A Numerical Framework to Investigate Intake Aerodynamics Behavior in Icing Conditions

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Abstract**—**One of the major parts of a jet engine is air intake, which provides proper and required amount of air for the engine to operate. There are several aerodynamic parameters which should be considered in design, such as distortion, pressure recovery, etc. In this research, the effects of lip ice accretion on pitot intake performance are investigated. For ice accretion phenomenon, two supervised multilayer neural networks (ANN) are designed, one for ice shape prediction and another one for ice roughness estimation based on experimental data. The Fourier coefficients of transformed ice shape and parameters include velocity, liquid water content (LWC), median volumetric diameter (MVD), spray time and temperature are used in neural network training. Then, the subsonic intake flow field is simulated numerically using 2D Navier-Stokes equations and Finite Volume approach with Hybrid mesh includes structured and unstructured meshes. The results are obtained in different angles of attack and the variations of intake aerodynamic parameters due to icing phenomenon are discussed. The results show noticeable effects of ice accretion phenomenon on intake behavior.

Keywords**—**Artificial Neural Network, Ice Accretion, Intake Aerodynamics, Design Parameters, Finite Volume Method.

I. INTRODUCTION

ICE accretion on aircraft surfaces is a persistent threat to aviation safety and a limiting factor of operational capabilities, particularly for small aircraft. Although the problem has been the focus of study for 50 years it remains as an important research priority. Early research on the icing problem involved wind tunnel and flight tests but, in recent years efforts have also included work on numerical simulation. The hope is that a robust modeling capability will enable designers to correctly assess icing rates and shapes and performance degradation due to ice accretion throughout the design process and not just at the flight test stage. Icing comes from the freezing of cloud droplets, or super-cooled droplets which remain in liquid state even at temperatures far below freezing, when they are stuck by the aircraft during the flight. Cloud droplets may freeze instantaneously and form rime ice on unprotected surfaces or run downstream and freeze later forming glaze ice structure. Icing is most severe when temperature is near zero centigrade degree may be encountered at temperature as low as -40 centigrade degrees. The amount and rate of icing depend on a number of meteorological and aerodynamic factors. Of primary importance are the amount of liquid water content of droplets, their size, the temperature of aircraft surfaces, the collection efficiency, and the extend of super-cooled droplets. Icing is described as trace, light, moderate or severe which depends on the type of clouds, the type of aircraft, and the type of icing protection systems. The distribution of potential aircraft icing zones is mainly a function of cloud structure and temperature, which in turn vary with altitude, location and season.

Although the earliest effort in ice accretion phenomena started during the end of the 1920's, the more important experimental and theoretical investigations were done in the 1940's and 1950's by NACA (National Advisory Committee in Aeronautics) of USA, in the Lewis Icing Research Tunnel, IRT. By the beginning of the 1980's more work continued on the investigation of aircraft icing. These significant studies started with the work of Bragg, Lozowski and Oleskiw, Frost and Cansdale and Gent. A mathematical model of glaze and rime ice accretion on a 2D airfoil was presented by MacArthur. In 1985, Bragg improved his previous model, derived a method to solve the droplet trajectories and impingement characteristics and gave some recommendations for further improvement of the method. In the light of these developments more experimental and theoretical investigations of icing have been performed by many researchers such as Flemming and Lednicer, Cebeci, Bragg and Khodadoust. A very large research program on aircraft icing has been conducted by NASA Lewis Research Center. A 2D ice accretion model, LEWICE, was developed in 1983 and later modified by Ruff and Berkowitz The original LEWICE code based on potential flow analysis, is capable of calculating the shape of the ice accretion on the airfoil under rime ice conditions. This code has been modified by Cebeci et al. to include viscous effects by using potential flow with Interactive Boundary Layer, LEWICE/IBL. The effect of compressibility has been incorporated by Potapczuk in the so-called LEWICE/E code which is an inviscid compressible flow ice accretion code based on solving the Euler equation for the flow field flow analysis. Potapczuk et al. extended the original LEWICE program by using the solution of the 2D Navier-Stokes equations in the LEWICE/NS code which includes a module for grid generation, predicts the flow field, calculates droplet trajectories and the shape of ice accretions based on energy balance calculations and predicts aerodynamic characteristics [1]. Currently several ice accretion codes exist in the international aircraft icing

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community such as LEWICE (U.S.A.), ONERA (France), DRA (UK), CANICE (Canada) and more recently CIRA (Italy) based on the physics of icing. Ice accretion phenomena can be modeled using Artificial Neural Networks, too. Icing phenomena have orderly nonlinear behavior that can be modeled by neural networks, which have a proven capability for modeling nonlinear systems. Ogretim et al. have utilized neural networks for aircraft ice accretion prediction in 2006 [2].

