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論 文 内 容 要 旨

To replace conventional space transportation systems, that is, Expendable Launch Vehicle (ELV), research on future or advanced systems, viz., Reusable Launch Vehicle (RLV) has actively proceeded these days. Our proposed system is so-called Two-Stage-to-Orbit (TSTO), consisting of the booster and orbiter stages. Application of air-breathing engines to the RLV booster stage produces enough large weight margin required for the vehicle reusability. Devices with function required for the reusable system can be applied to the booster stage, thanks to such a weight margin. The RLV experiences extremely wide range flight condition, that is, from sea-level to high altitude and/or from static to hypersonic. Correspondingly, incoming air flow condition for the air-breathing engine also varies moment by moment. For this reason, it is necessary for conceptual design of this type of vehicle to carry out performance prediction on every component of the vehicle under huge variety of flight conditions with iterative process. Under conceptual design phase, utilizing high-fidelity CFD is unrealistic, because it requires too much computation time and cost. Therefore, performance prediction model of which calculation cost is much lighter than such CFD, is necessary to launch the conceptual design, and our present concern of Scramjet External Nozzle (SEN) is no exception. Due to efficient Airframe Propulsion Integration (API) and/or reduction in vehicle weight and friction drag, the SEN is designed as a kind of two-dimensional Single Expansion Ramp Nozzle (SERN). With the goal of further performance improvement, the bottom side wall of the nozzle, termed as the cowl, is truncated. Meanwhile, from the viewpoint of structural strength, operability, and maintainability, the propulsion system is modularized, and as a result, the SEN entrance is clustered across structural member called cell base. For the SEN with the clustered entrance, the ambient environment and the cell base highly likely affect the SEN thrust performance. The performance prediction model including the above-mentioned effects, however, has not reported even today. On the basis of such a present state of the SEN research, my graduate work had been launched, to finally establish new design concept improving the SEN thrust performance. The wind tunnel tests had been, first, carried out in order to elucidate the aforementioned two effects on the SEN flow field, and followed by an experiment-based performance prediction model had been developed and well validated by both experimental and numerical ways. Finally, we had also performed the system analysis to clarify the SEN potentials for performance improvement, utilizing our novel two-dimensional prediction model.

To begin with, for the experimental investigation, cold nitrogen gas experiments had been conducted at a supersonic free jet wind tunnel, called Pilot Wind Tunnel (PWT) located on Kakuda Space Center – Japan Aerospace Exploration Agency (JAXA-KSPC). The cold nitrogen gas issued from the test nozzle simulating the SEN flow. Test ramp having the pressure measurement ports was continuously connected to the upper side inner wall of the test nozzle, which simulated the SEN ramp wall. Dry air flow, on the other hand, was injected from facility nozzle, simulating the ambient flow. The interacting phenomenon between the SEN flow and the ambient environment was simulated by that between the test and facility nozzle flows. The experiments had been conducted under both without and with ambient flow conditions. The ambient flow effect on the SEN thrust performance was investigated by comparison of the test ramp wall pressure distributions and their normalized integrals, called pressure coefficient, between with and without ambient flow cases. Test condition was defined by test parameter, viz., Nozzle Pressure Ratio (*NPR*) which categorizes the SEN flow into so-called over-, optimum-, and under-expanded conditions. Those expanded-conditions determine first pressure waves formed in the SEN flow with the ambient flow. Shock, no, and expansion waves are shaped in the SEN flow side, for the over-, optimum-, and under-expanded conditions, respectively. Each of the counterparts forms in the ambient flow side for each corresponding expanded condition. Test results showed that the ambient flow has an effect to reduce the magnitude of the wall pressure fluctuation induced by the impinging pressure waves. The pressure waves in the ambient flow side change the physical and geometric parameters of the pressure waves in the SEN flow side. The ambient flow side waves theoretically do not appear for without ambient flow case, because of ambient static state. The slip boundary divides the flow field between the SEN and ambient flow sides. Reflections of the pressure waves by the slip boundary make the pressure waves in the SEN flow side weaker and weaker. Due to this effect, the wall pressure distributions, induced by the impinging pressure waves, are finally kept approximately constant level. Such wall pressure differences between without and with ambient flow cases are well explained by the pressure wave pattern analysis. Those new findings taught us that the wave method with covering the ambient flow effect was recommended for the performance prediction method.

Next, we addressed the investigation on the clustering effect, three differently configured test nozzles were selected as test model, of which exit simulated the SEN entrance. First one has non-clustered exit, termed as NC test nozzle, while the other two has clustered exit with larger and smaller cell bases, termed as LC and SC test nozzles, respectively. The cell base bounds each clustered flow path in the test nozzle. For LC and SC test nozzles, the wall pressure on the cell base called the cell base pressure was measured. Measured results showed that the cell base pressure can be linearly correlated with the *NPR*, for fixed SEN entrance configuration, that is, the width ratio of the cell base to the flow path. This is because, except for the smallest *NPR* case, the cell base wake closes, so that only the test nozzle exit pressure dominantly affects the cell base pressure in such a closed wake. The test results comparison demonstrated that the entrance clustering effect on the SEN ramp wall pressure distribution appears manifest on the vicinity of the SEN entrance where the inputs are made for the model, because the cell base produces the low pressure region with the cell base pressure around the SEN entrance. The presence of the cell base produces the pressure waves in spanwise direction. In the approximately-optimum-expanded condition, the heightwise pressure waves are relatively weak compared with the spanwise waves. Thus, the spanwise waves, resulting from the entrance clustering, the most remarkably affects the SEN thrust performance, in the approximately-optimum expansion case. The entrance clustering effect on the SEN thrust performance is limited except for the approximately-optimum expansion. According to those two experimental studies, we proposed first developing the prediction model counting the presence of the ambient flow, and subsequently reflecting the clustering effect coming from the presence of the cell base to the developed model by the input correction.

