“Energy Flux” – The missing link in solving turbomachinery instability problems?

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Abstract

This paper forms Part 2 of ASME paper 97-GT-448 from 1997 entitled “Proposed Forcing Mechanisms and Non-Linear Effects on Subsynchronous Vibrations in High Performance Turbomachinery”. That paper proposed several forcing mechanisms which may cause severe vibrations in high performance turbomachinery. Considerable theoretical and experimental evidence has now been gathered that confirms many of these hypotheses about the forcing mechanisms in turbomachines.

A number of extensive CFD simulations have been run on a super computer and an expensive test rig has been built to help verify the results of rotating stall in high performance turbomachines. Inlet flow distortion causing stall is a major problem that can significantly reduce the machine’s performance and may lead to operational problems and reduction of the expected lifetime of the machine. This has been simulated using a transient unsteady flow 3-D numerical CFD model and has been verified using a shaft dynamometer and high speed photography on an experimental test rig under varying operating conditions which demonstrate the fluid structure interaction forces caused by the inlet flow distortion and rotating stall. Both in the CFD model and on the test rig it was possible to precess the shaft around in its clearance circle, thus inducing inlet flow distortion.

The hypothesis in this paper is that there are additional sources of energy in the system that are not usually included in the analysis because they are very small and may be much less than 1% of the total dynamic energy in the system, so they are usually neglected in a standard rotordynamic analysis. However, it is this “Energy Flux” that may destroy the machine! The influence of these sources of energy flux are best understood by a study of different types of energy flow between the mass, stiffness and damping elements, and indeed within these elements. The energy flux equation gives us a better insight into how to solve or at least how to reduce the consequences of such “non-linear instability problems”. In particular it seems to be the non-linear cross coupled mass effects and non-linear cross coupled stiffness effects that cause the problems because in practice they have the same equivalent effect as a negative damping.

In this paper it will be demonstrated how some of these non-linear energy flux mechanisms operate and some hints will be given about their control. In many cases these mechanisms will always exist and it may not be possible to get rid of them. However, the energy flux is a useful concept because it helps the engineer to better understand where the energy is coming from, and where it is going. This is a much more useful concept in practice than only considering the net sum of energy in a relation like $e=mc^2$ which may not tell us engineers the whole story. A better solution is to try and design the mechanical or fluid dynamic system in such a way that the detrimental effects of such energy flux and fluid-structure cross-coupling are minimized.

The paper will try to illustrate some of this hypothesis with some practical examples of fluid-structure cross-coupling with reference to simulated results using CFD, and by presenting experimental test

results that verify the occurrence of inlet flow distortion, diffuser rotating stall, and turbomachinery rotor dynamics instabilities using a full scale rotor dynamic pump test loop. Plots of wind spectra and roll and stamping induced motion of a floating offshore wind turbine foundation will also be presented and the practical consequences of this type of motion on the turbo-generator shaft-bearing and blade life will be discussed. This type of wind and wave induced foundation excitation is one of the worst possible from the point of view of inducing non-linear cross-coupling mass and stiffness effects due to the fluid-structure interaction and this type of excitation may lead to rotor dynamic behavior that can significantly affect the wind turbine and generator remaining operating life. Some observations and experimental results about how nature tries to compensate for such behavior will also be made, and some comments will be given about the extension of the energy flux method and the "Energy Flux" principle to try and explain what may cause the instability of projectiles in space.

Introduction to Energy Flux

É = KE + PE + WE + CE + RE + ME + ?

Where KE = Kinetic energy flux
PE = Potential energy flux
WE = Non-linear unstable energy flux mechanisms
CE = Cross coupling energy flux mechanisms
RE = Residual energy flux mechanisms
ME = Change of momentum due to acceleration/deceleration
? = As yet to be understood mechanisms (gravitational, electro-magnetic, sub-atomic etc.)

The generalized energy flux equation will be presented and an introduction to additional energy flux terms using 48 dynamic coefficients to describe such secondary things as the influence of added-mass terms on the gyroscopic non-linear cross-coupling effects, or the effects of foundation movement, important on floating wind turbines, and often neglected in studies of turbomachinery dynamics. Examples will be given from practical application to pumps, water turbines and wind turbines, including results of CFD studies and experimental full scale verification of some of the non-linear unstable fluid structure interaction mechanisms described in the ASME paper 97-GT-448 from 1997.

Conclusion

The conclusion is that we should be studying the "Energy Flux ", i.e. the flow of energy from the fluid into or out of the structure during fluid structure interaction, rather than using the more classical Rayleigh and Einstein type "Energy Equations" and assuming steady state " linearized" conditions.

By approaching the challenge of better understanding turbomachinery instability problems from another angle, by assuming that nature is normally in a non-linear unstable chaotic state, we could find new insight into some of the unexpected dynamic behaviour that we observe in real-life turbomachinery applications causing "instability", high vibration levels, poor reliability and shorter than expected operating lifetime.