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Comparison Study of Gear Dynamic Computer Programs at NASA Lewis Research Center

James J. Zakrajesek

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Comparison Study of Gear Dynamic Computer Programs at NASA Lewis Research Center

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Summary

A comparison study was performed on four gear dynamic analysis computer programs developed under NASA/Army sponsorship. These programs are GRDYNMULT (a multimesh program applicable to a number of epicyclic systems), TELSGE (a single mesh program), PGT (a multimesh program applicable to a planetary system with three planets), and DANST (a single mesh program). The capabilities and features, input and output options, and technical aspects of the programs were reviewed and compared. Results are presented in a concise tabular form. Parametric studies of the program models were performed to investigate the predicted results of the programs as input parameters such as speed, torque, and mesh damping were varied.

In general, the program models predicted similar dynamic load and stress levels as operating conditions were varied. Flash temperature predictions from programs GRDYNMULT and TELSGE indicated similar trends; however, actual values were not in close agreement. The program GRDYNMULT was found to be the most versatile in system size, type, and analysis capabilities. The programs DANST, TELSGE, and PGT are more specialized for specific systems; however, in specific areas they provide a more detailed treatment than GRDYNMULT.

Introduction

Since the late 19th century, gearing has become the simplest and most efficient means of transmitting mechanical power. Gears can be found in almost every application involving mechanical power transfer, and are usually considered a critical link in the power chain of that system. Because of this, gear designers are highly concerned with gear life and reliability. In industrial applications this concern is alleviated to some degree by over designing the gears, sacrificing cost, and increasing weight. However, in aerospace applications, where weight and size are premiums, gear systems are usually designed close to their projected limits. As a result, a number of computer programs have been developed in an effort to predict parameters such as dynamic load, surface damage, and surface temperature, that are integral factors in various gear failure modes. Several of these programs have been developed through NASA Lewis Research Center under NASA/Army sponsorship.

Of all the gear dynamic programs developed at NASA, the programs TELSGE, GRDYNMULT, PGT, and DANST are the most widely used. TELSGE was developed to study the effects of input parameters such as speed, load, and lubricant oil type on predicted quantities such as dynamic tooth mesh loads, surface temperatures, and lubricant film thickness in a single mesh system (refs. 1 and 2). Gear failure modes such as scoring, pitting, and lubrication failures are directly related to these predicted parameters. GRDYNMULT was developed to predict parameters such as tooth mesh loads, tooth stresses, and surface damage factors under a variety of input conditions for a single mesh, or multiple mesh epicyclic system (refs. 3 to 5). These parameters have a direct effect on failure modes such as tooth breakage, scoring, and pitting. The program PGT was developed for the dynamic analysis of a three planet planetary gear system under a variety of input conditions (ref. 6). The magnitude of the dynamic mesh load output from PGT indirectly influences the probability of tooth failure by breakage. The program DANST was developed to study the effects of input parameters such as tooth profile modifications and external shaft and mass magnitudes on predicted dynamic loads and stresses of a single mesh system (refs. 7 to 9). The tooth root stress parameter predicted is a critical factor in determining gear failure through tooth breakage.

The purpose of this study is to provide a comprehensive guide on the capabilities and nature of results obtainable from the four gear dynamic programs introduced above, and to provide some program verifications through direct comparisons. The report is divided into two main sections. The first section reviews the capabilities, input and output options, and technical aspects of the programs studied, and presents the results in a concise tabular form. The second section reviews comparison runs that were performed to compare the results obtained from each program using common input models and parameters. Finally, some concluding remarks are presented which generalize the results of the total comparison study.

Program Features and Models

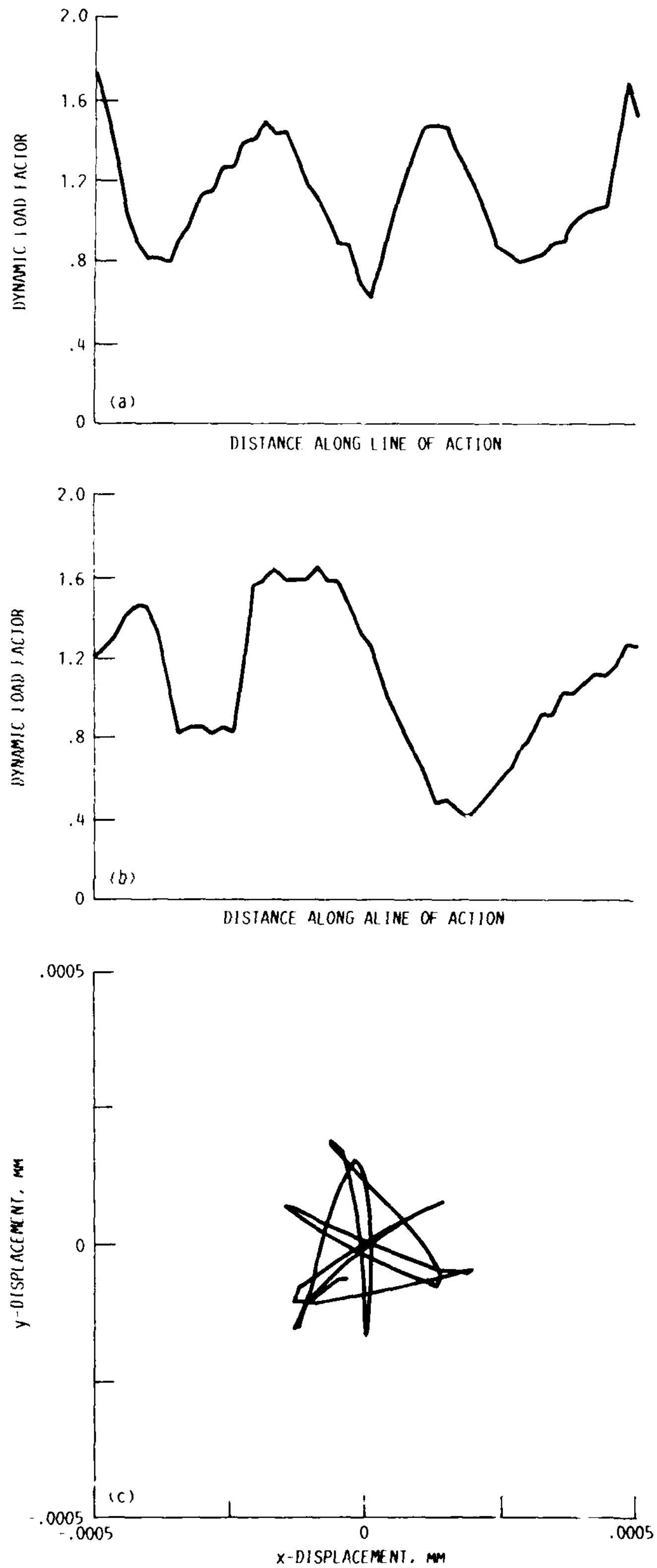
Research on each program was conducted to obtain the general and technical features of the programs on an individual and collective comparison basis. Program features,

capabilities, and options were tabulated in an effort to provide an easily accessible reference base for potential program users. Table I presents some general information on each program such as system sizes and types, gear types, and supporting documentation. Table II gives a direct comparison among the programs of the type and nature of the parameters calculated by each. A comparison of the input options available for each program with some basic descriptions of these options are presented in table III. Finally, table IV gives information on the printed and plotted output options available with these programs. In the following sections general program features, as presented in tables I to IV, are discussed, along with the various analytical models used in the programs.

General Capabilities, and Features

Program PGT.—The program PGT (dynamics of Planetary Gear Trains) (ref. 6) is a gear dynamic analysis program for a three planet planetary spur gear system. PGT is capable of modeling a planetary gear train with input and output shafts and masses. It calculates dynamic mesh loads and combined stiffness for each mesh as a function of roll angle. PGT also calculates the sun center movement in the plane perpendicular to the sun gear axis. Along with the standard input parameters, such as tooth geometry, torque, and speed, other parameters can be input, such as profile errors, sun center stiffness and damping, etc., as indicated in table III. The major features of this program are its ability to include input and output peripherals in the analysis and to calculate the movement of the sun gear center. The major limitation of this program is that it can only be applied to a three planet system. Sample plotted outputs of PGT are given in figure 1. The first two plots represent the dynamic load factor for the sun/planet and ring/planet mesh associated with planet number 1 of run 1 in table V. The dynamic load factor represents the ratio of dynamic to static tooth load, and is commonly used when plotting dynamic mesh loads. The sun center movement plot is the actual displacement of the sun center through one complete steady state revolution. It should be noted at this time that program PGT is not in an easily runable format. Some work would be required to revise the program to a more standard, commercially acceptable status.

Program GRDYNMULT.—The program GRDYNMULT (Epicyclic Gear Dynamic Analysis Program) (ref. 3) is a dynamic analysis program with the capabilities to model a variety of gear types and gear train systems. GRDYNMULT is capable of modeling single mesh, planetary, star, and differential systems with a maximum of 20 planets. This program can model spur or helical gear types, along with involute or buttress tooth forms. GRDYNMULT is capable of calculating a number of variables such as dynamic mesh loads, tooth root stresses, hertz stresses, flash temperatures, etc., as shown in table II. As illustrated in table III, nonstandard parameters such as tooth spacing errors, tooth profile modifications, sun center stiffness and damping, etc.,



