The Latest Development of Turboshaft Engines

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Abstract. As the main power of rotor aircraft, the turboshaft engine has always been the focus of scientific and engineering research and has achieved rich research results. This paper reviews and summarizes the research results at home and abroad in the past 10 years from the aspects of control systems, oil-electric mixing, pollutant emission and compressor internal flow field optimization. High altitude and low temperature is the best condition for turboshaft engine operation. Pre-mission fuel estimation is good for low emissions. Oil-electric mixing engines can effectively improve efficiency, but reducing weight and cost is a problem that needs to be solved. The interaction between the leakage vortex and the excitation wave in the compressor increases the total pressure loss in the vortex core downstream of the excitation wave. The modes associated with wheezing can be stabilised by feeding back small-amplitude perturbations. The universality of the surge suppression of transonic centrifugal compressors and the stability of most of the compressor surges by small disturbance feedback are the next research focus.

Keywords: Turboshaft engines, compressor, performance, surge, efficiency.

1. Introduction

Operational performance simulation and mission analysis of rotorcraft have been important topics of research in the rotorcraft industry. These topics are now attracting greater interest as aspects related to chemical emissions and ground noise impacts become progressively more important in environmental and social impact assessments. Design and production of concept rotorcraft using advanced technology inherently requires the development of an accurate and cost-effective methodology applicable to the determination of performance and associated environmental impacts. This is essential considering that the goal of new rotorcraft configurations is better overall fuel economy and reduced gas emissions. The stability and control of gas turbine engines has been a matter of interest to researchers and engineers from various perspectives. Reference [1] describes the analysis and design of engine control systems and reviews the basics of controlling a gas turbine engine while satisfying numerous constraints.

Power system of helicopters and other rotorcraft is generally the turboshaft engine, and the abnormal state of the power system is easy to cause serious flight accidents. This paper focuses on the overall performance of turboshaft engines and the technical status and future development of compressor components.

2. Turboshaft engine performance

On behalf of the turboshaft engine performance of the main parameters, shaft power (thrust), fuel consumption, emissions, turboshaft engine power can reach up to 6,000 hp or even 10,000 hp, and turboshaft engine fuel consumption has been able to reach 0.28kg/kw-h, while the specified gas emissions are soot accounted for 0.1%, HC accounted for 1.6%, CO accounted for 12.4% and NOx accounted for 85.9%. 85.9%, which is overall low compared to other engines. This paper discusses the current status and development of turboshaft engine performance from the above three aspects.

First of all, to investigate the stability of the turboshaft engine, Mehrdad Pakmehr and Nathan Fitzgerald et al, use the global linearisation method, with the help of a convex optimisation tool, to study the guaranteed stability of the gas turbine closed-loop system with a gain scheduling controller. Calculating a single quadratic Lyapunov function for the gain-scheduled engine system may be towards using formal methods to validate and certify gas turbine engine control software. Simulation results explain that the gain schedule controller designed using this method can stably regulate the large thrust command of the turboshaft engine with good tracking performance. Convex optimisation and global linearisation also have limitations respectively, the disadvantage of convex optimisation is that if the sample size is large, then the complexity of the inverse operation is higher and the gradient decreases. The disadvantage of global linearisation is that it requires high data accuracy, can only plan constraints for linear problems and is computationally intensive.[1]

Furthermore, hybrid engines are now a hot research topic, and this work focuses on the development and application of a general approach for the design, performance and environmental influence assessment of parallel hybrid propulsion systems, using recovery engine cycles which was simple and progressive.

Studies have shown that hybrid recovery units can improve fuel economy and environmental impact. As shown in Figure 1, the different simulation models are integrated into a mission analysis module for performance analysis of the aircraft and mission. There are two different design strategies for hybrid recovery units. Despite the extra weight that comes with a larger battery, a battery designed with optimal efficiency is still better than the MCR limit. In addition, energy management is an significant factor in nitrogen oxides emitted by each task mandate. Studies have indicated that the introduction of a heat exchanger with 40% HX and 5.1% DoH in a fixed-size task can achieve energy efficiency improvements of up to 4% and a 6% maximum range capability improvement under modelling design space, constraints, and operational requirements. At the mission level, above allocation can reduce fuel combustion CO2 emissions by 12.9% and nitrogen oxide emissions by 5.2%.

