Flow instabilities in centrifugal compressors at low mass flow rate

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Abstract

A centrifugal compressor is a mechanical machine with purpose to convert kinetic energy from a rotating impeller wheel into the fluid medium by compressing it. One application involves supplying boost air pressure to downsized internal combustion engines (ICE). This allows, for a given combustion chamber volume, more oxygen to the combustion process, which is key for an elevated energetic efficiency and reducing emissions. However, the centrifugal compressor is limited at off-design operating conditions by the inception of flow instabilities causing rotating stall and/or surge. These instabilities appear at low flow rates and typically leads to large vibrations and stress levels. Such instabilities affect the operating lifetime of the machine and are associated with significant noise levels. The flow in centrifugal compressors is complex due to the presence of a wide range of temporal- and spatial-scales and flow instabilities. The success from converting basic technology into a working design depends on understanding the flow instabilities at off-design operating conditions, which limit significantly the performance of the compressor. Therefore, the thesis aims to elucidate the underlying flow mechanisms leading to rotating stall and/or surge by means of numerical analysis. Such knowledge may allow improved centrifugal compressor designs enabling them to operate more silent over a broader operating range. Centrifugal compressors may have complex shapes with a rotating part that generate turbulent flow separation, shear-layers and wakes. These flow features must be assessed if one wants to understand the interactions among the flow structures at different locations within the compressor. For high fidelity prediction of the complex flow field, the Large Eddy Simulation (LES) approach is employed, which enables capturing relevant flow-driven instabilities under off-design conditions. The LES solution sensitivity to the grid resolution used and to the time-step employed has been assessed. Available experimental data in terms of compressor performance parameters, time-averaged velocity, pressure data (time-averaged and spectra) were used for validation purposes. LES produces a substantial amount of temporal and spatial flow data. This necessitates efficient post-processing and introduction of statistical averaging in order to extract useful information from the instantaneous chaotic data. In the thesis, flow mode decomposition techniques and statistical methods, such as Fourier spectra analysis, Dynamic Mode Decomposition (DMD), Proper Orthogonal Decomposition (POD) and two-point correlations, respectively, are employed. These methods allow quantifying large coherent flow structures at frequencies of interest. Among the main findings a dominant mode was found associated with surge, which is categorized as a filling and emptying process of the system as a whole. The computed LES data suggest that it is caused by substantial periodic oscillation of the impeller blade incidence flow angle leading to complete system flow...
reversal. The rotating stall flow mode occurring prior to surge and co-existing with it, was also captured. It shows rotating flow features upstream of the impeller as well as in the diffuser.

**Key Words**
Centrifugal compressor, flow instabilities, rotational flows, rotating stall, surge, compressible Large Eddy Simulation