Unbalance Response Analysis of Twin Spool Aero-Gas Turbine Engine

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Abstract: ***Twin spool Aero-gas turbine engine is rotating equipment having two rotors called low pressure (LP) Spool and high pressure (HP) Spool. The rotors are mainly assembly of axial flow compressor and axial turbine connected by shaft. The rotors are designed to rotate at wide range of rotational speeds to meet operational requirement. During this regime of speeds, rotor mechanical behavior is very critical in terms of its vibratory behavior. The vibratory behavior of rotor is analyzed by specialized technique called Rotor dynamics. In brief, rotor dynamics computes critical unbalance response of rotor.***

Keywords: Twin spool, whirling,rotordynamics, steady state response

1. Introduction

Most human activities involve vibration in one form or other. For example, we hear because our ear drums vibrate and see because light waves undergo vibration. Breathing is associated with vibration of lungs and walking involves (periodic) oscillatory motion of legs and hands. We speak due to the oscillatory motion of larynges (and tongues). Early scholars in the field of vibration concentrated their efforts of understanding the natural phenomena and developing mathematical theories to describe the vibration of physical systems. In recent times, many investigations have been motivated by the engineering applications of vibration, such as the design of machines, foundations, structures, engines, turbines and control systems.

Most prime movers have vibrational problems due to the inherent unbalance in the engines. The unbalance may be due to Faulty design or poor manufacture. For example, the wheels of some locomotives can rise more than a centimeter off the track at high speeds due to imbalance. In turbines, vibrations cause spectacular mechanical failures. Engineers have not yet been able to prevent the failures that result from blade and disc vibrations in turbines. Naturally, the structure designed to support heavy centrifugal machines, like motors and turbines, or reciprocating machines, like steam and gas engines and reciprocating pumps, are also subjected to vibration. Furthermore, the vibration causes more rapid wear of machine parts such as bearings and gears and also creates excessive noise. In machines, vibration causes fasteners such as nuts to become loose.

Whenever the natural frequency of vibration of a machine or structure coincides with the frequency of the external excitation, there occur a phenomenon known as Resonance, which leads to excessive deflections and failure .Because of the devastating effects that vibrations can have on machines and structures, vibration testing has become a standard procedure in the design and development of most engineering systems.

1.1 Basic Concepts of Vibration

A vibratory system, in general, includes a means for storing potential energy (spring or elasticity), a means for storing kinetic energy (mass or inertia), and a means by which energy is gradually lost (damper). The vibration of a system involves the transfer of its potential energy to kinetic energy and kinetic energy to potential energy and alternatively. If the system is damped, some energy is dissipated in each cycle of vibration and must be replaced by an external source if a state of steady vibration is to be maintained.

1.2 Classification of Vibration

Vibration can be classified in several ways. Some of the important classifications are as follows:

- Free vibration: If a system, after an initial disturbance, is left to vibrate on its own, the ensuing vibration is known as free vibration. No external force acts on the system. The oscillation of a simple pendulum is an example of free vibration.
- Forced vibration: if a system is subjected to an external force (often, a repeating type of force), the resulting vibration is known as forced vibration. The oscillation that arises in machines such as diesel engines is an example of forced vibrations. If the frequency of the external force coincides with one of the natural frequencies of the system, a condition known as resonance occurs, and the system undergoes dangerously large oscillations.
- Undamped vibration: If no energy is lost or dissipated in friction or other resistance during oscillation, the vibration is known as undamped vibration.
- Damped vibration: If any energy is lost due to friction or any other resistance during oscillation, it is called damped vibration.
- Linear vibration: If all the basic components of a vibratory system; the mass, the spring, and the damper behave linearly, the resulting vibration is known as linear vibration.
- Non Linear vibration: If, any of the basic components of response of the system behave non linearly the vibration is called non-linear vibration.

Here the paper is mainly dealing with the dynamic vibration of an engine.

2. Steps Involved in Vibrational Analysis

A vibratory system is a dynamic system for which the variable such as the excitations (inputs) and responses (outputs) are time dependent. The response of a vibrating system generally depends on the initial conditions as well as the external excitations. Most practical vibrating systems are very complex, and it is impossible to consider all the details for a mathematical analysis. Only the most important features are considered in the analysis to predict the behavior of the system under specified input conditions. Often the overall behavior of the system can be determined by considering even a single model of the complex physical system. Thus the analysis of a vibrating system usually involves mathematical modeling, derivation of the governing equations, solution of the equations and interpretation of the results.

