JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 31, No. 6, November–December 1994

TRANSYS—Space Transportation System Preliminary Design Software

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TRANSYS (TRANsportation SYStem) is a multidisciplinary modularly structured, interactive software system for preliminary design, analysis, and evaluation for a broad range of future space transportation systems. Modules being integrated in the present version, TRANSYS 1.1, are aerodynamics, propulsion, trajectory analysis, geometry, mass estimation, and cost and economics. Each module consists of several application programs and databases. To provide the necessary high degree of flexibility, each module can be applied individually. In the scope of an iterative vehicle design and optimization process, a group of selectable modules has to be executed successively. The data management and the interaction between the individual modules is controlled by an engineering database system. Expendable and reusable launch vehicles with rocket propulsion as well as orbital transfer vehicles can be designed, analyzed, or evaluated with the present version, TRANSYS 1.1.

Introduction

THE software system TRANSYS (TRANsportation SYStem) is being developed to support conceptual and preliminary design studies, parametric studies, and comparative evaluations for a broad range of future space transportation systems, including Earth-to-orbit (EOV) transportation systems, orbital transfer vehicles (OTV), and planetary transport vehicles (PTV).

First considerations and conceptions of TRANSYS date from 1986; the development started at the end of 1989. Over the first $1\frac{1}{2}$ years, TRANSYS was developed on a mainframe computer. In mid-1991 it was transferred onto workstations and merged with a menu-driven user interface that is based on the OSF motif. TRANSYS version 1.0[1] was finished in October 1991, and since April 1992 TRANSYS version 1.1 has been available.

TRANSYS is a multidisciplinary system, comprising engineering software tools for aerodynamics, aerothermodynamics, propulsion, flight mechanics, structure mechanics, guidance and control, etc., as well as operations and environmental impacts of space transportation systems (see Fig. 1).

At present, the main applications of TRANSYS deal with derivatives and post Ariane 5/Hermes vehicles as well as vehicles beyond, including evolutionary concepts and novel systems, e.g., fully reusable winged single-stage and two-stage launchers and ballistic single-stage systems like the Delta Clipper concept. Further, rocket-powered orbital transfer vehicles (OTV) with and without aerobraking at the Earth's atmosphere are being studied at present. Orbital transfer vehicles with unconventional propulsion systems (e.g., nuclear-thermal propulsion) will also be investigated in the near future. Studies with respect to planetary transportation vehicles will follow later on.

TRANSYS Structure

TRANSYS is modularly structured, with each module consisting of various computer codes and databases. To guarantee a high degree of flexibility, each module can be used as a stand-alone package (e.g., for performing aerodynamic or trajectory analyses) as well as a module in an iterative computational chain for designing and optimizing vehicles.

The data management, as well as the monitoring of computational chains and loops, is based on the engineering database system RSYST,[2] which is specifically designed to integrate large engineering and science software. RSYST, of course, allows the generating of computational chains and loops of programs from one single TRANSYS module or from different modules. This is useful not only for vehicle design iterations but also for parametric studies.

Performance Capabilities of TRANSYS 1.1

With the present version, TRANSYS 1.1, rocket-powered Earth-to-orbit vehicles as well as rocket-powered orbital transfer vehicles can be designed, analyzed, or evaluated.

For the Earth-to-orbit vehicles, the performance capability of TRANSYS ranges from multistage expendables to partial or fully reusable single- or two-staged vehicles. The vehicles may be winged or ballistic and launched vertically or horizontally. Further, air-launched vehicles can be investigated. Altogether, Earth-to-orbit vehicles may be composed of a maximum of three stages and two different booster types. Tandem staging, as well as parallel staging, is allowed, and for the parallel staged vehicles, propellant transfer can also be modeled.

For orbital transfer vehicles, the performance capability of TRANSYS 1.1 is composed of rocket-powered conventional systems with a maximum of two stages and aeroassisted orbital transfer vehicles (AOTV). The AOTV configurations in TRANSYS 1.1 are restricted to blunt and slender re-entry bodies.

