Suppression of Vibratory Stresses in Turbine Structural Components Subjected to Aerodynamic Loading (TITLE PAGE)



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ISLAMABAD

JANUARY, 2017

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# Abstract

Vibratory stresses are the main cause of failure in gas turbine engines and other rotating machinery components. These stresses must be attenuated to an acceptable level through an efficient process in order to prevent failures in turbine blades. Previous studies have shown that a thin magneto mechanical coating layer can make a significant contribution to the damping and reduction of these vibratory stresses. Previous studies on analyzing the damping characteristics of these coatings for various applications, such as beams and turbine blades, employed general solid mechanics loads. In this study, we numerically compute aerodynamic loads on one and a half stage axial turbine and applied these loads on the blade via a mapping procedure in order to bring more reality to the problem. We employ a three-dimensional finite-volume based solver to simulate the flow in the turbine using SST model to account for turbulence effects. Sliding mesh technique is used to allow the transfer of flow parameters across the sliding rotor/stator interfaces. In order to model a single passage configuration, profile transformation method is used. A free vibration analysis has been performed to obtain natural frequencies and corresponding mode shapes to analyze resonance conditions. The computed CFD loads are then applied to an uncoated and coated turbine blade through a finite-element analysis (FEA) package. A forced response analysis is performed at the critical frequencies to obtain vibratory stresses. Numerical results show suppression of vibratory stresses at various low and high frequency vibration modes. The results are benchmarked against published data and closely match the expected outcome. The research presents an effective procedure for suppression of vibratory stresses in gas turbine engine component subjected to real world aerodynamic loading. The new procedure is a significant improvement towards more realistic simulation based solutions for vibration suppression problems.

**Key Words:** *Vibratory Stresses, Forced response analysis, Magneto mechanical material coating*

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# CHAPTER 1: INTRODUCTION

The research work in this dissertation has been presented in two parts. First part is related to the detailed three dimensional flow investigation of one and a half stage axial turbine. The objective of this part is to study the effect of rotor stator interaction and the computation aerodynamic forceson turbine blade. The second part includes the free and forced vibration analysis of the turbine rotor blade to study the vibratory stress suppression.

## Background, Scope and Motivation

Turbomachine is a device in which the energy is transferred either to or from a continuously flowing fluid by the dynamic action of one or more moving blade rows. It plays a major role in particular in aircraft, marine space (liquid rockets), land propulsion system but also in hydraulic, gas and steam turbines applications. It is also involved in industrial pipeline and processing equipment such as gas, petroleum and water pumping plants. Other applications can be related to heart-assist pumps, industrial compressors and refrigeration plants, among others.

The turbomachinery field includes turbines, pumps, fans, compressors. A turbomachine is composed of several basic elements including the blade (also called vane if it is non-rotating), hub, and shroud. Several technological effects involving clearances, seal leakages and cooling holes among others can complete the machine. Due to the complexity of the blade shapes, the presence of technological elements and the rotation of machine, the nature of the flow are strongly three-dimensional, often depicting complex flow paths.

The turbomachine which we have chosen for our analysis is a gas turbine whose principle is to extract energy from the fluid and convert it into mechanical energy as power output at the shaft.

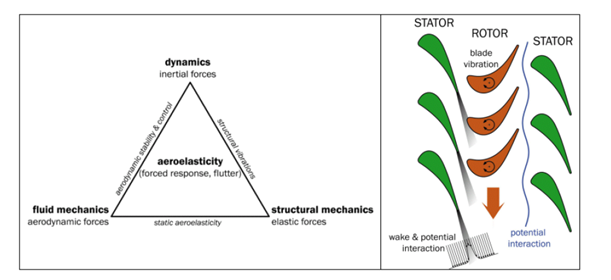
### Fluid Dynamics and Rotor Stator Interaction

CFD research on turbo machinery has provided various tools for predicting the detailed flow behavior in multistage turbines. High performance and narrow design margins demand an optimized design and accurate flow analysis prediction. Advancement in computational power and numerical methods which solve the Reynolds averaged Navier Stokes equations not only provide the flow details but also become an important element of the turbo machinery design.

Relative movement of blade rows induces unsteady flow phenomena in multi stage turbo machines called potential effect. This effect cause the interaction of various lifting force fields in time, hence primarily affecting the flow behavior in the gap area between rotor and stator blade rows. Dring et al. [1] in his experiments on a single stage axial turbine with 22 stators and 28 rotors observed that the temporal pressure fluctuation close to the rotor blade leading edge can be as much as 72 percent of the dynamic pressure at exit, when the axial gap between them was reduced to 15 percent of the blade chord length (for the chosen geometry and operating conditions). Therefore, it is very much essential to consider the stator and rotor airfoils as a system in cases where interaction effects are predominant. The presence of three dimensional viscous boundary layers and wakes also contribute to the unsteadiness in the multi blade rows. Slow decay of these wakes causes them to continue further downstream as compared to potential interaction and interact in time with the flow field of the downstream blade rows resulting in unsteadiness [2]. Secondary flow phenomena and vortices associated with it is another source of unsteadiness which gained the attention of many researchers in the past two decades. The effect of unsteadiness on loss mechanisms in turbo machines is described in detail by Denton [3, 5] and in AGARD-CP-571 [6]. Studies performed by Dawes et al. [7] using Navier Stokes simulations indicate that 29 percent of the stator end wall loss was caused by unsteady flows. He observed an increase in loss and boundary layer thickness due to tip leakage vortex near the tip region of the downstream stator blade. Furthermore, Sharma et al. [8] measured the losses in unsteady flows in typical turbine blade rows to be 25 percent higher than those measured in the steady environment for the same blade rows. Busby et al. [9] studied the flow pattern in transonic turbo machines and concluded that the effect of shock waves on the surrounding blade rows results in further unsteady interactions. All the above mentioned sources of unsteadiness largely affect the total pressure, velocity, total temperature, and turbulence intensity and result in the loss of performance and efficiency. Therefore, unsteady analysis need to be analyzed thoroughly and should be a necessary part of every modern design. Considering all the above mentioned studies related to the importance of analyzing unsteady flow phenomena, we have done both steady state and unsteady state analysis on one and a half stage axial turbine case and have discussed their comparison in both fluid and structural domains.