2.1 Mathematical Modelling

The purpose of the mathematical modeling is to represent all the important features of the system for the purpose of deriving the mathematical (or analytical) equations governing the system's behavior. The mathematical model should include enough details should be able to describe the system in terms of equations without making it too complex. The mathematical model may be linear or non-linear depending on the behavior of the system's components. Linear models permit quick solutions and are simple to handle; however, non-linear model sometimes reveals certain characteristics of the system that cannot be predicted using linear models. Thus a great deal of engineering judgment is needed to come up with a suitable mathematical model of a vibrating system.

2.2 Derivation of governing Equations

Once the mathematical model is available, we use the principles of dynamics and derive the equations that describe the vibration of the system. The equations of motion can be derived conveniently by drawing the free body diagrams of all the masses involved. The free body diagram of a mass can be obtained by isolating the mass and indicating all externally applied forces, the reactive forces, and the inertia forces. The equations of motion of a vibrating system are usually the form of a set of ordinary differential equations for a discrete system and partial differential equations for a continuous system.

The equations may be linear or non-linear, depending on the behavior of the components of the system. Several approaches are commonly used to derive the governing equations. Among them are Newton's Second Law of Motion, D'Alembert's principle, and the principle of conservation of energy.

2.3 Solution of the Governing Equations

The equations of the motion must be solved to find the response of the vibrating system. Depending on the nature of the problem, we can use one of the following techniques for finding the solution; standard methods of solving differential equations, Laplace Transform methods, Matrix methods and Numerical methods. If the governing equations are non-linear, they can seldom be solved in closed form. Furthermore, the solution of partial differential equations is far more involved than that of ordinary differential equations. Numerical methods involving computers can be used to solve the equations. However, it will be difficult to draw general conclusions above the behavior of the system using computer results.

2.4 Interpretation of Results

The solution of the governing equations gives the displacements, velocities and accelerations of the various masses of the system. The results must be interpreted with a clear view of the purpose of the analysis and possible design implications of the results.

3. Rotordynamics

Rotor dynamics is a specialized branch of applied mechanical vibration concerned with the behavior and diagnosis of rotating structures. It is commonly used to analyze the behavior of structures ranging from jet engines and steam turbines to auto engines and computer disk storage. At its most basic level, rotor dynamics is concerned with one or more mechanical structures (rotor) supported by bearings and influenced by internal phenomena that rotate around a single axis. The supporting structure is called a stator. As the speed of rotation increases the amplitude of vibration often passes through a maximum that is called a critical speed. This amplitude is commonly excited by unbalance of the rotating structure; everyday examples include engine balance and tire balance. If the amplitude of vibration at these critical speeds is excessive, then catastrophic failure occurs. In addition to this, turbo machinery often develop instabilities which are related to the internal makeup of turbo machinery, and which must be corrected. This is the chief concern of engineers who design large rotors or Aero Gas Turbine Engines.

Rotating machinery produces vibrations depending upon the structure of the mechanism involved in the process. Any faults in the machine can increase or excite the vibration signatures. Vibration behavior of the machine due to imbalance is one of the main aspects of rotating machinery which must be studied in detail and considered while designing. All objects including rotating machinery exhibit natural frequency depending on the structure of the object. The critical speed of a rotating machine occurs when the rotational speed matches its natural frequency of rotor system. The lowest speed at which the natural frequency is first encountered is called the first critical speed, but as the speed increases, additional critical speeds are seen depending on no of degrees of freedom in the rotor system. Hence, minimizing rotational unbalance and unnecessary external forces are very important to reducing the overall forces which initiate resonance. When the vibration is in resonance, it creates a destructive energy which should be the main concern when designing a rotating machine. The objective here should be to avoid operations that are close to the critical and pass safely through them when in acceleration or deceleration. If this aspect is ignored it might result in loss of the equipment excessive wear and tear on the machinery, catastrophic breakage beyond repair or even human injury and loss of lives.

