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The Airframe Digital Twin: Some Challenges to Realization

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A new structural modeling concept, the Airframe Digital Twin, for designing and maintaining airframes is proposed. The Airframe Digital Twin is a tail number specific computational model of an individual aircraft. It has the potential to improve the way U.S. Air Force aircraft are managed over their entire lifecycle by creating individualized structural management plans. The Airframe Digital Twin can provide configuration control for each aircraft in the inventory. Through computational simulations performed with an Airframe Digital Twin, it can serve as a virtual health sensor, and provide a forecast of future maintenance needs for an individual aircraft. The Airframe Digital Twin concept is considered possible because of advances in high performance computing. An essential part of the Airframe Digital Twin is the ability to reduce the uncertainty in the model with increasing service experience through Bayesian updating.

I. Introduction

IN this era of shrinking defense budgets and continuing operation of older aircraft, the U.S. Air Force needs to decrease maintenance costs while ensuring the continued airworthiness and availability of aircraft. Achieving this objective requires revolutionary changes in the way that aircraft are designed and maintained. A concept that creates just such a revolutionary change is the Airframe Digital Twin, or ADT.

An ADT is a cradle-to-grave model of an aircraft structure's ability to meet mission requirements. It is a submodel of an all encompassing Aircraft Digital Twin which would include submodels of the electronics, the flight controls, the propulsion system, and other subsystems. The ADT, as an ultra-realistic model of the as-built and maintained airframe, is explicitly tied to the materials and manufacturing specifications, controls, and process used to build and maintain the aircraft. It is a consistent model of an individual airframe by tail number that includes all variation and uncertainty in that aircraft.

While talked of as a single model, the ADT is really an integrated collection of submodels as illustrated in Figure 1. These submodels are currently used separately with limited sharing of information between them. The major differences between the ADT and the current structural modeling process are the degree of integration between the submodels, the level of fidelity of the submodels, and the quantification of uncertainty in all calculations. All the submodels use the same tail number specific structural definition. The dimensions of all details of the physical airframe, along with the measurement error, are recorded in the structural definition of the ADT. The states of all materials and any uncertainty are also tracked throughout the aircraft's life. Any repairs or modifications to the physical airframe during service are also captured in the ADT. All of the submodels contain the best available physics for the given discipline. The output from any submodel, for instance, temperature, stress, or strain fields, is readily accessible by any other submodel. The output of each of the submodels is not a single number, but a probability distribution over the range of possible outcomes based upon the uncertainty in the inputs. As experience with a particular tail number accumulates, the objective is to update the ADT for that tail number using various proven statistical methods to reduce the uncertainty in the submodels so that over time the ADT becomes more representative of the aircraft.

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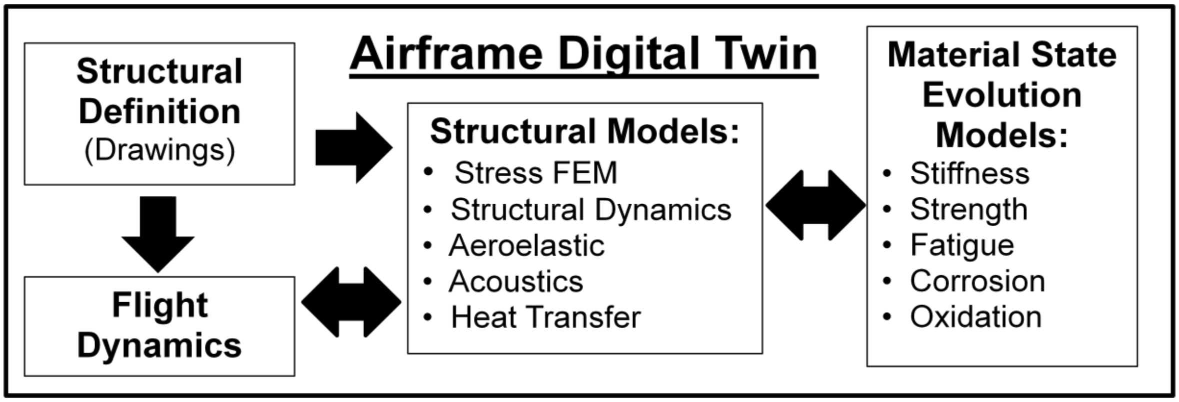