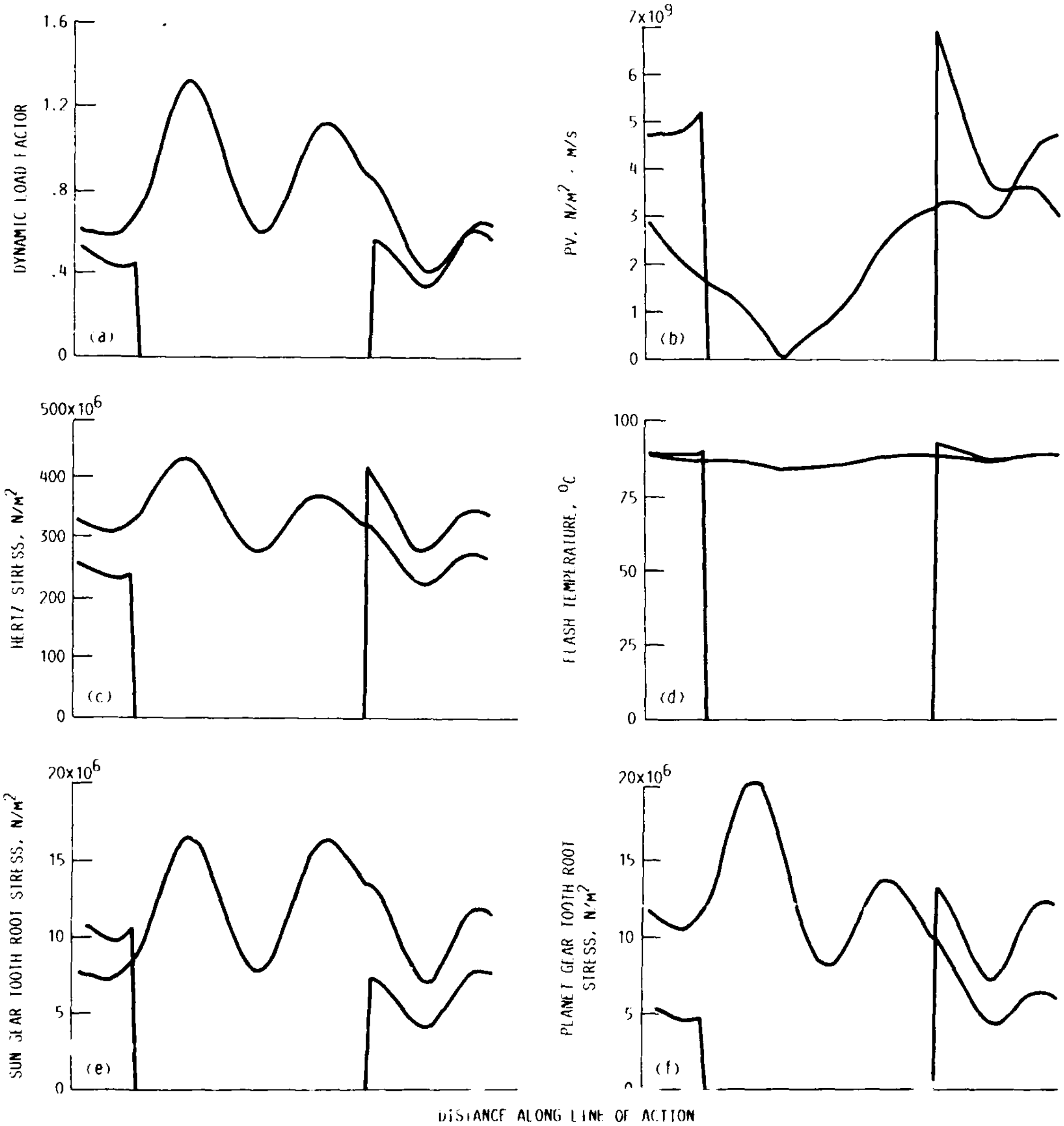
(a) Sun/planet tooth loads mesh 1.
(b) Ring/planet tooth loads mesh 1.
(c) Sun center movement.

Figure 1.—PGT sample plotted output. Input torque = 33.9 N•m; input speed = 4000 rpm.

ɔe input in the program. The major feature of this program ; variety in the type of calculations available, and the ber of gear train systems it can be applied to. The major :ation of this program is that it cannot include, in the ımic analysis, the effects of input and output peripherals :ally present in actual gear systems.

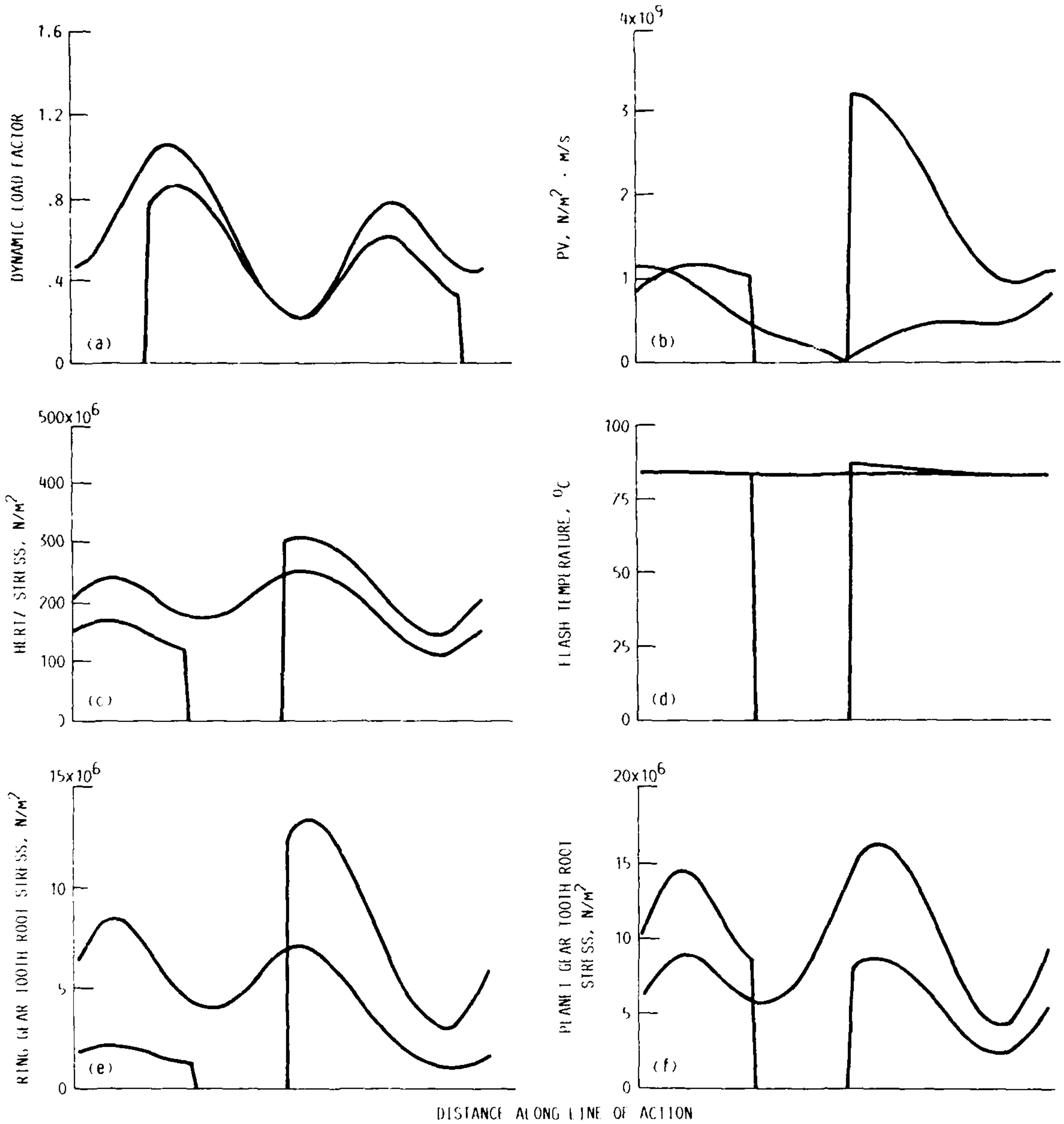
ımple output plots from GRDYNMULT are given in res 2 and 3. These plots are for the ring/planet, sun/planet h associated with planet number 1 of comparison run 1 ıble V. The first plot in each figure is the dynamic load ɔr for the mesh. The PV plot represents the product of ocal contact stress and the sliding velocity. The PV product sed in analyzing surface damage possibilities, such as scoring. The flash temperature plots represent the instantaneous gear surface temperature, and the hertz stress is the local contact pressure. The planet, ring, and sun gear stress plots refer to the tooth root stresses. The plots associated with GRDYNMULT appear different from those of other programs because GRDYNMULT presents only half of the tooth contact cycle, and the plot includes more than one tooth pair if more than one pair are in contact. Subsequent plots from GRDYNMULT have been replotted for easier comparison with the other programs.

Program TELSGE.—The program TELSGE (Thermal Elasto-Hydrodynamic Lubrication of Spur Gears) (ref. 1) is a dynamic analysis program for a single mesh spur gear



(a) Dynamic load plot.
(b) PV plot.
(c) Contact stress plot.
(d) Flash temperature plot.
(e) Sun gear tooth root stress plot.
(f) Planet gear tooth root stress plot.

Figure 2.—GRDYNMULT sample plotted output of sun planet mesh 1. Input torque = 33.9 N•m; input speed = 4000 rpm.

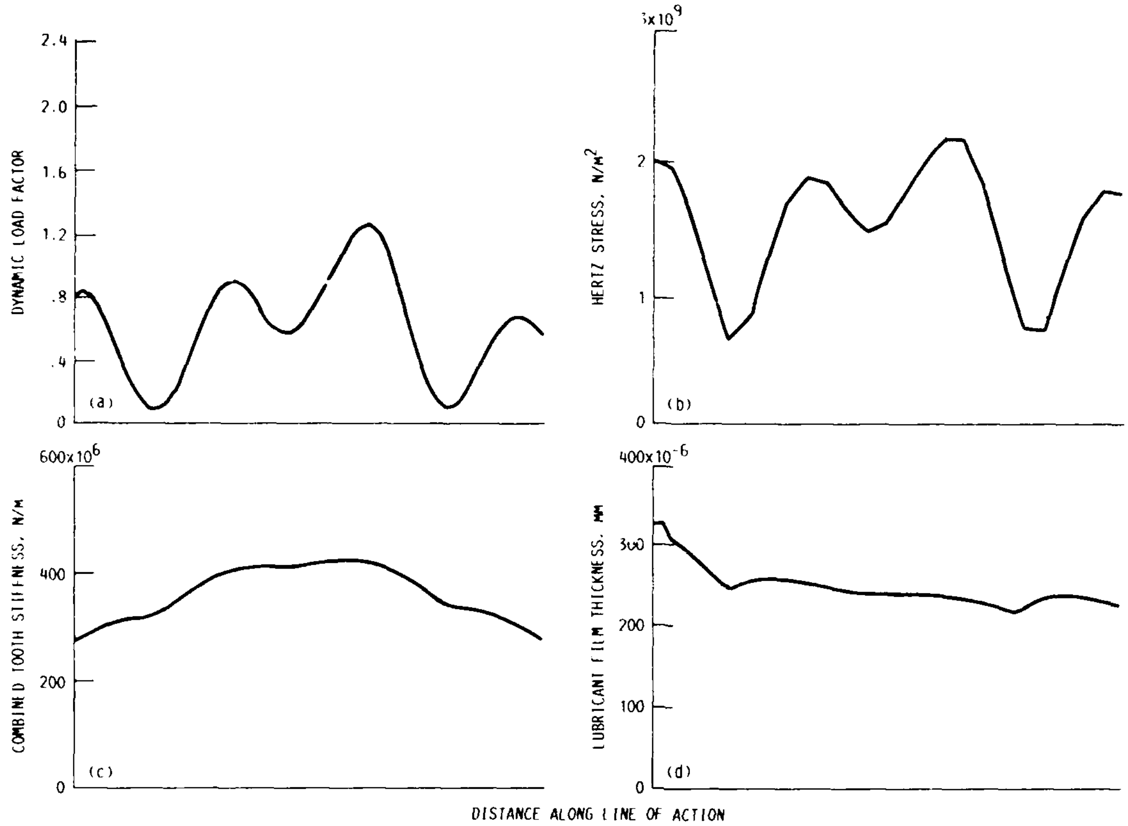


(a) Dynamic load plot.
(b) PV plot.
(c) Contact stress plot.
(d) Flash temperature plot.
(e) Ring gear tooth root stress plot.
(f) Planet gear tooth root stress plot.

Figure 3. —GRDYNMULT sample plotted output of ring planet mesh 1. Input torque = 33.9 N•m; input speed = 4000 rpm.