Rotor dynamic analysis is carried out using FE(Finite Element) model of rotors. Finite element is discretization technique to represent geometry of rotors which can be analyzed. Further, material properties and boundary conditions are assigned on FE entities and further it is analyzed with commercial software ANSYS Version 18.1. Ansys is a Finite Element Analysis package .The element of Ansys is an entity into which the system under study is divided.

4. Engine Details

The engine considered is a turbofan engine. Unlike other engines, here the considered engine is a twin spool engine. Spool means shaft. The engine comprises of two shafts, one outer shaft which will be a hollow circular tube shaft. And an inner shaft which is a solid circular shaft. The two shafts will connect the compressor and turbine sections. The compressor here is an axial flow compressor and the turbines are also axial flow turbines. The engine will be having two stages of compression and two stages of expansion.

The compression section will have two compressions- low pressure compressor and high pressure compressor. Similarly, for the turbine- low pressure and high pressure turbine is present. Low pressure compressor is followed by the high pressure compressor. In the turbine section, the high pressure turbine is in the front of the low pressure turbine. Both the low pressure components are attached to a shaft and the other high pressure components are attached to another shaft. The low pressure compressor and low pressure turbine will be connected by an inner shaft. The high pressure compressor and high pressure turbine are connected with the outer shaft.

The main advantage of a twin spool engine is that, it allows different components to rotate at different speeds. Besides of the weight increase of the engine a twin spool engine can make more efficient power helping for more thrust. A twin spool engine will allow the compressor and turbines to rotate at their optimum speed which will match the local airflow inside the engine. The twin spool engine is only the upgraded turbo engine.

It can have a bypass. It also advantage over the control over air flow through the engine. Thus a lot of issues with the pure single shaft engine turbojets can be solved. The low pressure compressor will be having lengthy blades attached to a small disc whereas for a high pressure compressor the disc area is more on which the mounted blades will be smaller in length. The same matters for the turbine section. The low pressure turbine will be having lengthy blades with small disc and high pressure turbine will have small blades, large disc.

Programming Terms
mp- material property
EX- Young's Modulus
DENS- Density
PRXY- Poisson's ratio
Et- element type
Sec type- section type
C solid- circular solid
C tube- Circular tube
r- radial constant
n- node
vm- volume method
FE- fatigue event parameter
FL- fatigue location parameter

5. Model Details

From the model design we can say that there are four disk at the points 2, 7, 10 and 12 respectively. Bearings are given at points 1, 8, 9 and 13.Thus, there are four bearings. The inner spools are from point 1 to 8. And it is in the form of circular solid. The outer spool is from 9 to 13 and it is in the form of circular tube which forms the covering of the inner spool. There are totally 13 nodes. From 1 to 13, there are 11 beam elements. The total numbers of elements are calculated by adding number of beam element+ disc+ bearing. That is 4+4+11 = 19. So there are 19 beam elements. The beam elements are COMBI214 and MASS21 as per the commands followed.

The four bearing considered consists of roller bearing, ball bearing and inter shaft bearing. The inter shaft bearing connects the points of the inner and outer spool.
Total number of elements -19
Number of Disks- 4
Number of disk element- 4
Number of bearings- 4
Number of bearing element- 4
Number of Beam Elements- 11

Figure 1: Model design

6. Input details

The design input for a twin spool engine has been enclosed without showing the values assigned for obtaining the desired twin spool engine design. Variables are used in place of actual values.
/batch,list
/title, twin spools - unbalance (inner spool) response

```
/PREP7
!ORIGINAL VM OF ANSYS
mp,EX ,1,x
mp,DENS,1,y
mp,PRXY,1,z
! shaft
et,1,188,,,2
sectype,1,beam,csolid
secdata,x,32
sectype,2,beam,ctube
secdata,x,y,32
! disks
et,2,21
r,3,x1, x2, x3, x4, x5, x6
r,4,y1, y2, y3, y4, y5, y6
r,5,z1, z2, z3, z4, z5, z6
r,6,a1, a2, a3, a4, a5, a6
! bearings
et,3,214,,1
r,7 ,l, l
r,8 ,m1, m2
r,9 ,n1, n2
r,10,o, o
! nodes
n,1
n,2 ,a
n,3 ,b
n,4 ,c
n,5 ,d
n,6 ,e
n,7 ,f
n,8 ,g
n,9 ,h
n,10,i
n,11,j
n,12,k
n,13,l
! bearings second nodes
n,101,     ,a
n,108, a, b
n,109, c, d
! components elements
type,1
secn,1
e,1,2
egen,7,1,1
type,2
real,3
e,2
real,6
e,7
cm,inSpool,elem
type,1
secn,2
e,9,10
egen,4,1,10
type,2
real,4
e,10
real,5
e,12
esel,u,,,inSpool
cm,outSpool,elem
allsel
! bearings
type,3
real,7
e,1,101
real,8
e,9,109
real,9
e,6,13
real,10
e,8,108
```