Figure 1. Elements of the Airframe Digital Twin

II. Why Develop an Airframe Digital Twin?

The shrinking defense budget and the increasing cost of the next generation of aircraft have resulted in fewer new aircraft being purchased. This means there will be fewer aircraft in the USAF inventory, and these aircraft will be kept in the inventory longer. These events have created a need for:

1. More efficient design and certification to reduce the acquisition cost;
2. Greater availability of aircraft; and
3. Decreased maintenance and support costs.

Specific goals that can help to satisfy these needs are:

1. Reducing the number of design changes after certification testing;
2. Minimizing the number and duration of certification tests;
3. Eliminating unanticipated cracking and failures; and
4. Minimizing the number and frequency of structural inspections;

With an ADT, a proposed design can be flown and tested virtually before any components are fabricated. Structural components that are unlikely to meet requirements can be redesigned before the first aircraft is assembled and tested. As our ability to develop and utilize an ADT improves, there should be fewer surprises during testing and fewer redesigns required after testing. Airworthiness certification tests then become a means to validate the ADT, instead of the design. Certification tests can be efficiently planned for model validation using design of experiments. This will reduce the amount of certification testing required.

After aircraft are fielded, the ADT for individual tail numbers can be flown virtually to reproduce the flight history and estimate the damage currently in an airframe. In addition, the ADT can be flown any number of missions into the future in order to forecast the development of damage in the aircraft and anticipate the maintenance needs of the airframe. As uncertainty in the ADT decreases over the service life, the ADT can be relied upon to set inspection intervals so as to eliminate frequently repeated inspections during which no damage is found.

A. Applying an Airframe Digital Twin

The ADT can be used throughout the life-cycle of a mission design series and of individual aircraft as illustrated in Figure 2. An overarching ADT (OADT) is created as the design of the aircraft model takes shape. The OADT contains the nominal design and designed in uncertainty, i.e., part tolerances, material property variation, etc. The probability of producing an individual aircraft that does not meet requirements can be determined with the OADT. Those design parameters which are most responsible for a failure to meet design requirements can be identified and the design modified prior to a single aircraft being built.