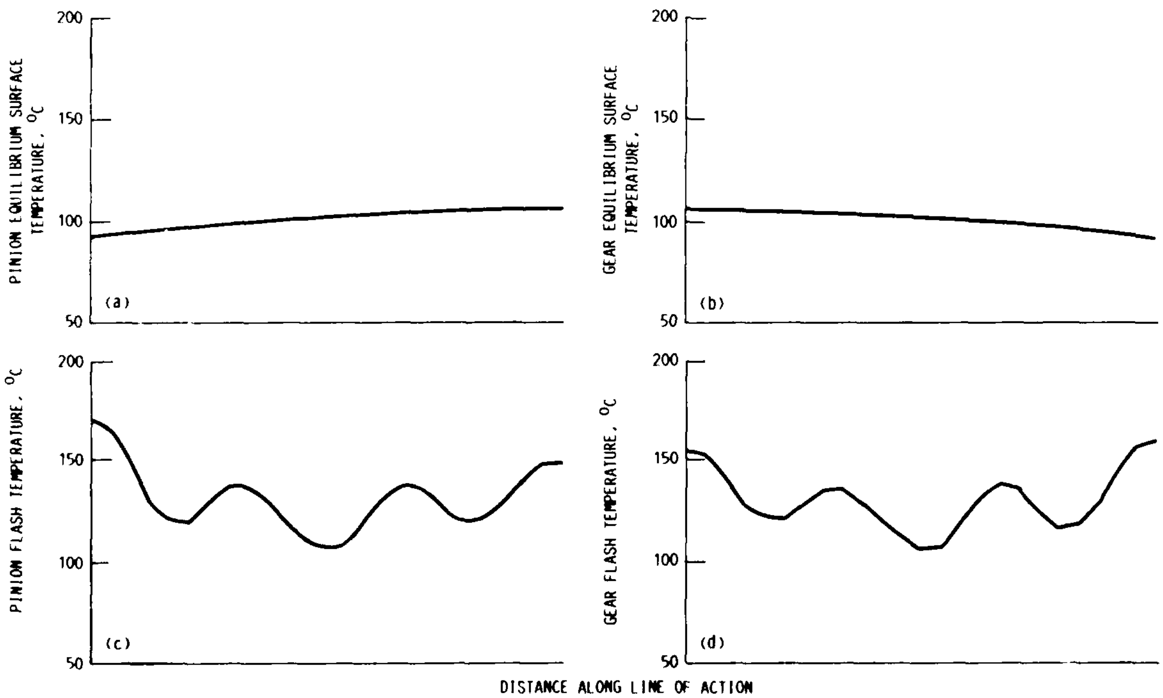
system. As illustrated in table II, TELSGE is capable of calculating variables such as film thickness, flash and equilibrium surface temperatures, dynamic mesh loads, and hertz stresses, etc., which are important parameters in gear tooth surface failure models. TELSGE predicts fatigue life of the gears based on these calculated variables. Additional input parameters for TELSGE include tooth profile error/modification array, thermal and viscous properties of the lubricant, etc., as seen in table III. The major feature of this program is its comprehensive treatment of the dynamic and thermal effects of the lubricant on the resulting life of the gears. The major limitation of this program is that it applies only to a single mesh system. Sample plotted outputs of TELSGE are given in figures 4 and 5. The plots shown were constructed using a postprocessing graphics program, as the current CRAY version of TELSGE does not have a plotting routine.

Program DANST.—The program DANST (Dynamic ANalysis of Spur gear Transmissions) (ref. 9) is a dynamic analysis program for a single mesh spur gear system. DANST is capable of modeling a system with input and output peripherals included in the analysis. As illustrated in table II,



(a) Dynamic load plot.
(b) Contact stress plot.
(c) Combined tooth stiffness plot.
(d) Film thickness plot.

Figure 4.—TELSGE sample plotted output. Input torque = 203.4 N•m; input speed = 6000 rpm.



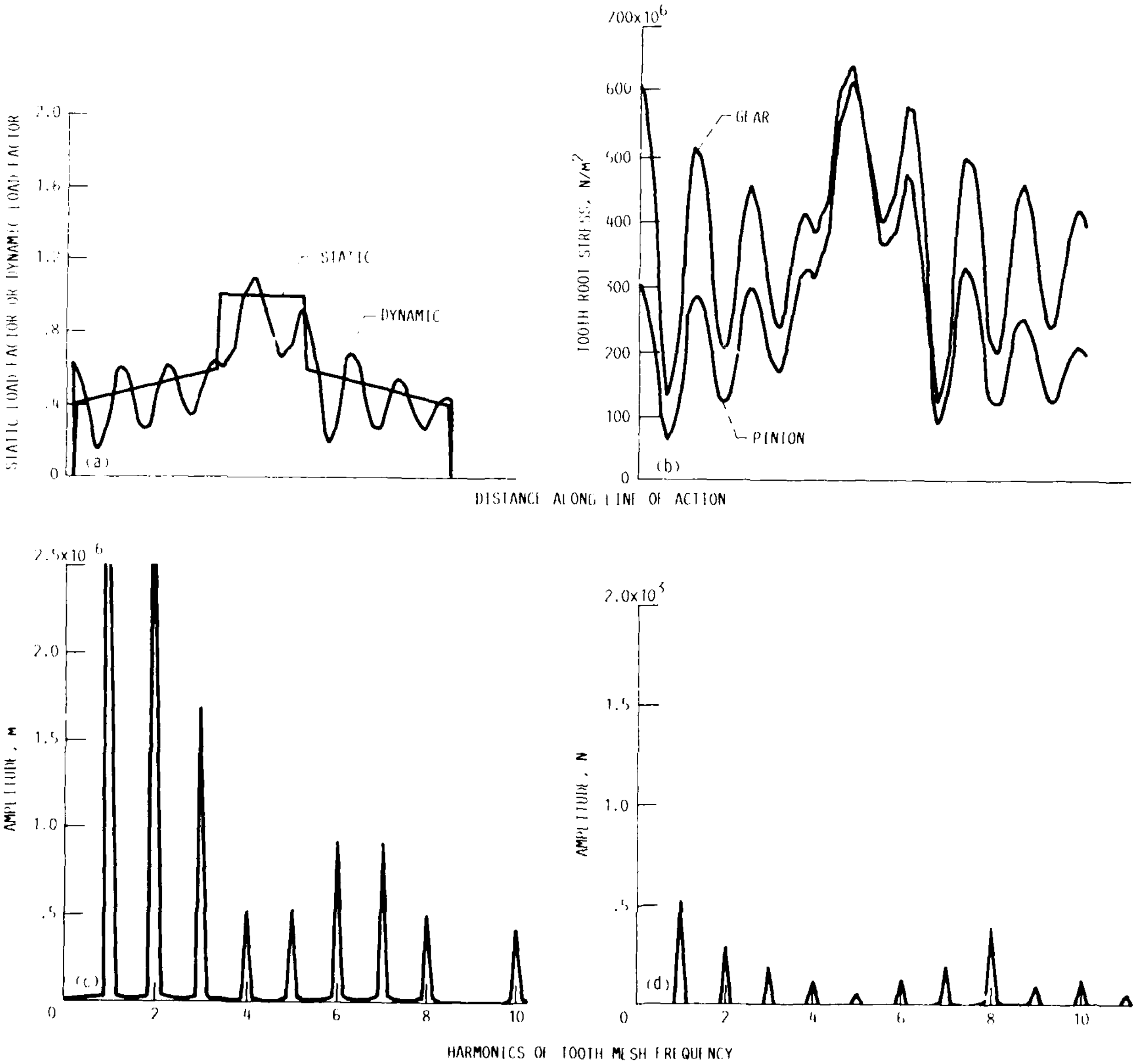
(a) Pinion surface temperature plot.
(b) Gear surface temperature plot.
(c) Pinion flash temperature plot.
(d) Gear flash temperature plot.

Figure 5.—TELSGE sample plotted output. Input torque = 203.4 N•m; input speed = 6000 rpm.

ANST is capable of calculating dynamic mesh loads, root esses, combined stiffness, etc., as a function of contact sition. Along with standard input parameters, DANST ows input of a user defined tooth profile deviation array, indardized tooth profile modifications, input and output shaft d mass data, etc., as seen in table III. The major feature this program is the detailed tooth profile error/modification put available to the user. A major limitation of this program that it applies only to a single mesh system. Sample plotted itputs from DANST are given in figures 6 and 7. As seen figure 6, DANST provides a plot of the Fourier transform of both the static transmission error and the dynamic tooth loads. These plots can be useful when comparing the analytical results with test results in the frequency domain.

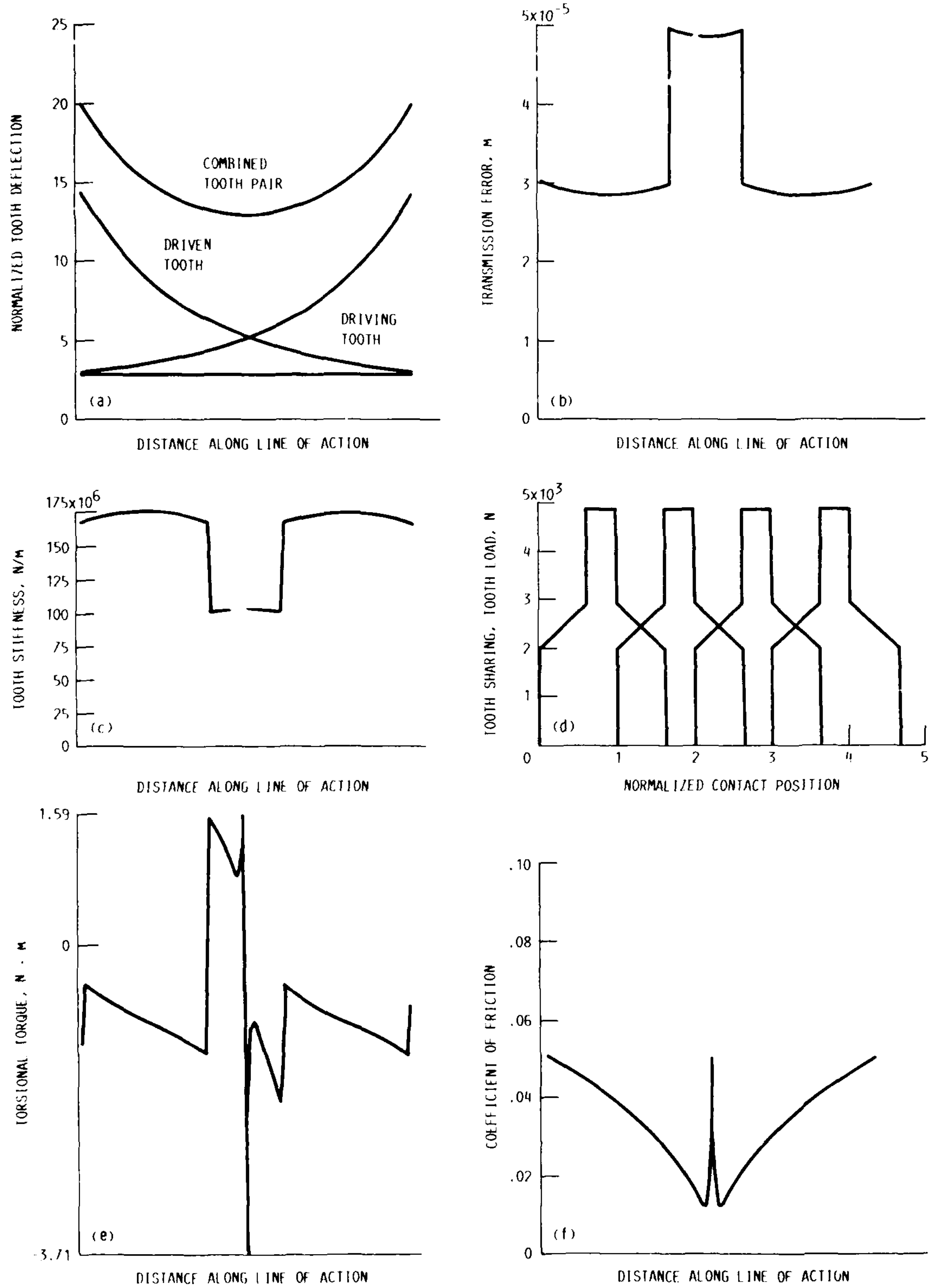
Program Models

Dynamic models.—To describe the dynamics of the systems, each program uses differential equations of motion based on mathematical models simulating the various masses, springs, and damping present in the actual systems. The mathematical model used in PGT is shown in figure 8. As depicted in this



