped rotors are subjected to transverse vibration due to presence of unbalance load. The prediction of rotor dynamic design parameters such as critical speeds and unbalance response are not accurate in simple Jeffcott model as the shape of the rotor model is quite complex. In the present work the rotor dynamics analysis is performed using commercial finite element analysis software ANSYS® by importing complex shape turboexpander rotor model from SOLIDWORKS®. The prototype rotor is 16 mm diameter and operating at designed rotational speed of 2,40,000 rpm with radial unbalance of 40 mg-mm near the bearing location.

Keywords: Turboexpander, Critical Speed, Campbell diagram, ANSYS®.

1. Introduction:
Transverse vibration is one of the major causes of the failure of high-speed turbomachinery which creates whirling and thereby bending of the shaft. This leads to failure of the rotor-bearing system. Rotor dynamics analysis helps to reduce such type of vibration by the prediction of dynamic properties like critical speeds and mode shapes in accordance to which design can be done such that the operating speed of turbomachinery is far away from the critical speed [1]. Apart from critical speed and mode shapes, the unbalanced response is very important for the vibration analysis of the rotor. The unbalanced mass in a rotor which may occur due to material homogeneity, manufacturing process, and unsymmetrical slots, if present, causes excessive transverse vibration in the rotating shaft. Thus the analysis of unbalance response is very much essential in high-speed rotor system to minimize these unbalance mass which can be done by proper rotor balancing procedure. For these reasons, rotor dynamics analysis is an important
procedure in the turbomachinery design process. FEM being the most practical approach in current times and it can be applied to a large complex rotor-bearing system with its easy implementation using certain commercial software such as ANSYS® [2]. In current research work, a detailed rotor dynamic analysis of the high-speed turboexpander is done to design the rotor bearing system of a cryogenic turboexpander using ANSYS®.

2. Literature Review
In 1919, Jeffcott wrote a paper that published the fundamental theory of rotor dynamics [3]. In 1924, a book was written by Stodola named ‘Steam and Gas turbines’ where the developments in the field of rotor dynamics up to that time were recorded in a detailed manner. The computer based codes for rotor dynamics evolved from tabular method, transfer matrix method and to finite element method. The finite element method (FEM) was originally developed for structural dynamics and then its use was extended to other fields of physics. In 1972, Ruhl and Booker applied finite element method to rotor system [4]. The commercial software such as ANSYS® has developed at a rapid pace to meet the requirements of Industry. In 2010, Kumar [2] discuss the various features available in ANSYS mechanical program to study the dynamic characteristics of rotors and their supporting systems. In 2019, ANSYS has been successfully used for torsional vibration by Quiroga et al [5]. They utilized the analytical iterative Holzer method to determine any number of natural frequencies for a multi-DOF system. On the other hand, results are compared with a numerical model implemented in ANSYS.

3. Rotor-bearings Model
The rotor model of a cryogenic turboexpander consists of an expansion turbine and a compressor connected at both ends of a shaft. The shaft is with a collar for taking thrust or axial loads, which are illustrated in Fig (1).

![Fig-1: Turboexpander model and its schematic](image)
The shaft material is K-Monel 500 and turbine and compressor is designed in Aluminum alloy. A pair of aerodynamic gas foil journal and a pair of gas foil thrust bearings are used to take radial and axial loads respectively. The stiffness and damping for the gas journal bearings considered for the modeled cryogenic rotor are $4 \times 10^3$ N/mm and $2 \times 10^{-3}$ N·s/mm respectively [1]. The model is created in SOLIDWORKS and imported to ANSYS workbench.

4. Results and Discussion

4.1. Modal Analysis:

Modal analysis was carried out in ANSYS® workbench taking a maximum number of modes as 10 with proper analysis settings. The mode shapes at 1st, 2nd, 3rd and 4th critical speeds are shown in Fig-2. The 1st critical speed is rigid critical speeds (conical). The 2nd, 3rd and 4th are the bending critical speed. Critical speeds are estimated using the Campbell diagram in Fig-3.

![Mode shapes at 1st, 2nd, 3rd and 4th critical speeds](image)

**Fig-2:** Mode shapes at 1st, 2nd, 3rd and 4th critical speeds

![Campbell diagram](image)

**Fig-3:** Campbell diagram

The 2nd critical speed is nearly 3,60,000 rpm and the mode shape corresponds to the bending critical speed appearance to half sine wave. The design speed of the rotor is 2,40,000 rpm and this is much below the bending critical speed. Thus the designed rotor is safe to rotate at the designed speed. The 1st rigid critical speed appears to be at 21,000 rpm, so there is a possibility of failure at the bearings near this speed. Therefore, a preventive measure is essential to overcome this speed during experimentation. This can be done by increasing flow rates of the process gas to turbine, whenever the rotor reaches near 21,000 rpm.
4.2. Harmonic Responses

Harmonic analysis is carried out to show the frequency response of the system by applying an unbalance force of 40 mg.mm in two radial or journal bearing locations as shown in Fig-4.

![Fig-4: Unbalance response near journal bearing on turbine side and compressor side](image)

From Fig-4, it is seen that amplitudes at 1\textsuperscript{st} and 2\textsuperscript{nd} critical speeds are nearly 4µm and 2µm respectively which is far away from designed radial clearance near journal bearings i.e. 25µm and hence the designed rotor was found to suitable to run at the designed speed of 2,40,000 rpm.

5. Conclusions

From the modal and harmonic analysis, it was seen that at the working rotational speed, i.e. 2,40,000 RPM the turboexpander model is safe to design taking some preventive measures near first critical speed. Thus it can be concluded that ANSYS® is the efficient, faster and easy-to-handle software for the dynamic analysis of complex shape high-speed rotor using Finite Element Method even with the much more complex geometry.

References