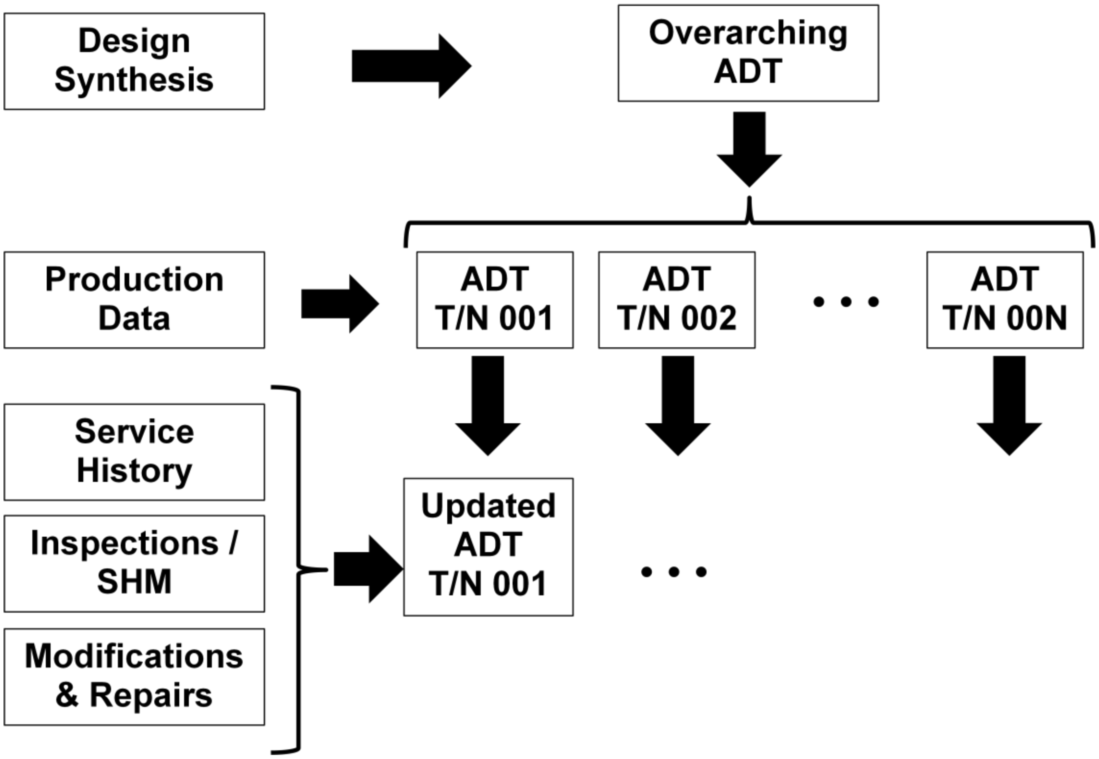

Figure 2. Hierarchy of Airframe Digital Twin Creation and Inputs at Each Level.

Tail number specific ADTs (TADT) are derived from the overarching ADT for each aircraft as it is built. Beginning with the pre-production and test aircraft, individual TADTs are created and refined by tests conduction on these aircraft. Because of the previous analyses with the OADT, there should be few, if any, surprises during the certification tests. The number of structural redesigns required after testing should decrease significantly. The certification tests become a means to gain confidence that the appropriate physics models of the proper fidelity are contained in the OADT. By the time an aircraft program enters Low Rate Initial Production, there should be confidence in the OADT. The data that is needed to create a TADT should be defined, and the process for capturing that data established.

The TADT for each production aircraft provides knowledge of the configuration for a specific aircraft. The loss of an F-15 in 2007 due to an out of tolerance longeron in the forward fuselage provides a good example of why this knowledge is important. The nonconforming longeron was accepted during assembly because the reduced fatigue life of the longeron as a result of the discrepancy was predicted to be longer than that of the wings. The paperwork on the discrepancy was filed and the aircraft was put into service. As the loads on the aircraft changed with changes in the aircraft's mission and the service life goal of the aircraft was extended, the life limit for the longeron was forgotten until it failed. That began a hunt through the entire fleet to find and repair any other out of spec longerons.

Had there been TADTs, the information about nonconforming longerons would not have been filed and forgotten. The discrepancy would have been evident in the individual TADTs. The life limit of that longeron, and the effect of changes in mission, would have been evident every time that another flight was simulated with the TADT. Identifying other aircraft containing the out of tolerance longerons would have been as simple as querying all the TADTs. Updating the TADT to include the repair of the upper longeron in the forward fuselage for those aircraft that were repaired would make it possible to track those aircraft going forward, too.

During the Operation and Support phase of the lifecycle, the TADTs would be used in the Individual Aircraft Tracking Program to track and anticipate the life limit of all structural parts to avoid catastrophic failures. Flight history data gathered for each aircraft as part of the Aircraft Structural Integrity Program can be used to "fly" each TADT virtually and simulate the internal loads and temperatures that the airframe experienced during each flight. The material state and damage evolution submodels in the TADT use the internal loads and temperatures to predict the condition of every component of the airframe. Findings from Non-destructive Inspections (NDI) or Structural Health Monitoring system queries are used to update the condition of airframe components which in turn reduces the uncertainty in the material state and damage evolution submodels in the TADT. Eventually, the uncertainty in predicting the damage state will become small enough that robust prognoses for each aircraft in the fleet can be developed by "flying" the TADTs out ahead of the fleet. Structural issues that would arise as the aircraft continue in service can be anticipated, repairs designed, and individual aircraft scheduled for repair. An efficient and robust individualized Force Structural Maintenance Plan can be implemented.

