Ph.D. Defense

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“Modeling of Multistage Axial-Centrifugal Compressor Configuration using Streamtube Approach”

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Abstract:
Quasi-1D flow models based upon mean-line analysis are quite popular for design and performance evaluation of multistage axial and centrifugal compressors. However, they are not so readily used for analyzing the dynamic behavior of the compressor. In this work, an unsteady 1D axial-centrifugal compressor model is developed, where the stage elements i.e., rotors and stators are modelled as diffusing streamtube elements. The analysis being independent of any stage aerodynamic force and work terms, accurately predicts the performance of axial and axial-centrifugal compressors by the incorporation of various loss mechanisms compounding to stagnation pressure losses within stage elements. The off-design performance especially close to the surge and choke line is captured using novel models, particularly developed for incidence/sudden turning and mixing losses. These inlet turning and mixing loss models constitute an important feature of this work and are implemented by the inclusion of a single model parameter. This parameter called mixing loss factor, is then tuned for nominal shaft speed and is subsequently used to predict the compressor performance for different speeds ranging from 50% to 105%. The surge line is also accurately predicted by correlating slope change criteria of constant speed characteristic curve to instability onset point, which aligns well with the suitable choice of critical/stall incidence angle for the stage elements. Further, the tuned model is used to predict the performance of axial-centrifugal compressor at the aforementioned range of speeds. The diffuser loss, diffuser incidence angle and throat Mach number are computed for well-known UTRC-High Efficiency Centrifugal Compressor (HECC) and the results are validated with literature data.

The dynamic communication between two connected streamtubes is established using a novel boundary element called Compact Interface Element (CIE) which is developed by making use of
the characteristics-based approach. CIE achieves reference frame transformation between the successive diffuser elements and also incorporates complex loss mechanisms due to sudden flow turning, mixing, shocks etc. Within the streamtube, 1D time-dependent conservation equations are solved using second-order accurate Kurganov-Tadmor scheme; while at the boundary between streamtubes, the dynamic compact element updates the interface conditions with time.

Another aspect of compressor operation is the observance of aerodynamic instabilities as the compressor is throttled towards stall. Several simulations indicate onset of instabilities close to the peak of compressor characteristic for large plenum attached at the compressor end. Without any end plenum or low speed operation, it is found that few stable points exist on the positively-sloped portion of the characteristic curve. Importantly, Greitzer’s B-parameter provides a good qualitative validation of the instability onset point. Further throttle closure, however, leads to oscillations where low frequency mode represents fundamental axial mode of the compressor. It is illustrated that the instability modes obey a general Rayleigh’s criterion where they are affected by the phase between pressure fluctuations and shaft power addition oscillations.

The model finds applications in compressor design and diagnostics where the simulation results together with the test data through pressure signatures, provide the identification of stalling and choking stages.

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