Aircraft engine inlets are subject to ice accumulation while flying through a cloud of super-cooled liquid water droplets. Ice formation generally occurs on leading surfaces such as intake lips and detrimentally affects the Engine performance. In cases where the ice accretes on lifting surfaces, such as wings and tails, aerodynamic performance degradation occurs due to decrease in lift, increase in drag and stalling speed, and reduced stability and controllability of the aircraft. Although the problem is limited to subsonic speeds, supersonic jets are also exposed to the hazardous effects of icing during low speed maneuvers such as take-off/climb, descend, landing, and hold stages. In addition, the ice formed on leading nacelle surfaces distorts the intake air flow and reduces propulsion efficiency. In the Present work, the effects of lip icing are investigated on intake behavior, based on CFD simulation using Neural Networks for icing phenomena calculations. The details are given in the following sections.

II. Intake Aerodynamic Design

The major types of intake in practical use are classified in four different regimes, Subsonic (Pitot configuration), Low Supersonic (Pitot configuration), Mid-Supersonic (External Compression with center body), High-Supersonic (Mixed compression with center body). The principles on which they are based may be described by considering the way in which, in a condition of high speed flight, the air is retarded relative to aircraft motion, from the initial high speed to the value of Mach number required at the compressor face. In this research, the first kind is supposed for icing phenomena calculations.

With a subsonic intake, the retardation takes place in two stages, first in the streamtube ahead of the entrance and second, in the diffuser section between the entry and compressor face stations. A designer's choice of entry area determines the split between the two retardation stages. There are some major parameters in intake aerodynamic design, called pressure recovery, compressor face flow distortion and intake external drag. Pressure recovery is most commonly defined as the ratio below [3] ,[4]:

$$\eta_{\sigma} = \frac{P_{0_f} - p_{\infty}}{q_{\infty}} \quad (1)$$

where, P_{0f}, p_{∞} and q_{∞} denote average total pressure at compressor face section, freestream pressure and dynamical head respectively. The effect of intake pressure recovery on engine thrust force depends on engine characteristics. Generally, a change in intake pressure recovery is translated directly into a change in engine thrust force, the relationship being of the form [3]:

$$\frac{\Delta X}{X} = K\frac{\Delta P_0}{q_{\infty}} \cdot \frac{q_{\infty}}{P_{0_{\infty}}} \quad (2)$$

where $K, P_{0_{\infty}}, \Delta P_0$ and ΔX denotes proportionality coefficient, freestream total pressure, total pressure variation and thrust force changes respectively. *K* is a factor the value of which depends on the type of engine but is greater than unity and generally closer to 1.5. On the other hand, intake and engine must remain aerodynamically compatible throughout an aircraft flight envelope. This is to say that situations which lead to compressor stall, engine surge or other malfunctioning of the propulsion system must be avoided or at least reduced to a tolerably low frequency of occurrence. Such situations are produced by departures of the airflow, as delivered by the intake to the engine, from the ideal of a flow uniform in pressure, temperature. In terms of intake aerodynamics, it is evident that any loss of total pressure which occurs in a manner other than uniformity across the intake streamtube results in a degree of distortion in the flow. The main sources of distortion at compressor face can be described as: boundary layer profile distension on the inside walls of bends, wall separation from high diffusion rates, lip separation due to high flow ratio or icing phenomena, shock and boundary layer interaction, spillage of the aircraft front fuselage, boundary layer into the intake, the ingestion of aircraft vortices, emanating from upstream sources, etc. Generally, distortion coefficient in 2D is defined for comparative purposes as below [3], [4]:

$$DC = \frac{P_{\max} - P_{\min}}{P_{mean}} \quad (3)$$

where $P_{\max}$, P_{min} and P_{mean} denotes max, min and average pressure on compressor face section respectively. In 3D investigation, total distortion is described as a distortion average on the different rings on compressor face using four elements, includes the circumferential intensity element, the circumferential extent element, the multiple-per-revolution element, the radial intensity element, but for 2D investigation and comparative purposes the relation (3) is utilized as mentioned before.