Coupling the forecasts from the TADTs with appropriate cost models will enable the economic service life of individual airframes to be determined. Retirement of individual aircraft can be scheduled based upon the reliability and cost of maintaining that specific aircraft, not just the reliability of other aircraft of a similar age. Declines in fleet strength can be anticipated in time to begin development and production of replacements.

The cost and effort of developing and maintaining a "fleet" of TADTs will be considerable. However, the price of the F-15 that was lost was approximately equivalent to 150 man-years of effort. And a fifth generation fighter costs even more. While the labor hours spent on inspecting the fleet is miniscule in comparison, the cost to national security of having all these aircraft unavailable could be incalculable in certain situations.

III. Some Technical Challenges in Developing the Airframe Digital Twin

A complete ADT will be a massive collection of computer models that will require high performance, parallel computing to use effectively. The flight-by-flight execution of each TADT will create an enormous database of simulations that must be interrogated to understand what the aircraft has experienced and forecast when it will need maintenance. The mechanics of performing these calculations and maintaining the database of results are not trivial. However, they are better addressed in other organizations focused on advanced simulation and high performance computing such as the U.S. Department of Energy[1] and the Department of Defense High Performance Computing Modernization Program. The discussion here will focus on the physics and engineering challenges of the ADT.

There are numerous physics and engineering challenges that need to be addressed for the ADT to become a reality. The physics and engineering modeling challenges can be grouped into the following broad categories:

1. Establishing the initial conditions for the ADT;
2. Applying correct flight loads to the ADT;
3. Selecting and integrating the submodels for the ADT; and
4. Managing and reducing the uncertainty in the ADT.

The details of these challenges are discussed in the following sections along with some developing technologies that have the potential to overcome them.

A. Initial Conditions

As with any mathematical model, it is important to start the ADT with the proper initial conditions. The actual aircraft that is built may differ from the design due to manufacturing errors such as misdrilled holes and repairs of these errors that will affect how that aircraft responds to loads. Without knowledge of these anomalies, the uncertainty in the simulations using the ADT could be large. In addition, information about how the detail parts were fabricated and processed can be used to reduce the uncertainty in material properties and part dimensions. The ADT needs to start at time equal to zero with the as-built configuration of the aircraft in order to minimize the uncertainty as much as possible. Building a model of the as-built aircraft is not especially difficult, except for carrying the uncertainty along, if the information about the as-built aircraft is available.

The Lockheed Martin's F-35 Digital Thread[2] is collecting much of the data needed to model the as-built condition of each aircraft. In the digital thread, the same 3D solid models from engineering design are used in manufacturing for programming numerically controlled machines for fabrication and coordinate measurement devices for inspections. Laser measurements are used to virtually mate parts in order to identify potential fit up problems prior to actually mating the parts. The Digital Thread, along with the F-35 production rates, have enabled Lockheed to used automated hole drilling in many places. Therefore, to within the accuracy of the production measurement systems, the dimensions of many of the detail parts and the location of many of the fastener holes are known during production. It becomes a matter of passing that information along to the ADT.

Besides the Digital Thread, Integrated Computational Materials Science and Engineering (ICMSE) has the potential to provide information about the material state and resulting properties as a consequence of the thermomechanical processes involved in fabricating the parts. With ICMSE, physics based computational models enable an analytical representation of a material from processing, through microstructure optimization, to the prediction of physical and mechanical properties in a form suitable for integration into structural models.