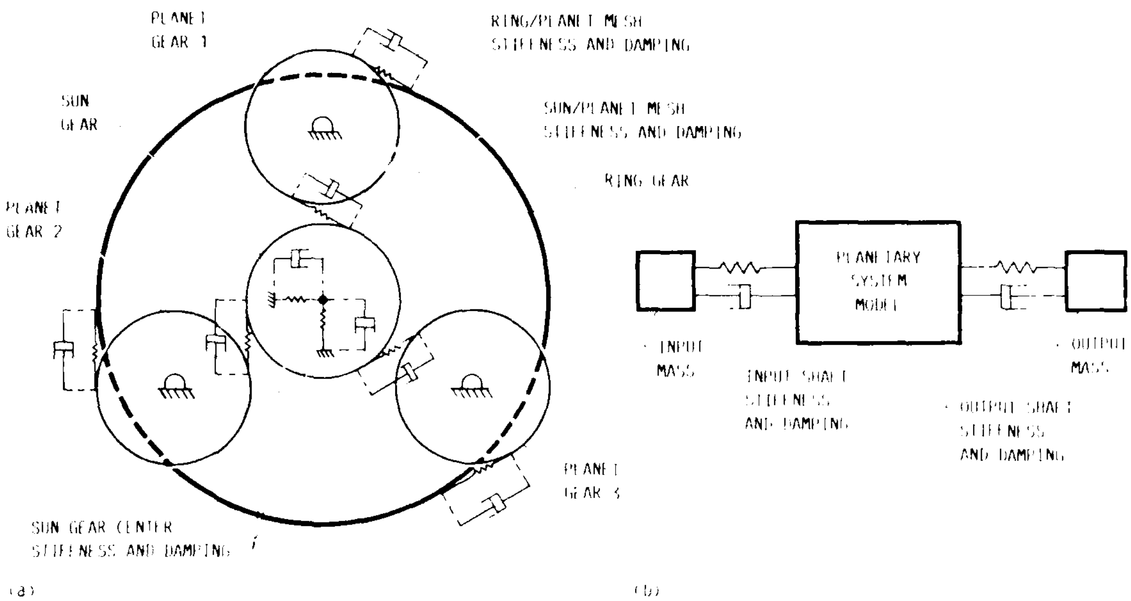
(a) Static and dynamic load plot.
(b) Tooth root stress plot.
(c) Fourier transform of static transmission error.
(d) Fourier transform of dynamic tooth loads.

Figure 6. DANST sample plotted output. Input torque = 203.4 N•m; input speed = 2000 rpm.



(a) Normalized tooth deflection plots. (b) Static transmission error plot.
(c) Tooth stiffness plot. (d) Tooth load sharing plot.
(e) Torsional torque plot. (f) Coefficient of friction plot.

Figure 7.—DANST sample plotted output. Input torque = 203.4 N•m; input speed = 2000 rpm.



(a) Planetary system model

(b) Overall system model

Figure 8. - Program PGT system model

figure, each mesh is represented by an equivalent spring and dashpot. The spring represents the combined stiffness of the gear teeth in mesh, and the dashpot represents the resulting *mesh damping*. The springs and dashpots shown at the sun center are present to model the flexibility and damping of the sun gear shaft and bearings. The stiffness, masses, and damping associated with the input shaft and driver and output shaft and driven device are also included in the model. Figure 9 illustrates the model used in the program GRDYNMULT. The mesh stiffness and damping, and sun center stiffness and damping, are presented similarly as in the PGT model. As seen in figure 9, additional springs representing flexibilities between ring gear rim segments and between planet carrier segments are included in the GRDYNMULT model. Figures 10 and 11 represent the models for programs TELSGE and DASG, respectively. As seen in figure 11, the DANST model includes the mass and elastic data of the input and output peripherals. Again, the mesh springs represent the combined stiffness of the gear teeth in mesh. For a more thorough description of the individual models and the iterative methods used to solve the resulting differential equations, refer to the supporting documentation for each program as given in table I.

Tooth stiffness models. - To model the complex stiffness of gear teeth during mesh, all of the programs use a nonlinear tooth compliance model. Programs TELSGE, GRDYNMULT, and DANST use R.W. Cornell's nonlinear compliance model (ref. 10) that formulates tooth stiffness as a function of position along the line of action. This compliance model is based on a combination of the stiffness of the tooth as a cantilever beam, local hertz contact compression, and fillet and tooth foundation flexibility effects. All of the above except the local contact compression are linear functions of the load. The nonlinearity of the compliance equation is due to the hertzian deflection. PGT uses a "variable-variable mesh stiffness" (VVMS) model for the tooth stiffness. The VVMS model is also nonlinear due to local hertz contact compression. The model includes tooth bending effects and tooth profile errors as a function of contact position.

Tooth root stress models.—Of the four programs investigated, only GRDYNMULT and DANST are capable of calculating tooth root stresses. Both programs use the modified Heywood formula for tooth stress sensitivity as given in reference 11. The modified Heywood formula calculates the maximum root stress as a function of tooth contact position, mesh load, face width, stress concentration factor of the fillet, and basic tooth geometry. The formula is also capable of predicting the location of the maximum root stress on the tooth fillet. The modified Heywood formula expresses the root stress as a linear function of the applied load. It was found that the formula predicts the maximum tensile root stress within about 5 percent of finite-element and other analysis methods (ref. 11).

Input error models.—Actual gear systems inherently have one or more types of errors present. In an attempt to more accurately model actual systems, all of the programs have provided some means of including errors inherent in these systems. The program GRDYNMULT allows three types of errors to be input. These are: sun runout error, helix angle errors, and tooth errors. The sun runout error, applicable to a single mesh system only, converts a sun center displacement input into a sinusoidal tooth spacing error array to simulate errors associated with eccentrically manufactured gears. The

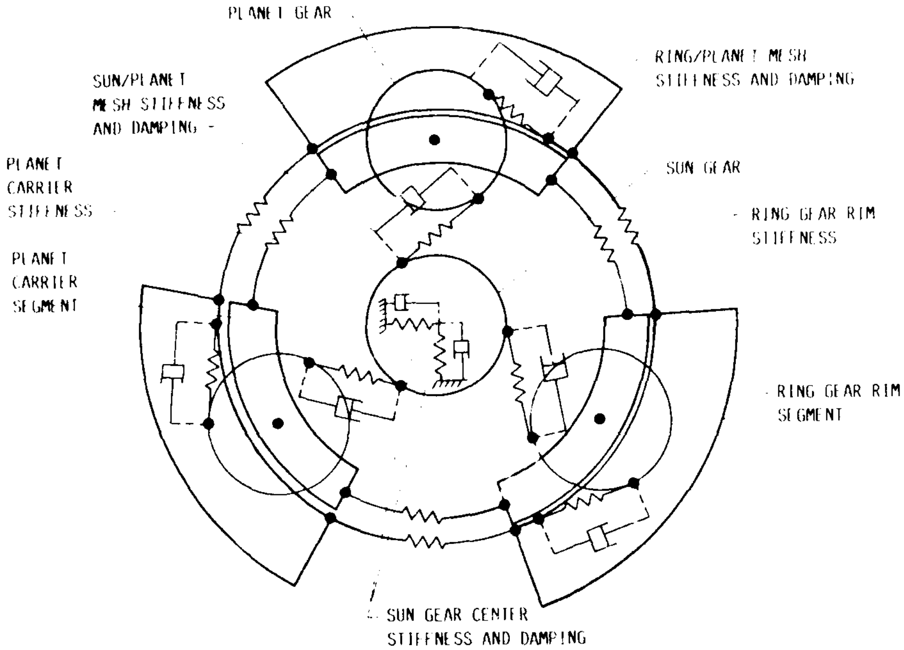


Figure 9. - Program GRDYNMULT system model

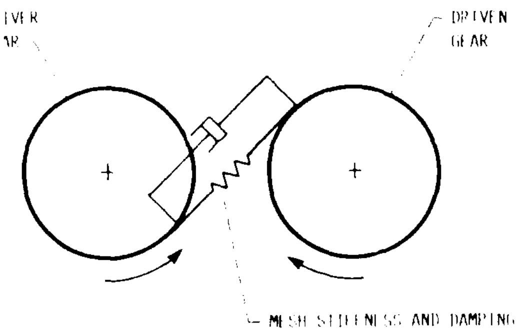


Figure 10. - Program TELSGE system model

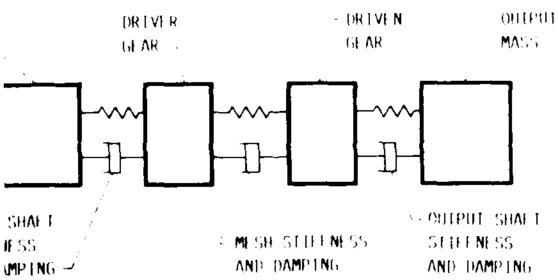


Figure 11. - Program DANST system model

gle errors allow the user to input a constant angular r each mesh for single and double helical gears. The rors are comprised of tooth error arrays on five teeth ı sun/planet, ring/planet mesh. This tooth error input ıts the statistical sum of tooth pitch error, profile error, l (or planet phasing) error. The tooth error is constant ıe profile of the tooth. The program PGT indirectly allows two types of error to be input, phase error and tooth error. The phase error is a constant lead, or lag, tangential positioning error of the planets, representing planet assembly inaccuracies. The tooth error consists of a sinusoidal error imposed on the tooth profile with the amplitude defined by the user. This error models gear tooth profile manufacturing process errors. The single mesh programs (TELSGE and DANST) have available tooth profile deviation arrays. Deviations from the true involute profile can be defined by inputting the corresponding array. Tooth spacing error can be simulated by inputting a constant deviation along the tooth profile.