Here, my graduate work shifted to the next category, that is, the prediction modeling and its validation. This study proceeded utilizing the clues for modeling, obtained from the preceding experimental studies. The prediction model was developed based on the wave method, but four modifications were newly applied, to reproduce the ambient flow and the clustering effect on the SEN ramp wall pressure distribution. Each of them was named "Mach wave production," "wave discretization," "Riemann interaction," and "input correction." First modification of the Mach wave production is employed to reflect flow ununiformity at the SEN entrance to the model-calculation. The Mach waves, produced from the SEN entrance, propagate the ununiformity in the combustor flow to the SEN flow. Second modification discretizes expansion fan into series of expansion waves for computation. Each of the expansion waves is severally reflected by the slip boundary. Those are transformed into the series of compression waves, through the slip boundary reflection. The computation for Riemann interaction is applied to the prediction model as third modification. The Riemann interaction means the interactions between pressure wave and pressure wave or pressure wave and slip boundary, which have finite strength. This computation can be mathematically translated into one of the initial value problem for partial differential equation. The physical and geometric parameters of the pressure waves or slip boundary after the interactions are derived so that equalities are completed for each of the static pressures and the flow directional angles across the slip boundary. Fourth modification is the input correction to cover the entrance clustering effects. The SEN flow side inputs for the model-calculation is corrected with empirically estimated cell base pressure. Two correction methods were proposed. As for first method, the only input pressure is addressed. The input pressure is arithmetically averaged with the cell base pressure. Second one equates three conservation laws for the flow at the SEN entrance, which are mass, momentum, and energy conservations. The corrected inputs are solutions from those three conservation equations in this correction. To cover subsonic flight case, two approximating manners were proposed. These are static and low supersonic approximations. First manner approximately treats the subsonic ambient flow as static, that is, Mach 0.00. In second one, the ambient flow Mach number with subsonic state is approximated as low supersonic in the model-calculation, that is, around Mach 1.00. The validation test and high fidelity CFD-based simulation confirmed the applicability of the prediction model to the conceptual or system analysis typed studies. The prediction model well reproduced the SEN ramp wall pressure distributions for all the cases set by both the tests and simulations. The prediction error for the SEN thrust performance never exceeded 10 %, with keeping around only 7 s implementation time by personal desktop computer with quad-core 2.90 GHz processor, so that the applicability to the conceptual design was ensured by the present validation study.

Thanks to the developed prediction model and confirmation of its validity as the conceptual design tool, here, we were able to reach to the conceptual or system analysis typed study. First of all, the SEN system analysis for baseline configuration and condition was performed to grasp the SEN general behavior assuming the actual operation. As a result, recovery on the SEN ramp wall pressure is rarely attained in the assumed actual operation. The pressure recovery is obtained from the impingement of the compression type pressure waves on the SEN ramp wall. This is because, except for around take-off phase, under-expanded jet forms in the SEN flow. Thus, the SEN-ambient flows interaction generates the expansion waves from the cowl trailing edge, in most cases. This wave is called cowl expansion wave. The cowl expansion waves have a dominant role on the SEN thrust performance from Mach 1 to 5 speed range, because those impingements on the SEN ramp wall reduce the wall pressure level. From Mach 6 to 12 speed range, the ambient flow no longer affects the SEN thrust performance, because the cowl expansion waves do not enter the SEN ramp wall in high speed regime. Angles of the cowl expansion waves decrease with increase in flow Mach number at the SEN entrance, which finally prevents those waves from entering the ramp wall. The impinging cowl expansion waves produce definite drop in the SEN thrust performance, from low to middle speed regimes. Accordingly, we proposed novel design concept for the SEN, based on its two-dimensional flow characteristics. One of the propositions for the new design methodology were confirmed by the additional system analysis. This is SEN entrance height extension to reduce the number of the cowl expansion waves impinging on the SEN ramp wall. Around 28 % height extension from the baseline configuration connects to around 15 % SEN thrust performance improvement under the middle speed regime. More practical system analysis was additionally performed, that is, the system analysis for the combustor followed by the SEN under set constraint. In addition to our developed performance prediction model for the SEN, we utilized previously reported combustor model. The constraint was set so that design change in the combustor with SEN did not affect performances of the other elements, such as, intake or airframe. The design modification is to vary ratio between the combustor and SEN portions in the propulsion system. The analyzing results demonstrated that the SEN has more potential to improve the whole thrust performance of the propulsion system than the combustor, so that sparing larger portion for the SEN leads whole thrust performance improvement.