III. Intake Behavior Due To Icing

The total pressure field on compressor face is substantially affected by the intake lip shape. In other word, intake behavior is dominated by the state of flow around the entry lips. When icing occurs on intake lips, the downstream flow filed will be complex due to the complexity of ice and intake shape combination; this will be more severe in greater angles of attack. Investigation of icing effects on intake behavior requires two different Bases, First ice accretion prediction on intake lips, second numerical simulation of intake flow field with Icicles and clear situations. In following parts, these two steps are followed and presented.

A. Intake Ice Accretion Modeling Using ANN

Two basic conditions must be met for ice to be formed: the ambient temperature must be below 0 C and supercooled water droplets must be present. Icing on aircraft occurs when the aircraft flies at a level where the temperature is at, or slightly below the freezing point and the atmosphere contains supercooled water droplets. When these droplets are hit by the aircraft they begin to freeze. When the liquid water content (LWC) or the ambient temperature is low, all of the liquid water that impacts a wing freezes on contact and forms rime ice. This situation is well understood and can be modeled with reasonably good accuracy. However, for warm ambient temperatures or relatively high LWC values, not all of the liquid water collected by the wing freezes on impact. This situation poses a much greater challenge to numerical simulations because the details of liquid water movement on the surface and the heat transfer between the air and wing surface must be resolved. The ice that forms in this situation is referred to as glaze ice and glaze ice shapes are much more difficult to predict than rim ice shapes using existing models.

The Messinger model was the first successful attempt to model ice accretion [5]. This model related the accretion to the impingement of supercooled droplets onto the aircraft surface. It proposed a thin water film around the ice surface, which was fed by oncoming droplets and was responsible for further growth of ice to downstream points. This method proved successful for rime ice accretion, although it had problems for glaze ice accretion. The LEWICE code based on the Messinger model, developed by the NASA Glenn Research Center, is one of widely used ice accretion prediction codes. LEWICE has also been subject to further development following recent findings that focus on physical phenomena, such as water film dynamics, droplet growth, droplet trajectories, heat transfer coefficient variation and boundary layer-ice roughness interaction as mentioned before. As a result of these studies and developments, the performance of this computer program rose to a reliable level for icing prediction. In terms of new methodologies for ice shape prediction, neural networks are a promising technology because of their ability to be trained and used for investigation of systems that involve nonlinear dynamics. Because of this proven capacity, neural networks have been applied in both aerodynamics and icing research. An artificial neural network (ANN) is a massively parallel distributed processor made up of interconnected processing units (Fig.1).

The present research uses an ice accretion prediction method based on the training of three perceptron neural networks. In this study, the lip geometry of the intake which was designed for icing effects analysis is the same geometry of initial part (one third) of NASA 0012 airfoil with 30 cm chord. By investigation of icing patterns of the airfoil in different icing conditions, it is obvious that the icing region happens only in the initial one third of the airfoil geometry, so in this case, NASA 0012 airfoil experimental database can be used for training of the neural networks in intake icing phenomena investigation. The two first ANNs learn experimental ice shape data for NASA 0012 airfoil in 15 different glaze ice shapes [2], [6] and flight conditions in the form of Fourier coefficients and the last ANN learns the experimental roughness data for NASA 0012 airfoil in 30 different flight conditions [7] for ice roughness prediction.

In analysis process, first Fourier coefficients of the 2D ice shape geometry in x,y coordinates sequences are calculated individually. The method uses the Cooley-Tukey algorithm and can be expressed in the following manner. The coefficients produced by method produce an interpolating trigonometric polynomial to the data. Then the dominant frequencies are determined and the energy in the spectrum of the shape signal is achieved. After all, the Fourier coefficients are determined.