Profile modification. – Profile modifications are often used in gears to lessen engagement impacts in attempts to reduce noise and vibration in gear systems. The programs GRDYNMULT, TELSGE, and DANST allow some form of modification to the tooth profile. GRDYNMULT incorporates an equation that allows the user to input the deviation magnitude at the tip, length of the modification on the tooth profile, and the shape of the modification curve. To determine the profile modification curve a shape factor is input. The default shape factor (0) produces a parabolic profile modification. A linear profile modification can be approximated with this equation with a shape factor of −0.5. Other shapes associated with different shape factors are given in reference 11. DANST allows two standard profile modifications and a user defined shape to be input. A standard linear or parabolic tooth profile modification can be chosen with the tip deviation magnitude and modification length along the tooth profile input by the user. By virtue of the tooth profile deviation arrays discussed earlier, other user defined profile

modifications can be input in DANST. Program TELSGE also allows profile modifications to be input by virtue of its tooth profile deviation array. Standard profile modifications such as linear and parabolic must be added point by point in the array.

Comparison Runs Study

Short of using experimental data, the most effective way of comparing computer programs is to compare their output results based on common input values. In this study the programs were operated using common models and input parameters. Where possible, runs where performed with parameters such as speed, load, and mesh damping varied in order to obtain program comparisons over a broad spectrum of input conditions. Input parameters common to at least two programs, such as sun center stiffness, were also varied for the comparison. Due to the nature of the programs, two types of input models were required: a planetary system with three planets, and a single mesh system. A discussion of the comparison study results are thus grouped under those two categories.

Planetary System Runs

Because of the system limitations of the program PGT, a three planet planetary system was used to compare programs PGT and GRDYNMULT. Table VI gives a description of the planetary model used in the analysis, along with the undamped natural frequencies of the system, as calculated by GRDYNMULT. As seen in table VI, to minimize the influence of the input and output peripherals of PGT in the analysis, external shaft damping and mass moments of inertia were minimized, and external shaft stiffness values were maximized. Table V documents the comparison runs matrix used, illustrating which parameters were varied and their corresponding values. Due to difficulties experienced with the program PGT and with the HP 1000 computer system, only nine comparison runs were achieved. Unfortunately this does not allow a detailed comparison to be made; however, some general observations can be drawn. Discussions on the various parametric runs are given below.

Speed variation runs.—To compare the effect of input speed on the maximum dynamic load factor, the programs were run over a range of speeds from 4000 to 8000 rpm. Figure 12 is a plot of the maximum dynamic load factor for the sun planet mesh as a function of input speed, as predicted by both programs. As seen in this figure, both programs show good correlation except at 6000 rpm input speed, where PGT predicts a peak dynamic load. GRDYNMULT predicts a peak at the 7000-rpm input speed point. As seen in table VI, this point (7000 rpm, 1633 Hz) is within 7 percent of the second harmonic of the second natural frequency (1530 Hz), as predicted by GRDYNMULT. The difference in predicted peak load speeds between PGT and GRDYNMULT could be due to the different mesh stiffness model used in each program. Figure 13 is the same plot as figure 12 except that the maximum ring planet mesh loads are plotted. Comparison of figures 12 and 13 show the same trends, with the exception that the ring planet plots show a much poorer correlation between the two programs.

A comparison of the dynamic mesh load plots from each program through one tooth mesh cycle at input speeds of 4000, 6000, and 8000 rpm are illustrated in figures 14, 15, and 16, respectively. As seen in figures 14 and 16, the sun planet mesh load plots are very similar in form between the two programs. The ring planet mesh load plots are dissimilar in both form and magnitude. Figure 15 further illustrates the discrepancy between the two programs at the 6000-rpm input speed. Here PGT is shown to predict tooth separation with a maximum

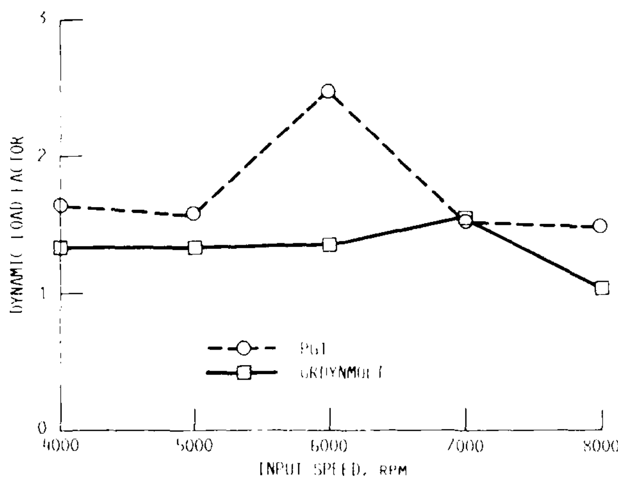


Figure 12.—Comparison of programs PGT and GRDYNMULT. Maximum dynamic load factor as a function of input speed for the sun planet mesh. Input torque = 33.9 N•m (Table V, runs 1 to 5).

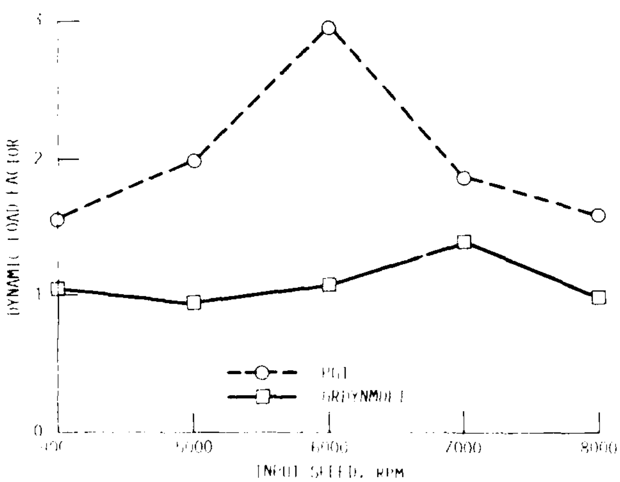
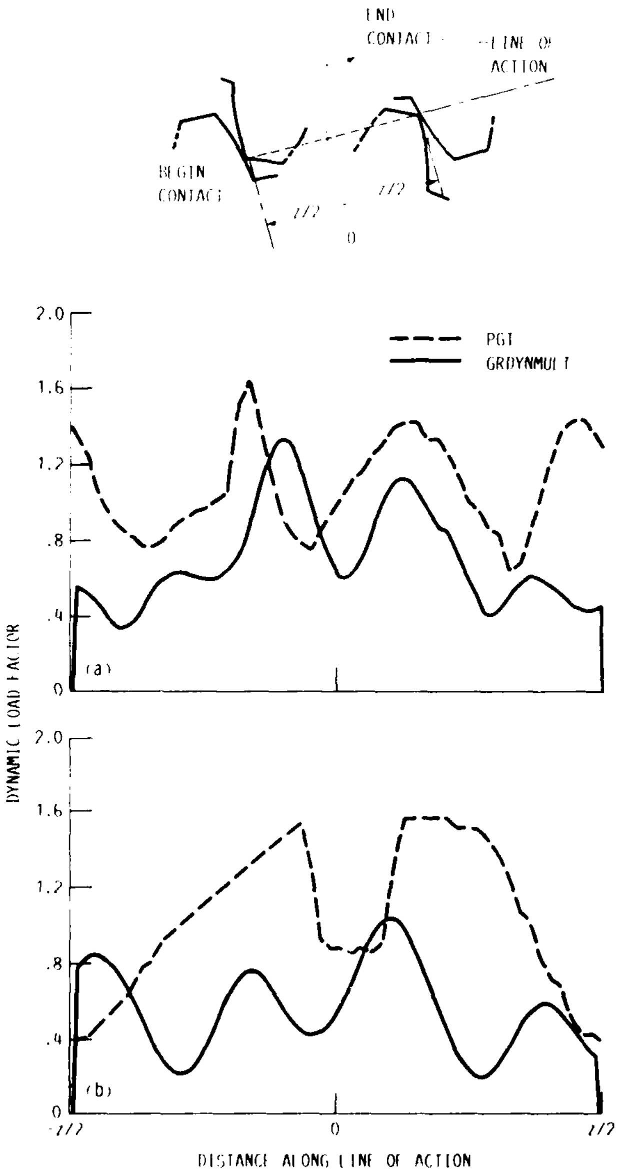
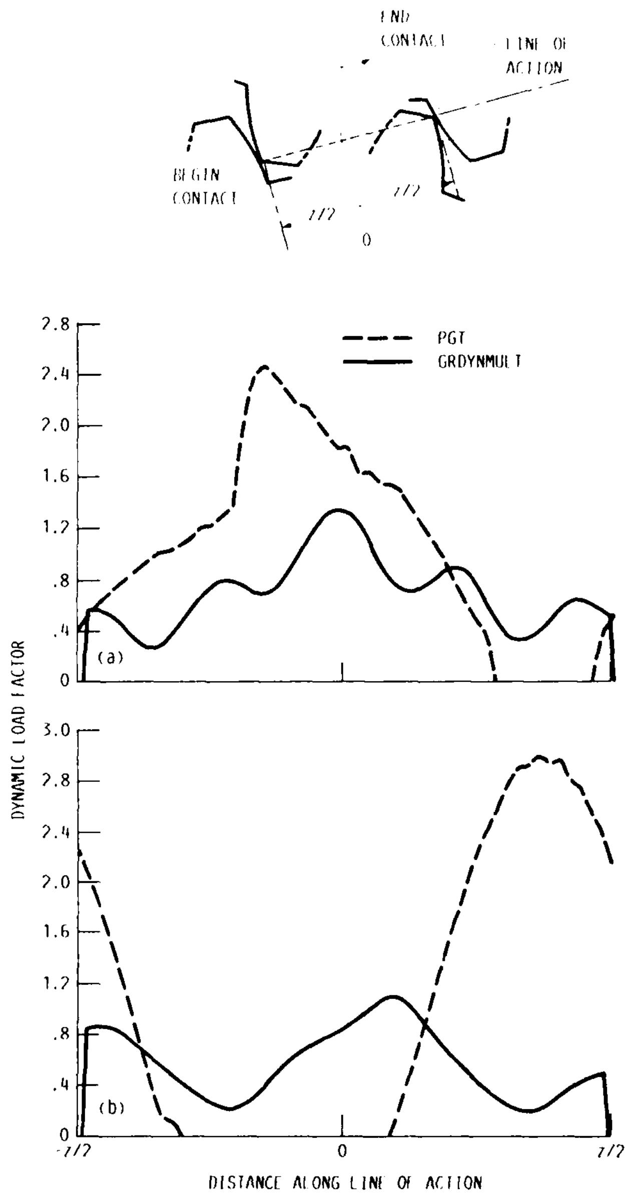


Figure 13.—Comparison of programs PGT and GRDYNMULT. Maximum dynamic load factor as a function of input speed for the ring planet mesh. Input torque = 33.9 N•m (Table V, runs 1 to 5).