As last part of my graduate work, we addressed relocation of the rocket engine from inside the combustor to on the SEN ramp wall to form so-called Rocket Spike Nozzle (RSN). This design modification is to maintain the ramp wall pressure high level by the rocket exhaust, and also mitigate the severe thermal load in the combustor. The rocket engine inside the combustor produces severe thermal load, because the rocket exhaust with high temperature is surrounded by the walls in this configuration. We can call this nozzle system the SEN-RSN hybrid nozzle, because of its configuration. Three rocket locations, viz., the RSN locations on the SEN ramp wall were set. Computation showed that the nozzle thrust performance is determined through interrelationship between the pressure wave pattern in the SEN flow and the RSN location. Since the hybrid nozzle produces much larger thrust than single SEN under appropriate operation and location, we finally concluded that this nozzle system has great potential to improve overall propulsion system performance.

論文審査結果の要旨

宇宙輸送機に空気吸込みエンジン技術を適用することで，機載酸化剤量を大幅に削減し，生じたシステム重量余裕をもって輸送機の再使用化を図る研究開発が進められている。空気吸い込みエンジンはロケットエンジンに対して推重比に劣るために加速飛行に不利であり，機体の後面も推力発生に用いる，いわゆる外部ノズル設置によって重量を増さずに推力発生を増やす工夫が必要とされている。本研究では，従来の外部ノズル性能推算手法に外気流影響及び三次元性影響を加え、システム最適化に織り込むための計算負荷の軽い推算手法を提案し，実験によりその有用性を示している。さらに同手法を用いて，推進性能向上の方策提案を行っている。本論文はこれらの研究成果をまとめたものであり，全編７章からなる。

第１章は緒論であり，本研究の背景，目的および構成を述べている。

第２章では，外気流が存在する場合の外部ノズル流への影響を実験的に調べている。外部ノズル流を支配する波を特定し，外気流が存在することで外部ノズル流との境界での波の反射過程が変わり，波の反射による圧力変動が抑えられることを実験と理論の両面から示している。 これは，性能予測手法構築に向けた重要な知見である。

第３章では、外部ノズル入口が，空気吸い込みエンジン部のダクト構造によるベース部分のために幅方向に不均一となる，いわゆるクラスタリングが外部ノズル流に及ぼす影響を実験的に調べている。想定される飛行条件では，ごく低速の条件を覗いてベース流れは closed wake となり，ベース部に働く圧力はノズル流の全圧に比例することを示している。クラスタリングが外部ノズル表面の圧力に及ぼす影響も評価し，クラスタリングの無い場合に比べ発生推力に 10%程度の違いが生じることを示している。この知見は，性能予測手法改良への重要な提案に繋がっている。

第４章では，前章までの結果を受けて，従来の静止大気中・二次元流れを基本とする性能推算手法に外気流及びクラスタリング影響を織り込む方法を提案している。前者については，外部ノズル流外縁にスリップ流線を導入する方法を，後者については入口条件の幅方向の平均化の方法を提案している。さらに，外部ノズル入口流に高さ方向の分布を与える方法を提案し，これらを組み合わせた性能予測の結果を，前章までの実験結果及び共同研究で実施された CFD 結果と比較して，精度 10%以内で推力性能を予測できることを示している。当該予測手法は最適化設計に組み込める規模の計算負荷で動作可能であり，システム検討に有益な予測手法を構築している。

第５章では，前章で構築した性能予測手法を用いて，JAXA でのロケット-ラムジェット複合エンジン搭載 TSTO 機のシステム検討で用いられている作動条件で,外部ノズル性能を向上させるための検討を行っている。まず前述のシステム検討での加速経路上の外部ノズル流状態を予測手法によって追跡し，外部流が超音速となれば外部ノズル流は不足膨張状態となり，その性能は外部ノズル流と外気流の境界から出る膨張波の外部ノズル面への入射の程度によるとしている。この知見に基づき，外部ノズル入口断面形状や空気吸い込みエンジン部の膨張比を振って，性能への影響を評価し，前者の変更で 15%程度の推力向上が見込まれることを示している。これは，システム全体の最適化設計において，空気吸い込みエンジン部及び外部ノズル部の設計に如何なるパラメータを含めるべきかの指標ともなり，予測手法の有効性とシステム推進性能向上への提言を示した有効な知見である。

第６章では，外部ノズル流れの予測法を応用し，これまでの複合エンジンでは空気吸い込みエンジン部分に内蔵されていたロケットエンジン部分を外部ノズル内に設置する場合についてのノズル性能を検討している。外部ノズル流と外気流の境界から出る膨張波の入射によって，ロケットノズルの性能低下もあることを示している。これは、システム推進性能向上への提言を示した有効な知見である。

第７章は結論である。

以上要するに本論文は，外部ノズル性能の計算負荷の軽い性能予測手法を提案し，更に同手法を用いてシステム推進性能向上に向けた提言を行ったもので，航空宇宙工学および宇宙推進工学に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。