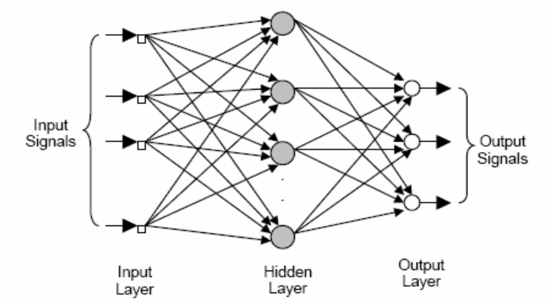

Fig. 1 Multi-layer perceptron ANN with one hidden layer

This part requires the experimental ice shape data points as the input. The next part of the study is the neural network training for ice accretion prediction. The activation functions for three neural networks are tangent hyperbolic function and linear function in the hidden and output layers respectively (Fig.1). For two first neural networks (X-Fourier coefficient prediction ANN and Y-Fourier coefficient prediction ANN), two 5-10-32 perceptron neural networks with 10 neurons in hidden layer are used and the input parameters are flight speed, accretion time, static temperature, MVD and LWC. The outputs are 32 X-Fourier coefficients and 32 Y-Fourier coefficients respectively. For the roughness of ANN, a 7-8-1 perceptron network is used with two additional parameters: Accumulation parameter and freezing fraction as inputs, these two parameters are defined respectively as below [7]:

$$A_C = \frac{V.LWC.\tau}{2R\rho} \tag{4}$$

$$n = \frac{C_{p,w}}{\Lambda_f}\left(\phi + \frac{\theta}{b}\right) \tag{5}$$

where A_C, b, n, ϕ, Λ_f, ρ, θ and τ denotes Accumulation parameter, relative heat factor, freezing fraction, droplet energy transfer term in energy balance, latent heat of freezing of water, ice density, air energy transfer terms in energy balance and accretion time respectively. The neural network output will be ice roughness in the training phase. Instead of employing the Fourier series expansion which is single value, one can use Fourier coefficients of real periodic x,y coordinates sequences of ice shape to express an ice shape that folds back on itself. The convergence history of the ANNs is shown in figures 2-4.

B. Numerical Intake Flow Simulation

Simulation of intake icing presents challenging problems for Computational Fluid Dynamics (CFD) due to irregular ice shapes with varying degrees of surface roughness and resulting complex flow phenomena. Quality grids are required to obtain viscous flow solutions around iced intakes sufficiently accurate to provide insights to flow phenomena and intake performance degradation. Unfortunately, grid generation for iced intake presents considerable difficulty because most ice shapes are highly irregular with sharp corners and segments with very high curvature. In addition to geometric complexity, the flow can be complex as it separates in the region aft of prominent ice shapes, even for moderate angles of attack. Thus, geometry preparation and grid-generation for two-dimensional icing problems are currently difficult and time-consuming. In this Study, a hybrid C-type mesh which includes structured and unstructured mesh is used in the physical domain. Around the ice shape and high gradient curvatures, unstructured mesh is applied because of the geometry complexity and for far field regions structured mesh is used (Fig.6). The flow calculation includes the internal and external flow solutions. At compressor face section, the boundary condition isn't clear, so we chose a large enough (30 times of intake length) computational domain around the intake which enables us to apply the far field boundary conditions. When the domain overall solution is achieved, the outlet solution will be obtained. The flow field is simulated based on 2D viscous Navier-Stokes equations and k-ε turbulence modeling using SIMPLE finite volume (F.V.) method.

IV. Results and Discussion

For investigation of intake icing effects in different angles of attack (AOAs), the flight conditions should be specified. For our case, it is assumed that the aircraft is flying in cruise in standard atmosphere with zero AOA and constant speed 67 m/s at constant altitude 3600 m with constant LWC 0.65 g/m^3, constant VMD 40 μm, specified accretion time 672 s, freezing factor 0.312 and accumulation parameter 0.3416, it is assumed the ice density is 917 kg/m^3, so ice accretion happens and the phenomena can be predicted considering these conditions using three trained perceptron neural networks. Fig.5 illustrates a comparison between the predicted ice shape using neural networks and NASA LEWICE code with experimental glaze ice shape. As it's clear the ANN prediction is excellent. To complete the modeling, mean ice roughness is calculated by the roughness ANN and equals to 3.15 mm considering above flight conditions. After accretion time, aircraft flies in non-icing atmosphere and experiences different AOAs.