For the analyses and evaluations with TRANSYS 1.1, the modules for aerodynamics, propulsion, trajectory analysis, geometry, mass estimation, and cost and economics (see Fig. 1) can be applied. Furthermore, the structural analysis and thermal analysis modules can be applied for estimating tank and landing gear masses and calculating unsteady temperature distributions for different body shapes. However, these two modules are not yet integrated into a vehicle design process with TRANSYS 1.1.

The performance capabilities of these modules are described in detail in the following sections.

Geometry

For the geometric modeling of space transportation systems in TRANSYS, the program GEOMOD (GEOmetric MODeling) has been developed.[3] The approach in GEOMOD is to model the outer contour of a single system element first. Next, the internal structure (i.e. arrangement of tanks, etc.) of this system element is geometrically modeled. The geometric models of mated configurations are achieved by composing the appropriate system elements. In GEOMOD several standard configurations for ballistic systems (Fig. 2), winged systems (Fig. 3), OTVs, and AOTVs are stored. These standard configurations are parameterized to guarantee a high degree of flexibility for the applications.

Received Jan. 29, 1992; presented as Paper 92-1193 at the AIAA Aerospace Design Conference, Irvine, CA, Feb. 3–6, 1992; revision received Jan. 4, 1993; accepted for publication Jan. 4, 1993.

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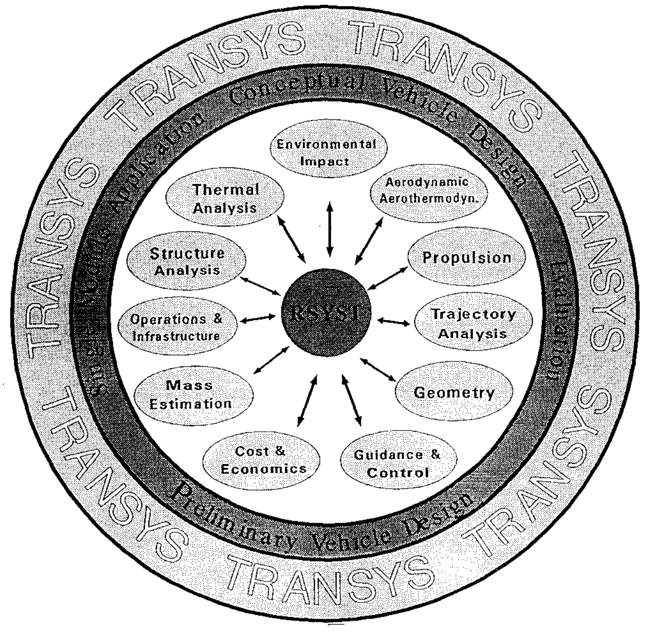

Fig. 1 Version TRANSYS 2.0.

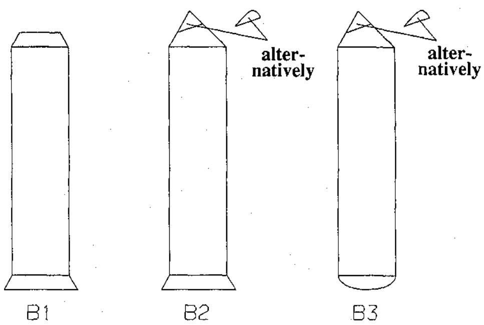

Fig. 2 Ballistic configurations in TRANSYS 1.1.

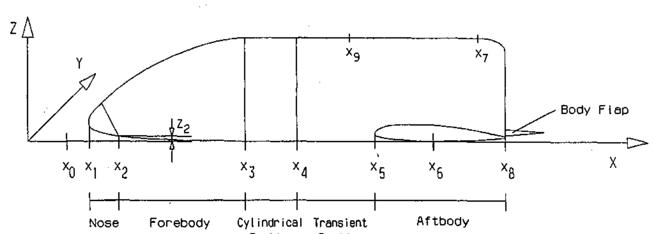

Fig. 3 Parameterized winged configuration.