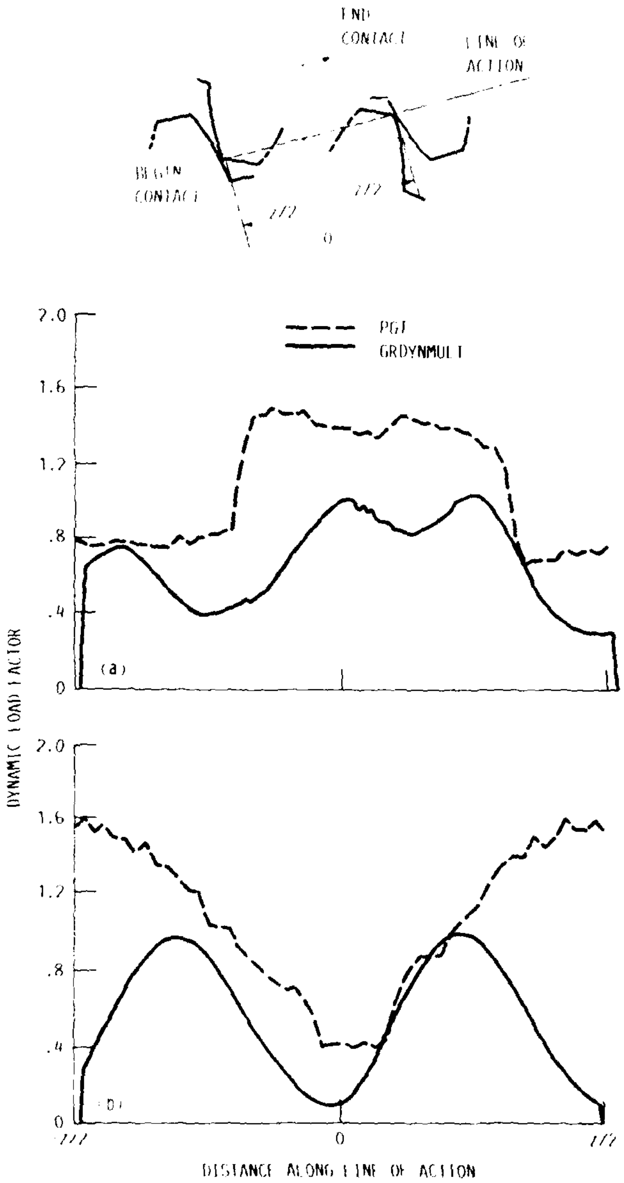
(a) PGT and GRDYNMULT sun planet mesh.
(b) PGT and GRDYNMULT ring planet mesh.

Figure 14. -Comparison of programs PGT and GRDYNMULT. Dynamic load factor as a function of contact position. Input torque = 33.9 N•m; input speed = 4000 rpm (Table V, run 1).



(a) PGT and GRDYNMULT sun/planet mesh.
(b) PGT and GRDYNMULT ring/planet mesh.

Figure 15.—Comparison of programs PGT and GRDYNMULT. Dynamic load factor as a function of contact position. Input torque = 33.9 N•m; input speed = 6000 rpm (Table V, run 3).



(a) PGT and GRDYNMULT sun/planet mesh.
(b) PGT and GRDYNMULT ring/planet mesh.

Figure 16.—Comparison of programs PGT and GRDYNMULT. Dynamic load factor as a function of contact position. Input torque = 33.9 N•m; input speed = 8000 rpm (Table V, run 5).

dynamic load factor in excess of 2.8. Again, the apparent difference in system critical speeds could be due to different mesh stiffness models. It is not known at this time why the ring/planet mesh loads experienced a poorer correlation than the sun/planet mesh loads.

Sun center stiffness runs.—The sun center stiffness input was varied in each program to compare sun center flexibility effects on the maximum dynamic load factor. Figure 17 plots the relative effects on the maximum dynamic load for the sun/planet mesh for three sun center stiffness values. Three points are not enough to provide a thorough comparison; however, some general trends can be deduced and compared using these plots. As seen in figure 17, trend results from the two programs do not fully agree. PGT favors a relatively stiff sun center for a minimum dynamic load factor, whereas GRDYNMULT indicates an optimum sun center stiffness exists between the two extremes. Similar plots for the ring/planet mesh are illustrated in figure 18. Some trends can

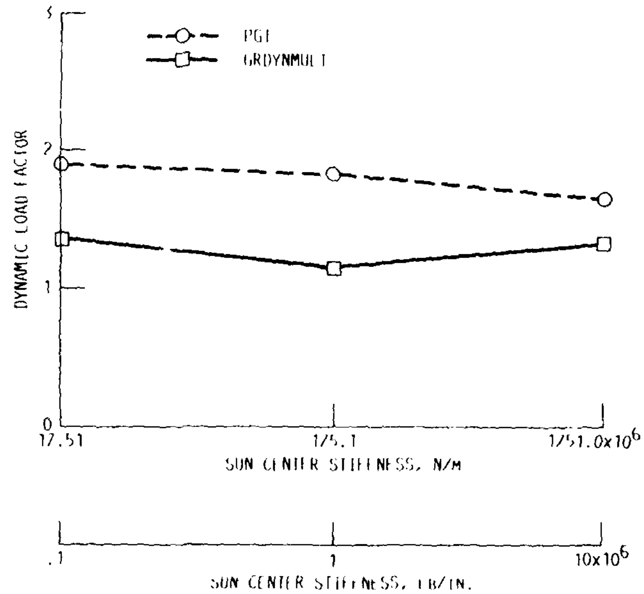


Figure 17.—Comparison of programs PGT and GRDYNMULT. Maximum dynamic load factor as a function of sun center stiffness for the sun/planet mesh. Input torque = 33.9 N•m; input speed = 4000 rpm (Table V, runs 1, 6, and 9).

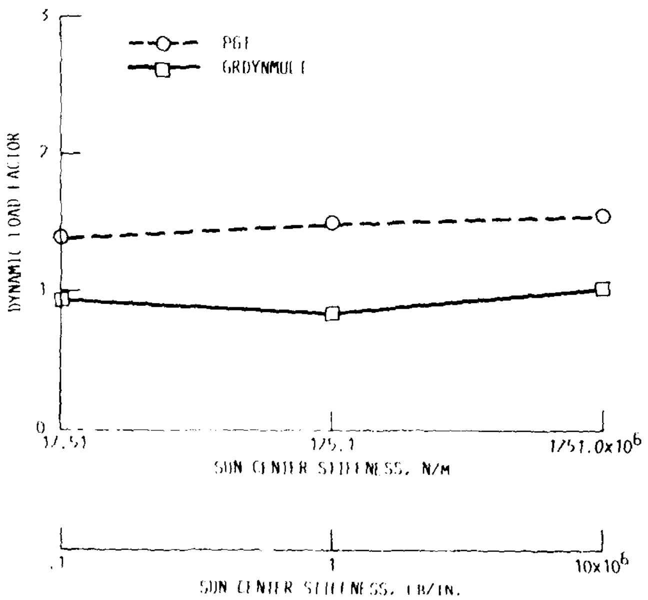


Figure 18.—Comparison of programs PGT and GRDYNMULT. Maximum dynamic load factor as a function of sun center stiffness for the ring/planet mesh. Input torque = 33.9 N•m; input speed = 4000 rpm (Table V, runs 1, 6, and 9).

be seen in this figure; however, they are not prominent enough to draw any conclusions.

Damping runs.—The mesh damping ratio and sun center damping coefficient were changed to compare the resulting effects on the maximum dynamic load factor calculated by each program. Figure 19 illustrates the effects on the maximum dynamic load factor of the sun/planet mesh at an input speed of 4000 rpm as mesh and sun center damping were changed. As seen in this figure, both programs show an increase in dynamic load (9.0 percent for GRDYNMULT, 12.1 percent for PGT) as the mesh damping ratio value is decreased from 0.10 to 0.03. No significant change was noted in either program as the sun center damping coefficient was changed. Similar plots

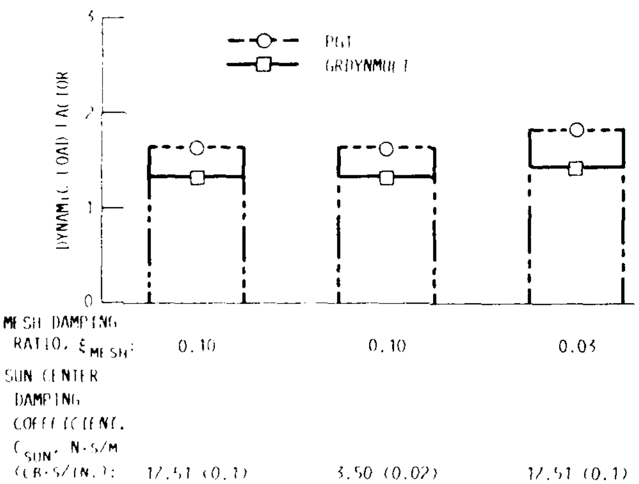


Figure 19. Comparison of programs PGT and GRDYNMULT. Maximum dynamic load factor at several damping conditions for the sun planet mesh. Input torque – 33.9 N•m; input speed – 4000 rpm (Table V, runs, 1, 7, and 8).

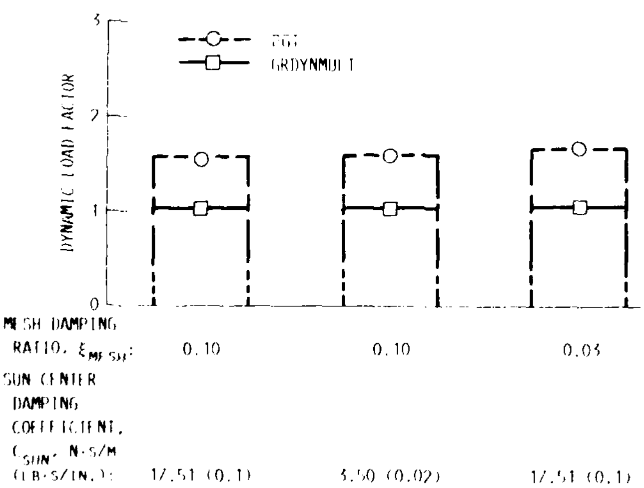


Figure 20. Comparison of programs PGT and GRDYNMULT. Maximum dynamic load factor at several damping conditions for the ring planet mesh. Input torque – 33.9 N•m; input speed – 4000 rpm (Table V, runs, 1, 7, and 8).