On account of the maximum energy and power requirements calculate the battery weight, and takes into account the cable, installation and cooling system, adding an additional mass factor of 10%. That means. The 3.5% change, while increasing the weight of the battery and thus achieving lower fuel consumption, increases the overall mass of the rotorcraft. As the DoH of rotorcraft increases, NOx emissions gradually decrease, and the total energy of the aircraft is insufficient to maintain an effective endurance property. effective range capability. This change increases difficulty of controlling and balancing both parts, and the structural complexity of itself and supporting cables and cooling systems will also increase.[5]

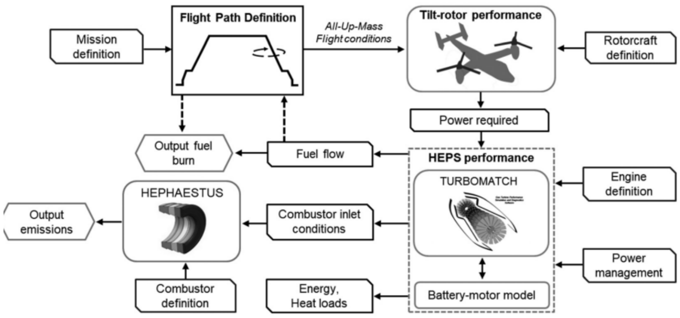

Fig. 1 Multidisciplinary hybrid-electric rotorcraft framework

Then, in daily helicopter missions, the paragraph indicates that there is a need for a trade-off between fuel and NOx minimisation, as the optimum velocity for NOx generation is usually lower than optimum velocity for fuel (the difference does not exceed 5 m/s).

The mission-level analysis was carried out in two situations: the impressions of ambient temperature, flight altitude and supercharger degradation were evaluated.

In EMS missions, the negative effects of high temperatures on fuel consumption and NOx emissions appeared to be enhanced, despite the observed reduction in helicopter power under cruise conditions. As a result, fuel of mission is increased by 2 per cent under hotter conditions. Compressor degradation adds a further 3 per cent to mission fuel (in the worst case of degradation) but has a negligible impact on nitrogen oxide formation. Under the specific conditions simulated in this paper, the nitrogen oxides produced during the task are slightly reduced, but the advantage and disadvantage of compressor degradation on nitrogen oxides depend on the shaft power level was necessary of the main rotor.

To regard of search and rescue missions, the infection of altitude on helicopter dynamics is much more important than the impression of temperature. The study also expressed that the combination of high altitude and microthermal had an advantage effect on NOx production and fuel consumption, negating the increased power during hovering, climbing, descending, and loitering for a given mission and resulting in mission fuel and NOx reductions of 12% and 40%, respectively.[2]

In addition to the above analyses, the turboshaft engine itself operates to emit gases that also have an impact on the environment. In order to reduce the emissions a stirred reactor model which is emerging, physically based is proposed for rapid computation of nitrogen oxide (NOx) emissions. A comparison of main rotor levelling power and control requirements was made with flight test data to calculate the corresponding payload-range diagrams, provided that the main rotor levelling power and control requirements were met. Nonlinear prediction of total fuel consumption and gaseous nitrogen oxide emissions for a mission were compared with experimental measurements and FOCA established approximate closed-form expressions. Results show that the favourable effect of altitude on engine thermal efficiency outweighs the detrimental effect on aircraft rotor performance in a typical operational envelope and it has been demonstrated that the rate of production of NOx emissions under these operating conditions is primarily influenced by the behaviour of the total inlet pressure of the combustion chamber upstream. Finally, it has been shown that accurate pre-flight estimation of on-board fuel supply has the potential to not only further fuel economy but is significant to reducing relevant environmental impacts. However, it must be considered that stirred reactors require larger power and oxygen supplies, higher equipment costs, higher energy consumption and greater weight. The proposed methodology is an enabling technique for evaluating existing and conceptual rotary-wing aircraft at the mission level regarding operational performance and environmental impact. [3]

It is well known that improving engine efficiency is a constant topic. Fakhre Ali, Ioannis Goulos and Vassilios Pachidis aim to propose a comprehensive multidisciplinary simulation framework for rotorcraft (RC) for comprehensive evaluation of RC power systems at the mission level. They use the composite tool diagram shown in Fig. 2. The proposed approach includes various separate modelling theories applicable to RC performance and flight dynamics, as well as to performance of gas turbine engines. An overall approach was adopted to perform preliminary trade-offs between the reference Simple Cycle (SC), the conceptual regenerative Twin-Engine Light (TEL) and Twin-Engine Medium (TEM) RC configurations, where process of prewarming the pressurized delivery air before the combustion chamber resulted in compared to the reference SC engine, it has lower fuel input requirements. The results obtained from the benefits of employing an onboard HE (heat exchanger) show a significant reduction in specific fuel consumption (SFC) in the main part of operating power range relative to the two RC configurations. The results obtained from the mission analysis trade-off study show that sub-optimal regenerative RC configuration can significantly reduce the MFB (mission fuel burn) while maintaining the respective airworthiness requirements with the single-engine inoperative.