For the winged configuration in Fig. 3, the geometric design of the outer contour shall be described briefly. Given wing design data such as leading-edge and trailing-edge angles, aspect ratio, ratio of exposed to theoretical area, span, etc., the theoretical wing area is calculated as well as the exposed area, structural and exposed span, exposed root chord, and other parameters. The appropriate procedure is applied for winglets and vertical tail, respectively.

The body is subdivided into five sections: nose, forebody, cylindrical section, transient section, and aftbody. Each section is marked by two x_i. The x_i have to be given in percentage of the body length. For the configuration shown in Fig. 3, x_1 equals 0 and x_8 equals 1. The body length must be given in meters, x_5 and x_6 result from the wing design, whereas the other x_i are input parameters. The body width results from the given ratio of exposed to theoretical wing area. With the given ratio of body height to width and a few other parameters, the outer contour of the system can be determined completely and subsequently can be visualized with a computer-aided design/computer-aided engineering (CAD/CAE) system.

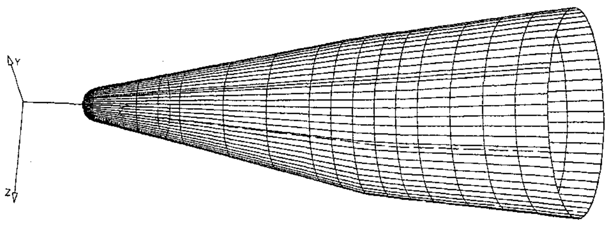

Fig. 4 Surface grid of a biconic AOTV.

Aerodynamics

For the different tasks of this module, the program package DADY (Design AeroDYnamics)[4] has been developed. One task of this module is to provide the necessary aerodynamic data for performing the trajectory analysis. A second task is to support the minimization of wing mass of winged vehicles. Moreover, this module includes a database with aerodynamic force and moment data of existing vehicles and of relevant vehicles, that have been designed with TRANSYS.

The aerodynamic coefficients can be provided for single system elements (e.g., stages, AOTVs) and for mated flight configurations. The calculation of subsonic force and moment data is performed by a program that is based on the singularity method. The hypersonic force and moment data are calculated by a program that is based on the Newtonian/Prandtl-Meyer method.

In this module, of course, the generation of surface grids, which are required for the aforementioned computer codes, are performed as well. The number of cross sections per vehicle section can be chosen arbitrarily, but the number and relative position of points per cross section are fixed. An example for the grid generation is given in Fig. 4.

The wing design program in DADY is used to size and shape a wing to satisfy hypersonic trim and/or landing requirements for a minimum wing mass. At present, only the hypersonic aerodynamic program is combined with an optimization algorithm. The subsonic aerodynamic program requires too much CPU time, and therefore it is unacceptable to integrate it with the optimization procedure. Thus, the resulting wing design from the optimization is a real optimum only if the landing conditions are dominated by the hypersonic trim requirements. If landing conditions dominate, the optimum wing design has to be found by parametric variations with the subsonic aerodynamic program. The wing parameters included in the optimization process are span, taper ratio, and leading- and trailing-edge angles.

Propulsion

The propulsion module is composed of the computer code ST (Systemanalyse Traeger)[5] for the calculation of performance data and masses of liquid rocket engines. The code ST has been developed over the past 10 years. Various engine cycles with different propellant combinations and various mixture ratios can be calculated using ST. The code ST has been adapted for TRANSYS.[6] After selecting the engine type, number of engines, and thrust-to-weight ratio at engine ignition, the user is required to input only mixture ratio, chamber pressure, expansion ratio, and sea level or vacuum thrust. Then, among other things, specific impulse, engine mass, and geometric properties are computed.

Furthermore, the propulsion module contains small databases for reaction control systems (RCS) and orbital maneuvering systems (OMS) engines and for air-breathing engines.