### Forced response

The field of aero elasticity deals with the interaction of Inertial, aerodynamic and elastic forces and their influence upon the behavior of the structures. These interactions were described by Collar in 1947[10] in his famous triangle called Collar triangle of aero elasticity shown in figure 1.1.



**Figure 1.1:** Collar Triangle of Aero elasticity (Left), Forced Response analysis principle (right)

# CHAPTER 2: ANALYTICAL MODELS AND NUMERICAL METHODOLOGY

An unsteady flow varies in time as either random or periodic manner. Both of them need to be addressed properly in order to predict the correct performance of the turbomachines. Two main features are associated with the unsteady flow phenomena. First is the aerodynamic performance associated with the blade row interaction and flow instabilities such as stall and surge. Second is the blade structural integrity when it undergoes flow induced vibrations i.e. forced response and flutter. In this study, we have simulated the aerodynamics of one and a half stage axial turbine and computed aerodynamic loads for performing forced response of uncoated and coated turbine blades.



## Navier Stokes Equations

The analysis presented in this study assumes an ideal fluid that undergoes an irreversible process during an unsteady flow. It does not involve body forces and chemical reactions. Any real turbomachinery flow phenomena is irreversible primarily because of friction and heat transfer effects which occur in the boundary layers and in the presence of strong shocks and vortices. Any non-reacting fluid flow which holds the definition of Newtonian fluids can be represented by the instantaneous equations of mass, momentum and energy conservation which are the governing equations for the current problem.



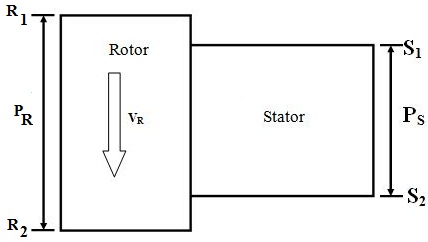
Where *τ*is the stress tensor related to the strain rate. Mathematically;

In equation 2.3, is the dissipation function as it contains viscosity affected terms.

Where *htot* represents the total enthalpy of the fluid. The term ∇*.(U.τ)* shows work done due to viscous stresses and the term *U.SM* shows work done due to the external momentum sources[13].

## Transient Blade Row Modeling Theory

For modeling cases like transient rotor-stator application by using conventional methods, huge computing resources are required to get accurate results especially for cases which involve non unity pitch ratios. Figure 2.3 shows, for non-unity pitch ratio, conventional periodicity is inadequate when we use single passage modeling for simulation of flow in turbines. In order to still solve the system with minimum passage configuration, the methods found in the literature are direct storage method by Erdos, Time inclining method of Giles, Fourier transformation method by He and the profile scaling method by Rai and Madaven. We have applied profile transformation method on one and half stage axial turbine whose geometrical characteristics are presented in table 2-1. The profile transformation method overcomes the unequal pitch problem by scaling the flow profile across the blade row interfaces in such a way that space time periodicity is then no longer required.



**Figure 2.1:** Single passage periodicity cannot be applied

**Table 2‑1:** Geometrical Data of IST Turbine [90]

|  |  |  |  |
| --- | --- | --- | --- |
| **Nomenclature and Symbols** | | **1st and 2nd stator Traupel profile** | **Rotor mod. VKI Profile** |
| **Hub diameter** | *dhub* | 490 mm | 490 mm |
| **Tip diameter** | *dcas* | 600 mm | 599.2 mm |
| **Passage Height** | *H* | 55 mm | 55 mm |
| **Tip clearance height** |  |  | 0.4 mm |
| **Height/chord ratio** | *H/c* | 0.887 | 0.917 mm |
| **Number of blades** | *z* | 36 | 41 mm |
| **Blade Pitch** | *X* | 10O | 8.78O |

# APPENDIX A

**Mapping procedure**

The fluid dynamic loads are mapped on to structural mesh nodes of turbine blade through Matlab command griddata3. For this purpose, the forces in x, y and z directions on the blade are computed separately in CFD post and interpolated on to the structured mesh nodes. MSC Patran converted these forces into a resultant force and the included angle on each node. The Matlab program used for the interpolation is given below

%

*Clc*

*Clear all*

*f=fluid;*

*s=structure;*

*f1=griddata3(f(:,1),f(:,2),f(:,3),f(:,4),s(:,1),s(:,2),s(:,3))*

*a=[s f1];*

*%*

The loads data f1 along with structure mesh nodes are written in Nastran input file which is then read into MSC Patran for preprocessing using spatial field. The interpolation is validated using the fluid FSI module by importing the mechanical meshed blade for mapping the fluid dynamic loads. A static structural analysis is performed for both the cases and the obtained results closely matched with each other hence validating the Matlab interpolation procedure.

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