As mentioned before, for CFD analysis a hybrid mesh which includes unstructured and structured meshes is used to discretize the physical domain. The flow field is simulated based on 2D viscous Navier-Stokes equations and $k-\varepsilon$ turbulence modeling using SIMPLE finite volume method. After internal and external flow calculation, all variables include velocity and static and total pressure of the nodes on real outlet of the intake section will be known.

Figure 7 shows the total pressure variations on the compressor face in 0, 5, 10, 15, 20 degrees of intake AOAs. As is shown in this figure, the variations of total pressure are mainly affected by icing phenomena.

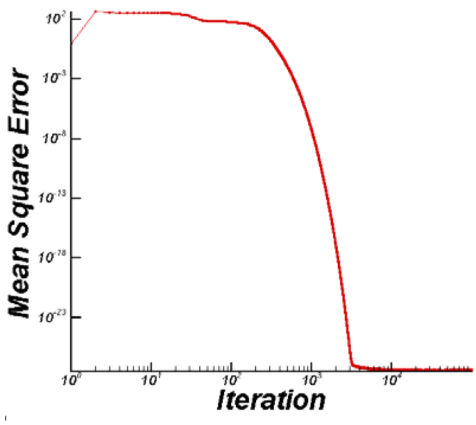

Fig. 2 X-coefficient ANN learning convergence

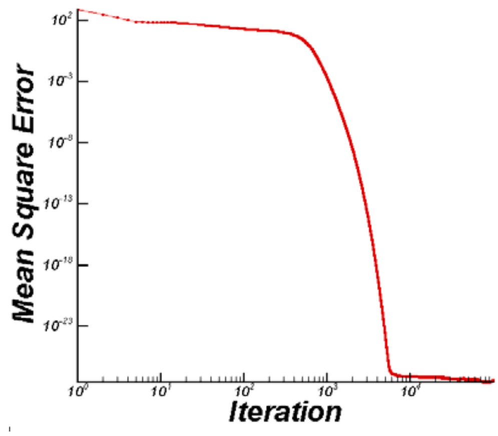

Fig. 3 Y-coefficient ANN learning convergence

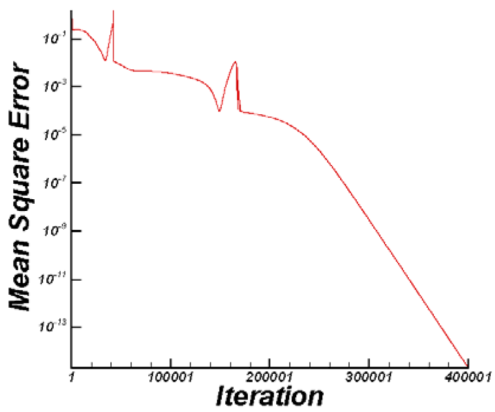

Fig. 4 Roughness ANN learning convergence

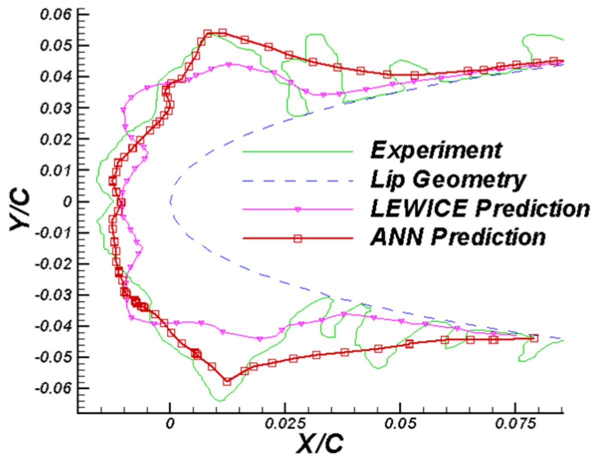

Fig. 5 Glaze ice shape on intake lip geometry

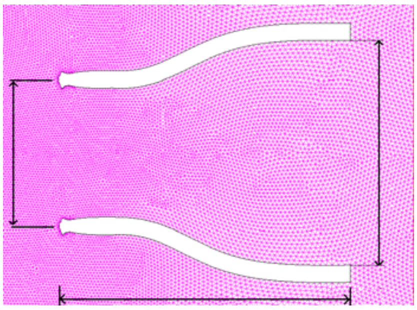

Fig. 6 Intake geometry with lip ice accretion and its domain mesh

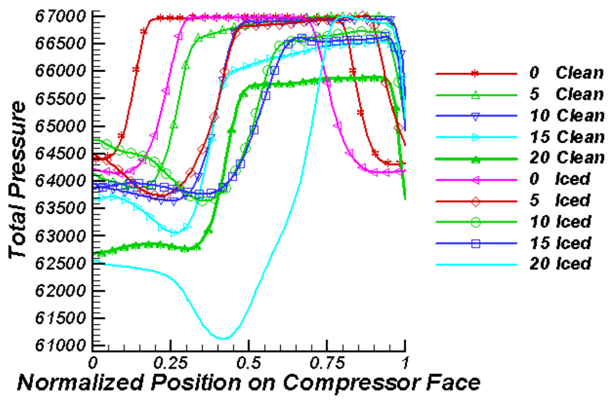

Fig. 7 Total pressure (Pa) variations across compressor face at different AOAs

The distortion increases by increasing AOA; this is more severe in icing cases. As mentioned before, intake behavior is dominated by the state of flow around the entry lips. The intake lip geometry is the key parameter in compressor face flow distortion, so when icing happens, the intake flow will be more complex due to separation in the region aft of prominent ice shapes, even for moderate AOAs, this results in more thrust loss and distortion values. Table I shows the icing effects on the intake distortion coefficient in different AOAs.

TABLE I
INTAKE DISTORTION COEFFICIENTS IN DIFFERENT ANGLES OF ATTACK

AOA (degree)	DC (%) Clean	DC (%) With Icing
0	4.033	4.324
5	4.726	4.990
10	5.021	5.145
15	5.327	5.603
20	5.421	8.498

As mentioned before, the pressure loss is translated directly to thrust loss, according to relation (2) and it is assumed that K is equal to 1.5. Table II shows the icing effects on the thrust loss in different AOAs. As it is clear, thrust loss increases due to icing, this is severe in high angles of attack.