Mass Estimation

For the vehicle mass and size analyses in TRANSYS, the program PEMDIT (Program to Estimate Masses and DImensions of space Transportation system) is applied. Originally, PEMDIT was developed to analyze exclusively reusable winged space transportation systems.[7] The new version, PEMDIT 2.0,[3] has been extended for analyzing conventional ballistic systems and a few configurations of OTVs and AOTVs.

The mass estimation in PEMDIT is based on statistical-analytical and empirical methods. It is an iterative process because many components of the vehicle mass are a function of vehicle mass, and vehicle mass is the summation of all individual component masses. Furthermore, some component masses depend on geometric parameters (e.g., wing, body, etc.).

Trajectory Analysis

For the trajectory analyses in TRANSYS the computer code TOSI (Trajectory Optimization and SImulation)[8] has been developed. TOSI is a generalized three-DOF tool for the simulation and optimization of trajectories. Because of the many vehicle configurations in TRANSYS and different missions, TOSI has been split into three subcodes: TOSI-L for calculating ascent trajectories, TOSI-R for calculating flyback and re-entry trajectories, and TOSI-O for the calculation of orbital transfer trajectories with and without aerobraking/aeromaneuvering at the Earth's atmosphere.[9]

Cost and Economics

In this module several versions of the TRANSCOST model have been implemented.[10,11] With the TRANSCOST model, estimations of development, production, operation, and life cycle cost for a given mission model can be made. Furthermore, a cost model taking system reliability into account is implemented in this module.

Structural Analysis

This module, not yet an integral part of TRANSYS, is composed of programs for the mass calculation of structural components with load analysis methods. With these programs, mass models can be developed for each structural component by parametric variations. The mass models will then be integrated in PEMDIT and replace the appropriate empirical models. This yields a considerable improvement of mass estimations in TRANSYS because different materials and structural designs are considered. At present codes for the mass calculations of integral and nonintegral propellant tanks with different geometries,[12] wings, and landing gears are available.

Thermal Analysis

This module is also not an integral part of TRANSYS at present. The computer code FAZIT (Fortranprogramm zur Analyse Zweidimensionaler Instationärer Temperaturfelder)[13] has been developed as a first step for the thermal analyses in TRANSYS. FAZIT is a code for calculating unsteady two-dimensional temperature distributions for different body shapes. Furthermore, the thermal analysis module contains a small thermal protection system (TPS) database.

Typical Design Process with TRANSYS 1.1

A typical design approach with TRANSYS 1.1 is shown in Fig. 5 for a winged upper stage. As can be seen in this figure, the single codes are applied sequentially in the scope of the iterative design and optimization process. With TRANSYS 1.1 the design payload masses up and down and the payload bay dimensions (diameter and length) have to be given. To meet this requirement, the vehicle's launch mass is varied until the resulting payload masses correspond to the design values. Starting the iteration loop, estimates of launch mass and empty mass ratio are required.

After definition of vehicle type (EOV in this example), the vehicle name and the number of the version, at first the outer contour and internal structure have to be selected. The next step is the determination and specification (e.g., thrust-to-weight ratio at engine ignition) of the propulsion concepts for the main engines, RCS, and OMS. The performance data, masses, and geometric properties of these engines are then calculated or given by a database (propulsion module).

With appropriate codes from the geometry module, the geometric properties of the vehicle's outer contour and internal structure are calculated. The main results here are the dimensions of the wing (theoretical area, exposed area, exposed and structural span, etc.) and the winglets, the dimensions of the body (width, height, surface, etc.), the dimensions of the entire system (length, width, height, planform area, etc.), and the dimensions of the tanks (length, width, height, volume, and surface).