Meanwhile, the initial AUM (all-up mass) of the regenerative RC has been updated to account for the weight of the onboard HE. In TEL missions, although the efficiency is increased to 80% in short-range missions, the ΔAUM is always negative, causing a weight burden; in 200 nautical miles and above missions, increasing the efficiency of the HE to 60% and saving 93 kg is the optimal method for such missions, however, when the efficiency of the HE is more than 60%, the additional weight of the HE is higher, and the positive ΔAUM decreases, and beyond 70% it becomes negative. In the TEM task, positive ΔAUM was achieved for HE efficiencies from 40%-80%, but the optimal efficiency point was 60%, with a ΔAUM of 231 kg. Nonetheless, increased efficiencies may increase the complexity of the structure increasing the cost of fabrication and may be accompanied by control issues. [4] Jesus Ortiz-Carretero, Ioannis Goulos, Alejandro Castillo Pardo and Vassilios Pachidis also said “The minimum NOx generation airborne average velocity variations were 7% and 7.5% with changes in AUM (all-up mass) and flight altitude, respectively.” [2]

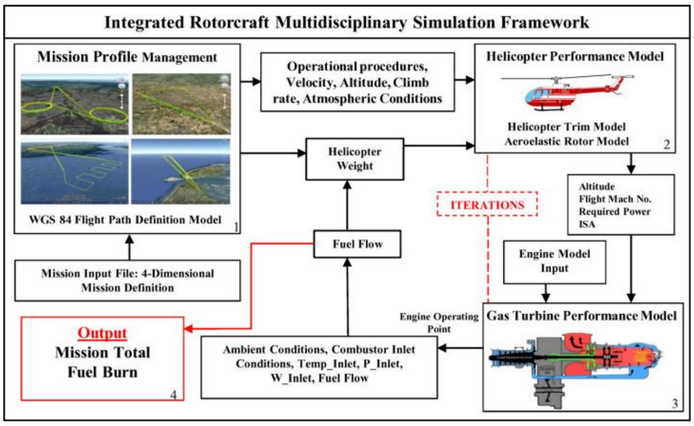

Fig. 2 Architecture of integrated RC multidisciplinary simulation framework

To sum up, the author of the above uses mathematical methods to establish a calculation model and uses this model to study fuel consumption and emissions of turboshaft engines, the overall stability, the efficiency of turboshaft engines, and gives the best efficiency and nitrogen emissions in different flight tasks. Recent literature demonstrates the usefulness of global linearization techniques that combine the idea of global linearization with the concept of incremental stability. When designing controllers for factories, we used gain scheduling, which is perhaps one of the most popular nonlinear control design methods and has been widely and successfully applied in fields such as aerospace and process control.

3. The compressor part of a turboshaft engine

Gas turbine engines with pressurised air are widely used in aerospace vehicles at present. The main parts are the propeller, reducer, compressor, combustion chamber and turbine. Among them, the compressor is one of the most important. The high-pressure ratio centrifugal compressor is widely used in turbochargers and turboshaft engines for its advantages of small size, high-pressure ratio and wide working range. This high-pressure ratio centrifugal compressor has a transonic inlet condition accompanied by a shock wave in the induced section. It is generally believed that the additional losses are produced by the interaction of the excitation wave with the boundary layer on the blade surface.

The operating principle of the compressor is based on thermodynamics and fluid dynamics, so to enhance the performance of the high-pressure-ratio centrifugal compressor, it is essential to understand its flow phenomena. In ‘Aerodynamics of a Transonic Centrifugal Compressor Impeller’. They observed the interaction of the excitation wave with the leakage vortex at the lobe tip of inducer and the flow distortion downstream of inducer and did not observe the interaction of excitation wave with the boundary layer. CFD calculations were then performed to visualise the vortex structure. Figure 3 describes from the measurements of static pressures on the shroud casing wall surface at the design obtained point isentropic Mach numbers. It also expresses isentropic Mach numbers obtained from CFD. As a result, the following results can be obtained.