TABLE II
INTAKE THRUST LOSS IN DIFFERENT ANGLES OF ATTACK

AOA (degree)	$\Delta X / X$ (%) Clean	$\Delta X / X$ (%) With Icing
0	1.497	2.544
5	1.848	2.664
10	2.679	3.531
15	3.670	4.166
20	5.285	6.742

In general, for inlet protection against icing the anti-icing protection system can be used, but de-icing systems are not particularly suitable since any ice shed from upstream inlet surfaces can subject the engine compressor or fan blades to serious damage upon impact. On the other hand, in some cases like some unmanned aerial vehicles, because of special considerations in mission like payload, launching weight and etc., use of anti-icing system is impossible or not preferred. In these cases it is necessary for a designer to calculate intake performance degradation due to icing includes thrust loss and flow distortion increase as a major aspect of intake design. At the end, the intake distortion accepted range depends on the distortion tolerance of the engine which is known by engine manufacturer.

V. CONCLUSION

In this paper, the icing effects on intake performance were investigated; in the light of the findings of this study it is clear that the icing cause lower pressure recovery and high flow distortion Quantities and this will be severe in high angles of attack. As a result, intake icing has persistent threat to intake performance and so inlet icing calculations base on the aircraft mission profile are strongly recommended in aircraft inlet design process particularly for small aircraft like unmanned aerial vehicles (UAVs). For future work, the following are recommended: extend the intake ice modeling and flow simulation and distortion analysis to 3D, train neural network using other ice/lip geometries to generalize the program based on further developed experimental data, use and study of more powerful and advanced neural network architectures to enhance ability to learn and predict nonlinear behavior of ice geometry more accurately, design and training a neural network to predict flow distortion using flight conditions and intake shape and angles of attack as inputs.

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