This input commands are extended for meshing, analysis by applying boundary conditions and initial conditions. Force values are applied and commands for finding the results are also done which is not included.

Unbalance Response Analysis

The general dynamic equation is:

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{f\} \quad (1\text{-}1)$$

where [M], [C] and [K] are the mass, damping and stiffness matrices, and {f} is the external force vector.

In rotor dynamics, this equation gets additional contributions from the gyroscopic effect [G], and the rotating damping effect [B] leading:

$$[M]\{\ddot{U}\} + \big[[G] + [C]\big]\{\dot{U}\} + \big[[B] + [K]\big]\{U\} = \{f\} \quad (1\text{-}2)$$

This equation holds when motion is described in a stationary reference frame, which is the scope of this guide. The gyroscopic matrix, [G], depends on the rotational velocity (or velocities if parts of the structure have different spins) and is the major contributor to rotor dynamic analysis. This matrix is unique to rotor dynamic analyses, and is addressed specifically by certain commands and elements.

The rotating damping matrix, [B] also depends upon the rotational velocity. It modifies the apparent stiffness of the structure and can produce unstable motion.

The Benefits of the Finite Element Analysis Method for Modelling Rotating Structures

Rotating structures have conventionally been modeled by the lumped mass approach. This approach uses the center of mass to calculate the effects of rotation on attached or proximal components. A major limitation of this approach is the imprecise approximation of both the location and the distribution of the mass and inertias, along with the resulting inaccuracy in the calculation of internal forces and stresses in the components themselves.

The finite element (FE) method used in ANSYS offers an attractive approach to modeling a rotor dynamic system. While it may require more computational resources compared to standard analyses, it has the following advantages:

- Accurate modeling of the mass and inertia
- A wide range of elements supporting gyroscopic effects
- The use of the CAD geometry when meshing in solid elements

- The ability of solid element meshes to account for the flexibility of the disk as well as the possible coupling between disk and shaft vibrations.
- The ability to include stationary parts within the full model or as substructures.

Terminology Used in Rotordynamics Analysis

The following terms describe rotor dynamic phenomena:

- Gyroscopic Effect
- Whirl
- Elliptical Orbit
- Stability
- Critical Speed

7. Results

From the commands used, the output obtained is the whirling of the Twin Spool Aero- gas Turbine Engine that we have considered. The animation of the given commands, which is an output required was successfully completed using Ansys Mechanical APDL.

If the spinning and whirling are in the same direction, this type of vibration is Synchronous. And if the whirling and spinning are in opposite direction, the vibration is Asynchronous.

To obtain the result one of the bearing is replaced by a non-linear spring. The movement of the non- linear spring is restricted and the motion of the shafts is based on the other three linear springs. The spinning movement can be observed spectacularly in the third bearing which is the inter shaft bearing connecting this two spools in twin spool aero- gas turbine engine. The inner spool response can be seen from the animated figure.