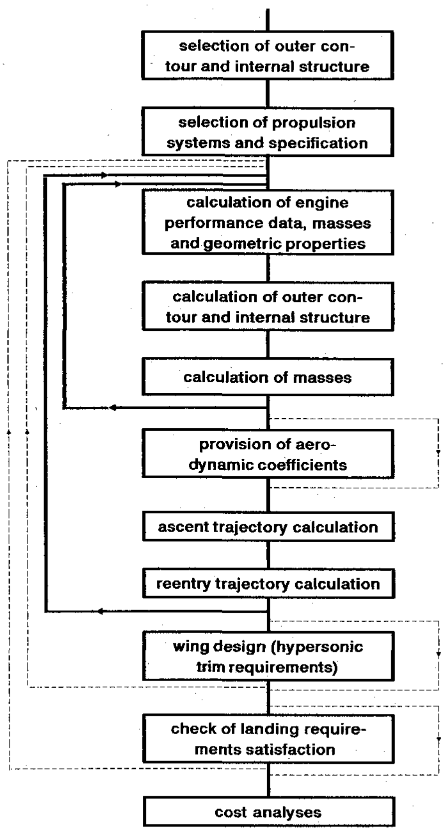

Fig. 5 Typical design process for a winged upper stage with TRANSYS 1.1.

After the calculations are finished, the vehicle can be visualized with a CAD/CAE system. If the outer contour of the vehicle does not satisfy the user, appropriate parameters can be varied.

Results of the mass analysis, which are performed by using PEMDIT, are the masses of all components (tanks, wing, thermal protection system, etc.), the vehicle masses (dry mass, empty mass, landing mass, etc.), and the payload masses up and down.

To obtain the prescribed payload masses another loop has to be run with a new estimate for launch mass, starting with the recalculation of engine performance data and masses (see Fig. 5). This has to be done because the given ratio of thrust to weight at engine ignition is held constant. The empty mass ratio is held constant in this case as well. The loop is iterated until the differences in payload masses remain below a given limit between two iterations. After this loop is finished, the vehicle can be visualized again.

The next step is the provision of the aerodynamic coefficients, which are required for the trajectory analyses (lift and drag coefficients). Then, the ascent and re-entry trajectory calculations are performed. With the resulting ascent propellant mass and, consequently, a new value for the empty mass ratio, another iteration loop can be started (see Fig. 5). The iterations are repeated until the differences for a few significant parameters remain below given limits or until a given number of iteration loops is exceeded.

A minimization of the wing mass taking into account hypersonic trim requirements is performed next. Before this process is started however, a surface grid is automatically generated for the vehicle. To check or manipulate this surface grid, the user visualizes it with the CAD/CAE system. After the check, the wing mass minimization process is continued.

Finally, the satisfaction of prescribed landing conditions for the vehicle is checked. If the landing conditions are not satisfied, the optimum wing design has to be found by parametric variations using the subsonic aerodynamic code.

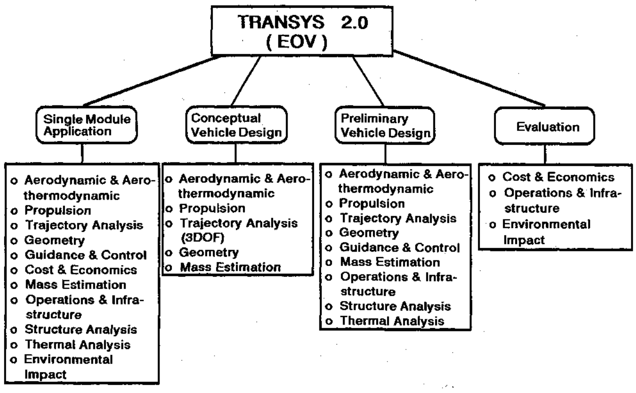

Fig. 6 Application alternatives of version TRANSYS 2.0.

After completion of the vehicle design process, the cost analyses and economic considerations can be performed for a mission model to be assumed.

TRANSYS 2.0

The version TRANSYS 2.0 was defined as the main goal for the ongoing development of the program system TRANSYS. This version includes the following modules (see Fig. 1): aerodynamics and aerothermodynamics, propulsion, trajectory analysis, geometry, guidance and control, cost and economics, mass estimations, operations and infrastructure, structure analysis, thermal analysis, and environmental impact.

In contrast to the present version, TRANSYS 2.0 shall offer the user four alternatives of applications: single module application, conceptual vehicle design, preliminary vehicle design, and evaluation.