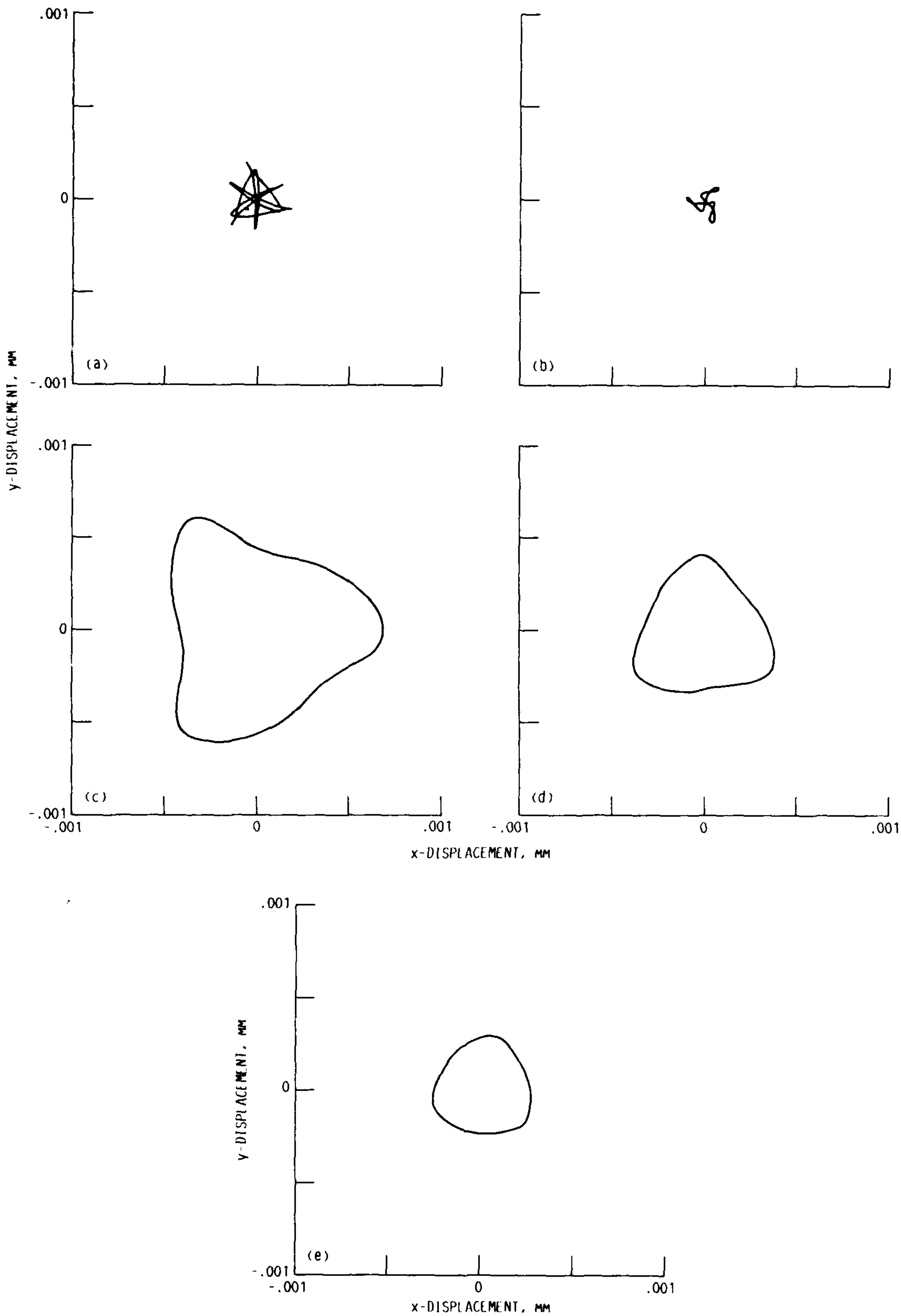
for the ring/planet mesh are illustrated in figure 20. The trends seen in figure 20 are similar to those noted in figure 19; however, they are not prominent enough to draw any conclusions from them.

Sun center movement.—Sun center movement is calculated by program PGT only, thus no comparison can be made with GRDYNMULT. PGT predictions of the sun center displacement, however, proved interesting and are discussed below. Figure 21 illustrates the sun center movement for one revolution at a variety of input speeds. The maximum displacement of the sun center is seen to occur at 6000-rpm input speed, the same as with the maximum dynamic load factor. As the speed increases, the sun center displacement approaches a pattern resembling shaft whirl. As expected, the sun center movement decreases with increasing sun center stiffness (see fig. 22). A decrease in mesh damping (from 0.10 to 0.03) results in an increase in sun center displacement of more than two times, as shown in figure 23. Also illustrated in this figure, a change in the sun center damping coefficient had no effect on the sun center displacement at this input speed.

Single Mesh Runs

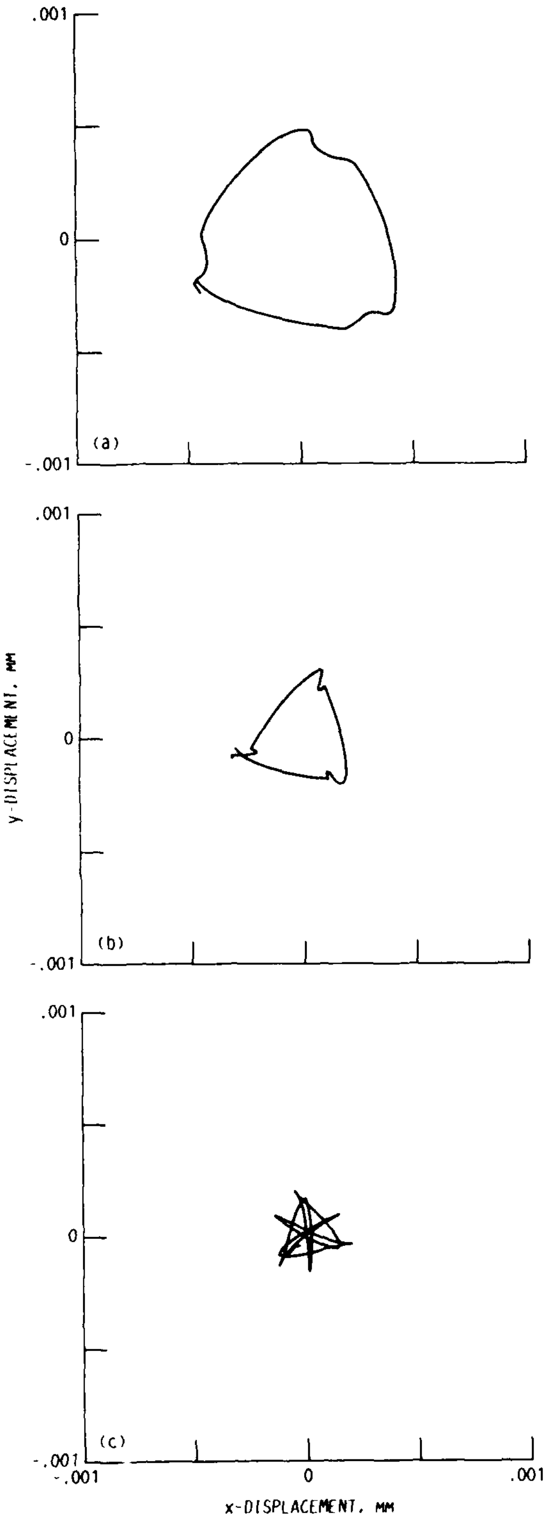
Because of the system limitations of DANST and TELSGE, a single mesh system was used to compare programs GRDYNMULT, TELSGE, and DANST. Table VII gives a description of the single mesh model used in the analysis along with the undamped natural frequencies of the system calculated by each program. As seen in this table, the programs predicted similar natural frequencies for the single mesh system (all within 13 percent of the calculated average of 4532 Hz). Of the three programs, only DANST includes external shafts and masses in the system dynamics. To maintain an equal comparison basis among the three programs, it was necessary to minimize the influence of the peripheral masses in program DANST. This was accomplished by using highly flexible input and output shafts in the program. In the planetary system runs program PGT used short, highly rigid shafts with small peripheral mass inertias to minimize their effects on the system dynamics. This method did not work as well with program DANST, thus the opposite approach of flexible shafts was used to isolate the peripheral mass inertias from the mesh dynamics. Figure 24 illustrates the effect of varying the magnitude of the peripheral masses on the maximum dynamic load factor, as predicted by program DANST with the flexible shaft configuration. As seen in this figure, the dynamic load factor changes minimally with peripheral mass changes, indicating good isolation of the mesh dynamics with this configuration. Table VIII documents the comparison runs matrix used, illustrating which parameters were varied and their corresponding values. Discussions comparing the effects of the various parametric runs on the variables calculated by the programs are given below.

Dynamic load factor.—A variety of input speeds and torques were used to compare the relative effects of speed and load



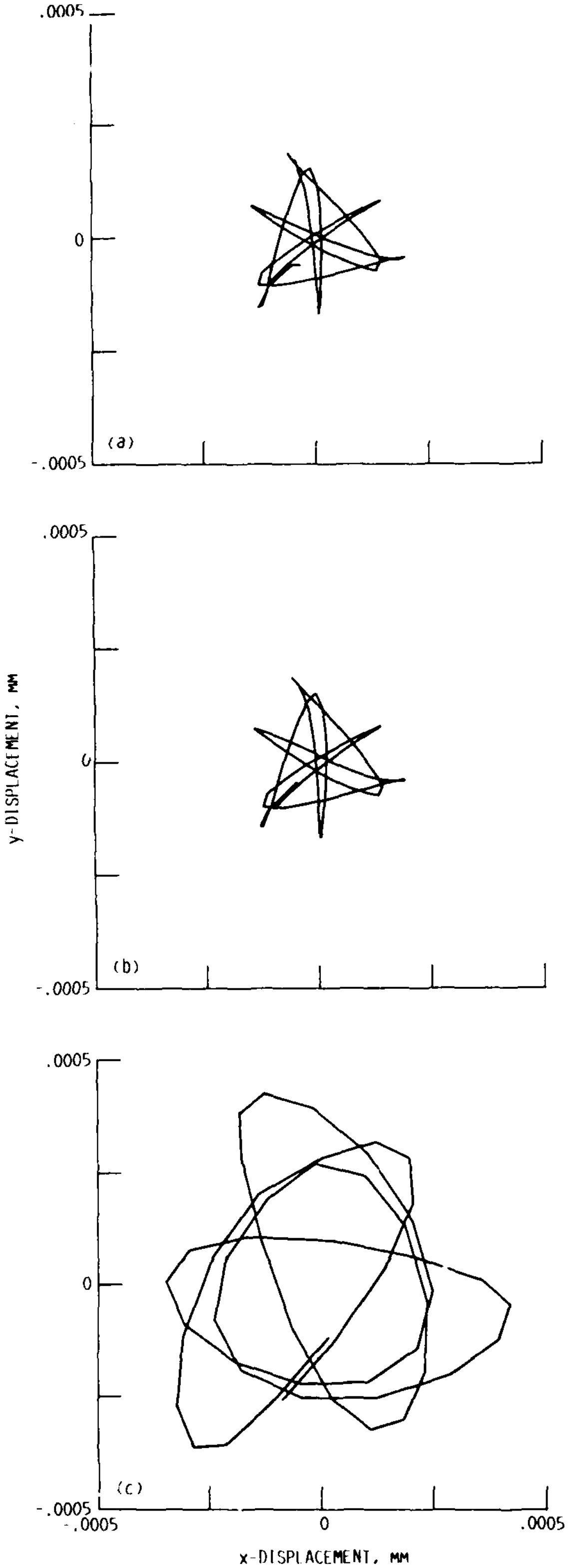
(a) Input speed = 4000 rpm.
(b) Input speed = 5000 rpm.
(c) Input speed = 6000 rpm.
(d) Input speed = 7000 rpm.
(e) Input speed = 8000 rpm.