B. Continuous Flight Loads

The power of the ADT comes from simulating the continuous time history of a flight. An important element of the simulation is to apply loads to the ADT that faithfully reproduce the loads on the airframe. These are generated with a flight dynamics model that solves the nonlinear six degree-of-freedom equations of motion considering the aerodynamics, control inputs, propulsion, and inertia loads. Current flight dynamics models use an aerodynamic database that, in the early stages of design, is developed from computational fluid dynamics analysis or wind tunnel of a rigid aircraft model. This database accounts for static aeroelastic effects, i.e., the magnitude of deflections, by including a flexibility factor. However, current flight dynamics models do not model dynamic aeroelastic response, i.e., transient vibratory loads, which may contribute to the fatigue damage. This lack of fidelity in the current approach to generating flight loads seriously limits the usefulness of the ADT.

Recent work by Chen et al.[3] overcomes this limitation by coupling a flight dynamics model and an aeroelastic solver. The aeroelastic solver uses the airframe state and control surface deflections from the flight dynamics model to calculate incremental forces and moments, and the structural oscillation at a sensor location, e.g., accelerometer. The incremental forces and moments are added to the aerodynamic forces and moments found from the aerodynamic database. The structural oscillation is added to the rigid body motion measured by sensors on the aircraft. This approach has been demonstrated for a flight dynamics model and a linear aeroelastic solver using flight test data from the F/A-18 Active Aeroelastic Wing program. AFRL-led work to validate a nonlinear aeroelastic solver coupled to a flight dynamics model is nearing completion[4]. The nonlinear aeroelastic solver should provide a better representation of the loads on the aircraft.

The higher fidelity loads that result from the combination of a flight dynamics model and an aeroelastic solver are beneficial not only for the design of the aircraft, but also for tracking the development of fatigue damage in service. The history of flight events is typically recorded using a vertical accelerometer that records N_z levels, or a flight data recorder that records a number of flight parameters from the flight control systems. A percentage of the fleet, a minimum of 20% for the U.S. Air Force, will have strain gages at selected locations in the airframe that provide load histories at those locations. For situations where strain gage data is not available, the flight dynamics model is used to convert these histories into external loads on the aircraft from which internal loads are subsequently derived. When just the flight dynamics model is used, only the static response of the airframe is determined. Combining an aeroelastic solver with the flight dynamics model enables the vibration of the airframe as it is put through a maneuver to be determined. These vibrations can have a significant effect on fatigue damage depending upon their amplitude. Thus, it is important that the dynamic aeroelastic response be captured in the ADT.

C. Selecting and Integrating the Submodels

The heart of the ADT is the structural models that describe how the airframe responds to static and dynamic loads, and heating. As mentioned previously, there is a collection of several finite element models (FEM): one for determining the deformation of the structure, one for determining the dynamic response of the airframe, and if necessary, one for determining the temperature fields. All three of these FEMs use the same geometry, but different material properties are of interest and different discretizations may be needed. Thus, the FEMs must be solved individually and the results shared between them.

Some commercial FEM codes allow such multi-physics analyses to be performed. These codes perform well for problems that can be addressed by passing results in only one direction, for example, where the temperatures in the structure affect the stresses, but not vice versa. However, this approach is a simplified model of the actual physics that may not be adequate for some situations like exhaust-washed panels where the expansion due to the temperature increase causes the panel to deform into the exhaust stream more, thereby exposing the panel to higher temperatures in the core of the exhaust stream. In this situation, two-way coupling between the different FEMs is necessary. Procedures for performing two-way coupled analyses have been investigated by Jaiman et al.[5] and Culler et al.[6].

A FEM of an entire aircraft is usually very simple consisting of rods, beams, and panel elements. Individual components are not faithfully reproduced. Joints between components, which are the origins of much of the fatigue cracking in an airframe, are not modeled at all. An effective ADT will require the ability to access higher fidelity structural representations for some parts of the FEM. Additional physics will be required in these locations as well. For instance, friction and contact between components must be considered when modeling a joint. However, modeling the contact and friction between two components clamped together in a mechanically fastened joint is not particularly well developed[7-9].