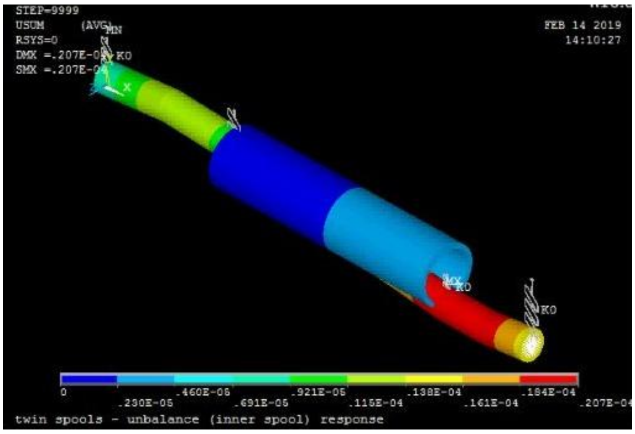

Figure 2: Nodal solution

Frequency charts are the charts that graphically display information about the frequency of data value such as the number of the instances data values appear within a data set. The frequency chart which indicates the amplitude at the node 7 is obtained through a graph. The amplitude and frequency chart implies various amplitudes in different frequencies at the specified node which is the node 7. From the graph we can observe that the amplitude is constant with time. The graph continues to be repeating. Thus at node 7, the vibration is constant in cycles with respect to time.

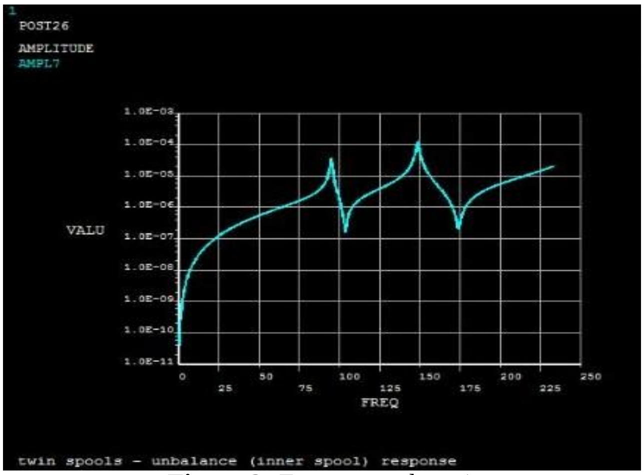

Figure 3: Frequency chart-1

As per the result requirements, the frequency chart at node 12 is also plotted. The chart indicates the amplitude at the node 12 is obtained through a graph. The amplitude and frequency chart implies various amplitudes in different frequencies at the specified node which is the node 12. From the graph we can observe that the amplitude is constant with time. The graph continues to be repeating. Thus at node 12, the vibration is constant in cycles with respect to time. After a certain time there is decline in the amplitude which can be seen in the graph.

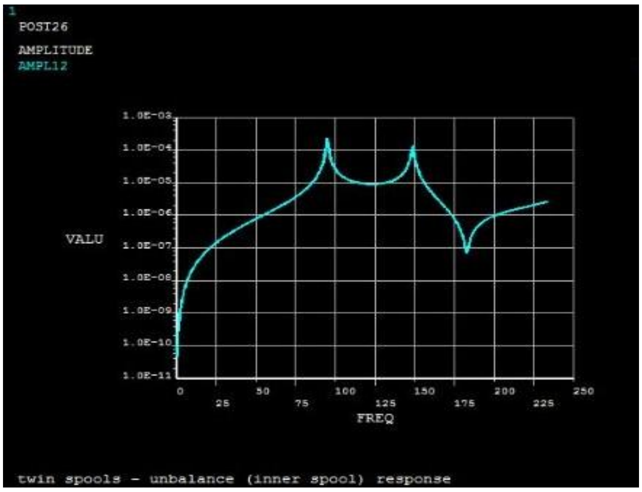

Figure 4: Frequency chart-2

8. Conclusion

Rotor dynamic analysis of an aero gas turbine rotor was carried out for following the contemporary approach using multi-harmonic elements for rotor modeling which accounts for flexibility of disc and eases modeling of complete rotor. Further, rotor blades were idealized as lumped mass which is standard practice for such analysis. Rotor model discretization was done with commercial package hyper mesh and element qualities were checked. Further, analysis was carried out using which has specific module for rotor dynamic analysis. Free-Free modal analysis was done and six rigid body modes ensured correctness of model. As next step, critical speed analysis was carried out assuming stiffness at bearing planes. Campbell diagram, which is an output of critical speed analysis, shows classic behavior of rotor where splitting of natural frequencies are evident. As last step, unbalance response analysis was carried out with normal unbalances at compressor and turbine. Bearing forces and displacement at pre-selected nodes were output of this analysis. The analysis procedure followed was as per standard practice and results obtained were similar in line and result trends were comparable.

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