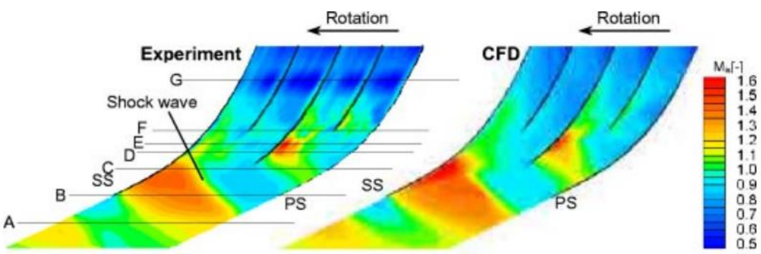

Fig. 3 Comparison of isentropic Mach number distribution of casing surface

Firstly, the low-speed region is formed downstream of the surge near the top of the suction surface of the whole lobe and the first manifold lobe. This is lead to by the interference between the surge and the leakage flow, as judged from the leaf crown wall pressure measurements and CFD analysis. Secondly, a comparison of the measurements with CFD (Dawes Code) shows that velocity distribution in the induced section is qualitatively and quantitatively consistent except for the velocity distribution in the vicinity of the impeller crown. The qualitative distribution in the back half of the impeller does not agree with the quantitative distribution in the flow phenomena modelled. Finally, vortex identification by CFD results revealed that in the induced section, leakage vortices coiled upwards from the gap increasing the total pressure loss. The interaction between the leakage vortex and the excitation wave increases the total pressure loss in the vortex core downstream of the excitation wave. The analysis shows that the next research should focus on the research direction of changing the axial position and strength of the leakage vortex by controlling the size and axial distribution of the gap to avoid its interference with the excitation wave or to mitigate the interaction. [6]

Then, Nicolas Poujol, Isabelle Trébinjac and Pierre Duquesne conducted experiments analysing the mounting angles were carried out on Safran Helicopter Engines designed and built a research centrifugal compressor at three inlet guide vane (IGV) stagger angles. The methodology for computing performance is then detailed, includes consideration of humidity minimization errors associated with operating atmospheric conditions. As the inlet guide vane stagger angle increases, the deflection of the surge line in the direction of low mass flow rate depends strongly on the rotational speed. Therefore, an experimental study of three inlet guide vane stagger angles was carried out for an aerospace centrifugal compressor stage. The results indicate that the effect of humidity should be considered in the calculation of performance. The non-linear effect of stagger angles on the blockage mass flow was observed. It was also observed that as the IGV stagger angles increased, the shift of the surge line towards a low mass flow rate was dependent on the rotational speed.

Figure 4 shows the results for the seven rotation speeds explored. In summary, the first-order stability analysis of the impeller and diffuser sub-components (IGVs) was carried out and the results show that the diffuser is less stable. The first unstable component at low speeds is the impeller, and increasing the stagger angle of the IGVs does not change this. [7]

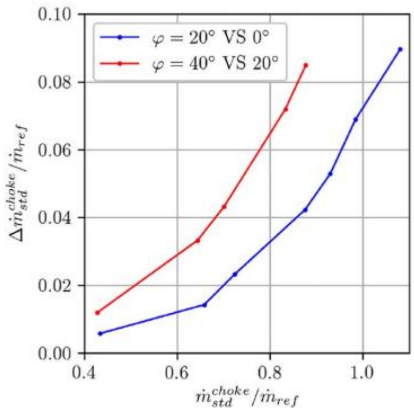

Fig. 4 Difference in choked mass flow due to a stagger angle increase

Compressor surge is a low-frequency, high-amplitude airflow oscillation phenomenon that occurs along the compressor axis after the compressor speed is reduced and deviates from the design operating conditions, which is extremely harmful to the impeller and shaft, causing flight accidents; and restricts the reduction of the speed and narrows the range of the normal speed, resulting in a reduction of engine efficiency.

To understand the characteristic problems such as the conditions for the occurrence of compressor surge, the surge characteristics of a transonic centrifugal compressor which is popular used in turboshaft engines for its high pressure ratio were investigated in the range of 40% to 100% corrected rotational speed.

The obtained results express the existence of both spiked wheeze and modal on compressor diagrams, with modal wheeze occurring at 90% calibration speed and spiked wheeze dominating at all other speeds. At 90% corrected speed, the impeller stops rotating at a load just above blockage condition and acts as an unstable constituent. At a speed equal to 70% of the shaft speed, a modal wave causing a slight surge appears in the impeller.

The details of the spiky wheeze signature varied with operating speed. Near the leading edge under subsonic inlet conditions of the impeller (from 85% to 40% of speed), the inducer can withstand larger incidence levels attributable to reduced losses at lower Mach numbers. Both impeller and diffuser channels experienced localised airflow disruptions when the foliation-free space was maintained in steady operation, and rapidly brought entire compression system into wheeze. When relative Mach number of the impeller leading edge exceeds 1, the incidence of induced wheel stall is reduced due to higher losses at higher Mach numbers. A spike-type disturbance is generated near the leading edge of the impeller, causing the entire compression system to rapidly enter a deep-surge state.