The allocation of modules to the appropriate application alternatives is shown in Fig. 6 for Earth-to-orbit launch vehicles. In this context, the section Fig. 6 titled of "Conceptual Vehicle Design" mainly corresponds to TRANSYS version 1.1.

The performance capability of TRANSYS is stepwise extended to allow investigations of air-breathing launch vehicles, control configured winged vehicles (CCV), reusable ballistic vehicles, orbital transfer vehicles with unconventional propulsion systems (e.g., electric propulsion, nuclear-thermal propulsion), and planetary transport vehicles with TRANSYS 2.0 at latest.

Furthermore, the environmental impact of launch vehicles will be taken into account as evaluation and optimization criteria in future. With that, not only effects produced by exhaust gases during ascent and eventually flyback are considered by the environmental impact module, but also effects produced by friction, surface interaction, and shock waves during re-entry. Moreover, future space transportation systems have to be strongly designed with respect to operations. This requires the availability of appropriate operation and cost estimation tools in the early vehicle design process.

At present a CAD/CAE system is fully integrated in TRANSYS. As a "subprogram," the CAD/CAE system undertakes the main tasks of the geometry module and is also applicable to the aerodynamics and aerothermodynamics, mass estimation, structural analysis, and thermal analysis modules.

For realizing TRANSYS 2.0, the following extensions have been started and/or planned.

Aerodynamics and Aerothermodynamics: Integration of results of Euler calculations; performance of stability analysis; development of codes for preliminary estimation of temperature distributions on the vehicle surface during ascent, flyback, and re-entry and during atmospheric flight of AOTVs.

Propulsion: Implementation of new rocket engine cycles; implementation of a database of air breathing engines; development of computer codes for performance calculations of unconventional propulsion systems (e.g., nuclear-thermal engines for OTVs).

Trajectory Analysis: Development of enhanced three-DOF and six-DOF simulation codes; development of codes for calculating transfer trajectories between Earth, moon, and Mars.

Geometry: Increasing the configuration variety of the present types of vehicles (outer contour, internal structure); integration of new vehicle types, e.g., winged systems with canards, lifting bodies, fully reusable ballistic systems, and transfer vehicles with unconventional propulsion systems.

Mass Estimation: Improvement of mass models by considering different structural designs and materials; introduction of additionally required components (e.g., canards).

Structure Analysis: Development of finite element models for designing and calculating the masses of main components (e.g., body, wing, thrust structure, etc.); development of codes for the analytical calculation of subsystem masses; generation of mass models for structure components by parameter variations, and integration of these models into the mass estimation module.

Guidance and Control: Implementation of guidance laws for ascent, flyback, and re-entry and for trajectories with aerobraking/aeromaneuvering; integration of control laws for ballistic and winged systems as well as for AOTVs.

Operations and Infrastructure: Integration of databases with terrestrial and orbital infrastructure elements (e.g., launch and landing sites); development of empirical models for preliminary design of infrastructure elements; development of methods and models for evaluation of operations of space transportation systems.

Cost and Economics: Improvement of existing cost estimation relationships with respect to operations cost.

Environmental Impact: Development of models and criteria to evaluate the environmental impact of space transportation systems.

Conclusions

The software system TRANSYS provides a foundation for conceptual and preliminary design, analysis, and evaluation of space transportation systems. Earth-to-orbit vehicles, orbital transfer vehicles, and, in the near future, planetary transportation systems can be investigated with TRANSYS. Because of its open, modular structure, vehicle design analyses, as well as parametric studies, can be performed easily.

Up until now, the development of TRANSYS has been in the foreground. Now continued development and applications of TRANSYS are equally important. For Earth-to-orbit vehicles, the main applications of TRANSYS involve the evolution of ARIANE 5 to a launch vehicle family and post ARIANE 5/HERMES launchers. Future launch vehicles, including supersonic-staged horizontal takeoff vehicles as well as fully reusable ballistic single-stage launchers, are also investigated. For orbital transfer vehicles, comparative evaluations of different AOTV concepts will be performed.

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