In addition to these FEMs, submodels for the material state evolution, e.g., fatigue cracking, is needed. Fatigue cracking is the only damage mechanism model in the current paradigm. The fatigue model is invoked on an ad hoc basis for locations chosen by engineers based upon some criteria that have been developed based upon experience and judgment. The stress and strain field for a given location is extracted from the deformation FEM and applied to an idealized model of the local geometry. The deformation FEM is not updated to include any cracking predicted in the structure. Thus, the possibility of load redistribution within the airframe due to changes in component compliances is not currently considered.

With an ADT, the ad hoc identification of locations that are prone to fatigue or other types of damage by engineers goes against the intent of the ADT. The goal is for the ADT to replicate what is happening in the physical aircraft and automatically bring locations with developing damage to the attention of the engineers. Doing this will require either applying damage models to every element in the ADT, or the development of a schema for determining those locations most likely to develop a particular type of damage. Just such a hierarchical "search and simulate" strategy for forecasting when and where fatigue cracks will form was developed by Embry et al.[10] in a Damage and Durability Simulator, DDSim. There are three main levels to the hierarchy in DDSim. Level I is a reduced order, probabilistic, low fidelity life prediction that is used to perform an initial screening of all the possible cracking locations in a structure. The Level I analysis is designed to be fast, conservative and used in Monte Carlo simulation so that the locations where higher level analyses are needed can be identified. The Level II analysis refines the estimate of the time required to grow a microstructurally large crack to failure, while the Level III analysis improves the fidelity for the estimate of the time for a microstructurally small crack to become a microstructurally large crack. If the results of the Level I analysis are adequate, the Level II and III analyses do not need to be performed.

The Level II analysis begins at the lower size limit for a microstructurally large crack by inserting the crack into the FEM at the prescribed location using FRANC3D[11]. The stress intensity factor is calculated for several sizes as the crack is automatically "grown" from this size to the critical crack size by FRANC3D. Integrating these stress intensity factors over time yields the number of flight hours to failure for a microstructurally large crack. This is a deterministic number.

Level III analysis performs coupled multiscale analyses to provide a more accurate probability distribution of the time taken to grow a microstructurally small crack to a microstructurally large crack. Multiple detailed FEMs of the possible material microstructure at the location are created for Monte Carlo simulations. These local microstructure FEMs can be executed simultaneously in a parallel or a cloud computing environment since they are independent of each other. One of the key features of the Level III analysis is the flow of information between the length scales: the effect of boundary conditions applied to the structural FEM flow down to the microstructure model, and microstructural response propagates back up to the structural FEM.

D. Managing and Reducing Uncertainty

Over time the uncertainty in the ADT can accumulate to unacceptable levels unless there is a concerted effort to manage and reduce uncertainty. The goal is for the ADT to become the twin of the physical aircraft over time by reducing uncertainty. Every flight is another "experiment" with the aircraft providing information from on-board sensors, nondestructive inspections, and post-flight visual inspections that can be used to refine and update the ADT. It is important that a formal process be established as part of the ADT to utilize this information to reduce the difference between the model and the actual aircraft.

The traditional approach towards bringing a model into agreement with reality is to "calibrate" the model to observed data. A structural FEM might be calibrated by adjusting the values of the material properties (e.g., Young's modulus, Poisson's ratio or the density) in the model to make the model outputs match observed data as closely as possible. Usually, a model is used to predict response over some range of input variables such as loads and temperatures. Since the model is a simplification of the actual structure and does not capture all that is happening in the physical structure, the material properties are chosen to provide a good fit to data over the range of input variables, thereby implicitly accommodating some of the uncertainties in the model and observation errors. This approach treats the post-calibration values of the material properties as if they are now known when in reality they are only estimated. The remaining uncertainty about the values of the material properties should be recognized in subsequent model predictions.