The observation of impeller-induced spiking-type surge refreshes traditional understanding that diffusers are usually stability-limiting assemblies of centrifugal compressors with vane diffusers. This is very important because the effectiveness of a surge suppression method depends heavily on whether the diffuser or impeller limits the operating range of the compressor. [8]

After they understood the characteristics of the compressor surge phenomenon, a study was made to control the surge phenomenon by E. B. Nelson, J. D. Paduano and A. H. Epstein. By feeling the static pressure of the engine inlet and the injection of air into the diffuser and compressor diffuser, they carried out a systematic identification and control study, and active stabilisation of wheezing was achieved on a horsepower class turboshaft helicopter engine named Allied Signal LTS-101 600A-2 600, reducing wheeze mass flow by 1% and increasing the operating range by 11%. The mass flow rate was reduced by 1% and the operating range was increased by 11%. Figure 5 explains the compressor map with or without control. System identification and modelling show that typical surge-type eigenmodes and eigenmodes related to the acoustics of the engine duct dominate the input-output characteristics of engine. The stability of the surge eigenmodes determines the open-loop surge mass flow rate. A robust linear controller with one output and three inputs stabilises the eigenmode without destabilising the acoustic modes. After 95% N1 correction, this controller reduced the surge mass flow rate by 1%; this increased the engine's choke to a surge-stabilised operating range by 11%. The following conclusions were drawn.

First, uncontrolled surging is caused by lumped parameter type oscillation mode instability. As originally postulated by Epstein et al, the modes associated with wheezing can be stabilised by small amplitude perturbations through feedback, thus ability to run in previously unstable and inaccessible states Useful value-domain extension dues to were obtained. Beyond that, they mention that acoustic modes are also present in the non-stationary behaviour of the engine. Modelling combined with one-dimensional pipe acoustics agrees well with the measured resonant frequencies. The acoustic modes of the engine can be fuelled by feedback. Therefore, the control rules used for the design of stabilised wheeze must take into account the presence of these modes. Systematic procedures for this type of control rate design have been demonstrated.

Although these results represent a comprehensive proof of concept for surge, much work remains to be done. No attempt was made to evaluate the trade-offs was relevant with actuation; only range extensions relative to the baseline are given. [9]

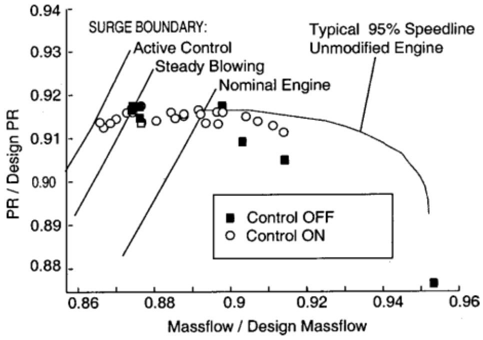

Fig. 5 Active stabilization of surge with compressor range extension

The author of the second part uses CFD calculation and experiments to study the compressor surge characteristics and inventive control methods to suppress the surge phenomenon in order to improve the compressor surge margin and efficiency.

4. Conclusion

As the main component of helicopters, the performance of turboshaft engines is the focus of modern scientists. The unit research focuses mainly on the compressor. After research and analysis, the following conclusions are drawn.

1) Overall stability is an important part of turboshaft engine performance, and the stability of closed-loop gas turbine systems is specifically analyzed to improve the overall stability.

2) The analysis of environmental conditions shows that high altitude and low temperature is the best condition for turboshaft engine operation.

3) Gas emissions of turboshaft engines should be controlled by pre-mission fuel estimation.

4) In terms of fuel economy and manufacturing costs, the performance of turboshaft engines can be improved by increasing efficiency, but concurrent problems such as weight need to be considered.

5) The interaction between the leakage vortex and the excitation wave in compressor increases the total pressure loss of the excitation wave in the vortex core downstream.

6)The modes associated with wheezing can be stabilised by feeding back small-amplitude perturbations.

5. Suggestion

1) How to overcome the high complexity of inverse operation of convex optimization and the shortcomings of global linearization, which requires high accuracy of data, only for linear problems, and a large amount of calculation, are the research directions of the future control simulation of the whole machine.

2) How to reduce the power and oxygen supply, cost, energy consumption and weight required for stirring reactors are challenges to reduce emissions.

3) Improving the battery power-to-weight ratio is a key factor in reducing the weight of the hybrid.

4) The universality of surge suppression of transonic centrifugal compressors is the next research focus.

5) Can all surge-related modes be stabilized by feedback of small perturbations?

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