A better approach for "calibrating" a computer model such as the ADT is the Bayesian model calibration procedure proposed by Kennedy and O'Hagan[12]. Bayesian model calibration quantifies a model's predictive ability, while accounting for many sources of uncertainty and calibrating uncertain inputs. The unknown model inputs that are being "calibrated" are represented as a parameter vector, $\boldsymbol{\theta} = (\theta_1, \theta_2, \ldots, \theta_m)$. Any knowledge that exists about $\boldsymbol{\theta}$ is used to construct probability distributions for each θ_i that express the uncertainty about θ_i. In the language of Bayes Theorem, these are known as prior distributions. Other important sources of uncertainty that come with using a computer model are also considered in the calibration, such as measurement error, code fidelity (2D versus 3D), mesh density, convergence criteria, etc. Measurements of the physical phenomena being modeled are used to derive updated, or posterior, distributions for $\boldsymbol{\theta}$ using Bayes Theorem. The uncertainty remaining in $\boldsymbol{\theta}$ is accounted for in the posterior distribution and propagated through subsequent predictions. If another set of physical data can be collected, as with aircraft service history data, for instance, another iteration of model calibration can be performed refining the probability distribution for θ even further. With repeated Bayesian model calibrations, the model becomes more of a "digital twin" to the physical process.

Calibrating the ADT as a single model based upon the prediction response of the entire aircraft during a flight may not be manageable. The ADT is a collection of interacting computer models. Therefore, the use of a Bayesian network may make uncertainty management more tractable. A Bayesian network is a probabilistic model in the form of directed acyclic graphs consisting of directed edges between nodes and a table of conditional probabilities of each variable on all its parents. The nodes represent probability distributions of the variables in a model. An arrow, or edge between two nodes indicates conditional dependence between the variables represented by the nodes. The node at the tail of the arrow is the parent node. The node at the head of the arrow is the child node. The Bayesian network expresses the probabilistic causal dependence between the variables and the flow of information within a model, as well as into other models[13]. A simplistic Bayesian network for the failure of a generic structural component is shown in Figure 3. The advantage of a Bayesian network is that it enables the reassessment of the probabilities of all the uncertain model inputs using Bayes theorem when new data becomes available for any node in the network.

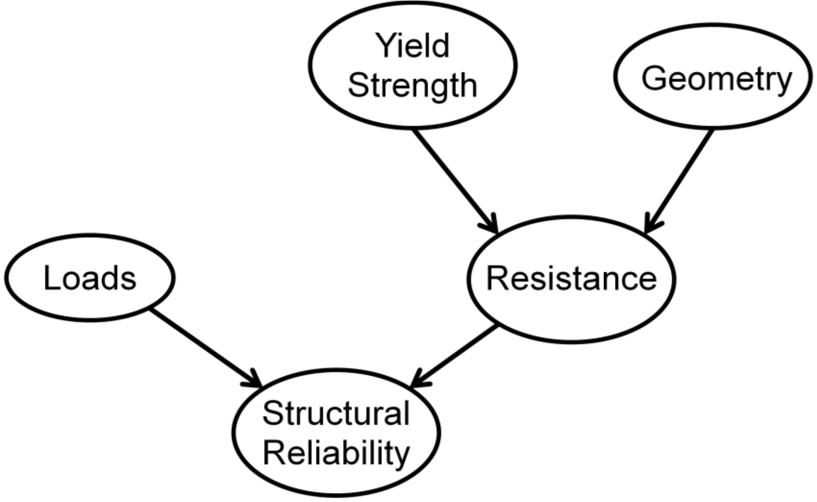

Figure 3. Generic Bayesian Network for Structural Reliability

IV. Summary

A new structural modeling concept, the Airframe Digital Twin, for designing and maintaining airframe was proposed. The Airframe Digital Twin has potential to improve the way U.S. Air Force aircraft are managed over their entire lifecycle by creating a tail number specific computational model for each aircraft. The ADT can provide configuration control for each aircraft in the fleet. Through computational simulations performed with an ADT, it can serve as a virtual health sensor, and provide a forecast of future maintenance needs for an individual aircraft. The ADT is considered possible because of advances in high performance computing. Essential to the success of the ADT is the ability to reduce the uncertainty in the model with increasing service experience through Bayesian updating.

Acknowledgement

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