Figure 21.—PGT program sun center movement predictions at various input speeds. Input torque = 33.9 N•m (Table V, runs 1 to 5).



(a) K_{sun} = 17.51 × 10^6 N/m.
(b) K_{sun} = 175.1 × 10^6 N/m.
(c) K_{sun} = 1 751 × 10^9 N/m.

Figure 22.—PGT program sun center movement predictions at various sun center stiffness values. Input torque = 33.9 N•m; input speed = 4000 rpm (Table V, runs 1, 6, and 9).



(a) ξ_{mesh} = 0.10; C_{sun} = 17.51 N•s/m.
(b) ξ_{mesh} = 0.10; C_{sun} = 3.50 N•s/m.
(c) ξ_{mesh} = 0.03; C_{sun} = 17.51 N•s/m.

Figure 23.—PGT program sun center movement predictions for various damping values. Input torque = 33.9 N•m; input speed = 4000 rpm (Table V, runs 1, 7, and 8).

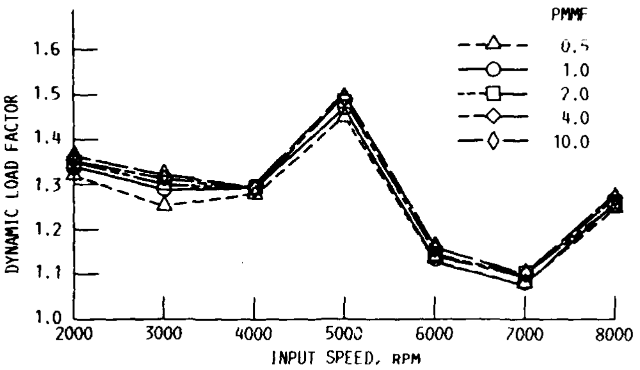


Figure 24.—Effect on maximum dynamic load factor, as function of input speed, as peripheral mass multiplication factor (PMMF) is varied in program DANST, with highly flexible input and output shafts. ($J_{\text{input mass}}$ = PMMF $\times J_{\text{driving gear}}$; $J_{\text{output mass}}$ = PMMF $\times J_{\text{driven gear}}$).

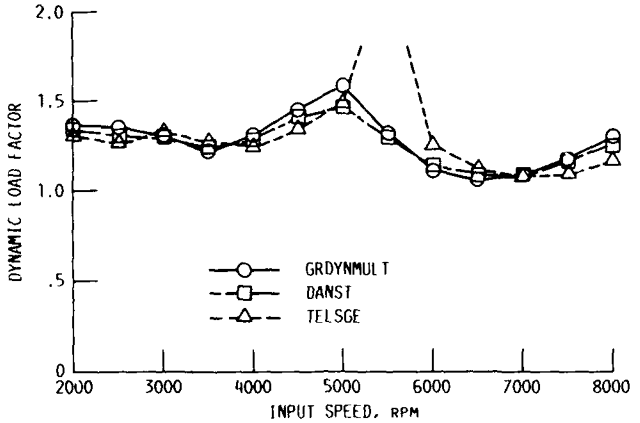


Figure 25.—Comparison of program GRDYNMULT, DANST, and TELSGE. Maximum dynamic load factor as function of input speed. Input torque = 203.4 N•m (Table VIII, run 1).

on the dynamic load factor as calculated by each program. Maximum dynamic load factors are plotted as a function of input speed for an input load of 203.4 N•m (1800 in.•lb) in figure 25. As seen in this figure, all three programs show good correlation (average difference within 5 percent) except at 5500 rpm, where TELSGE results diverge. This speed is within 8 percent of the speed corresponding to the half harmonic of the natural frequency predicted by TELSGE (5130 rpm). This half harmonic phenomenon is also seen in programs GRDYNMULT and DANST, although at a lesser degree. DANST and GRDYNMULT both indicate peaks at the 5000-rpm data point. The predicted half harmonic speed of program DANST (5191 rpm) is within 4 percent of this peak dynamic load point. The corresponding half harmonic speed of program GRDYNMULT (4246 rpm) is within 15 percent of the peak dynamic load point. Because the mesh stiffness varies with tooth position during mesh, the predicted natural frequencies are only estimates of the actual values, based on assumed constant mesh stiffness quantities. A

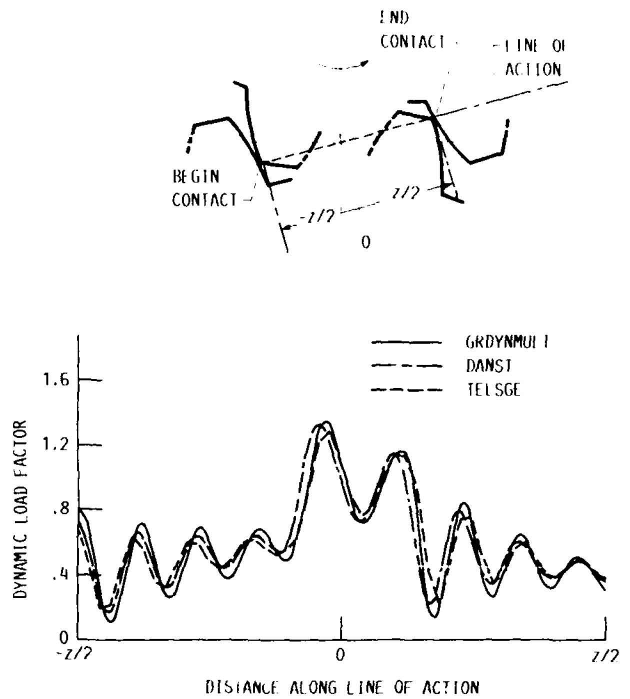


Figure 26.—Comparison of programs GRDYNMULT, DANST, and TELSGE. Dynamic load factor as function of contact position. Input torque = 203.4 N•m; input speed = 2000 rpm (Table VIII, run 5).

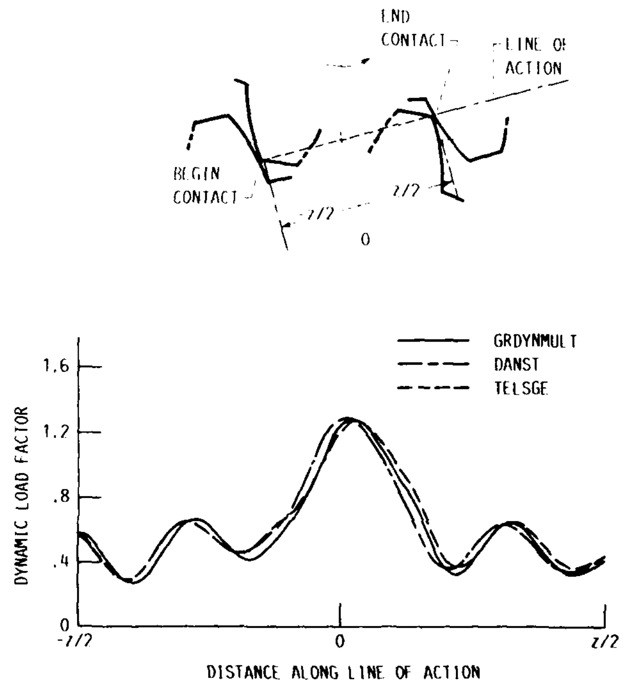


Figure 27.—Comparison of programs GRDYNMULT, DANST, and TELSGE. Dynamic load factor as function of contact position. Input torque = 203.4 N•m; input speed = 4000 rpm (Table VIII, run 7).

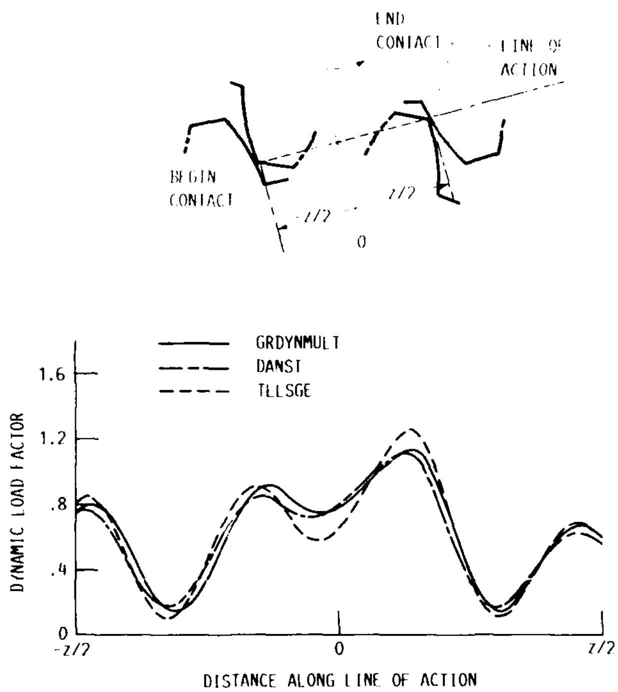


Figure 28.—Comparison of programs GRDYNMULT, DANST, and TELSGE. Dynamic load factor as function of contact position. Input torque = 203.4 N•m; input speed = 6000 rpm (Table VIII, run 9).

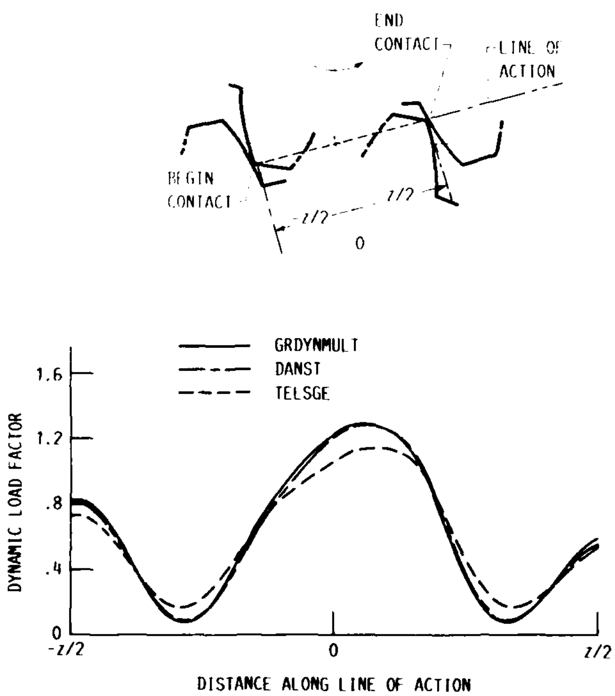


Figure 29.—Comparison of programs GRDYNMULT, DANST, and TELSGE. Dynamic load factor as function of contact position. Input torque = 203.4 N•m; input speed = 8000 rpm (Table VIII, run 11).

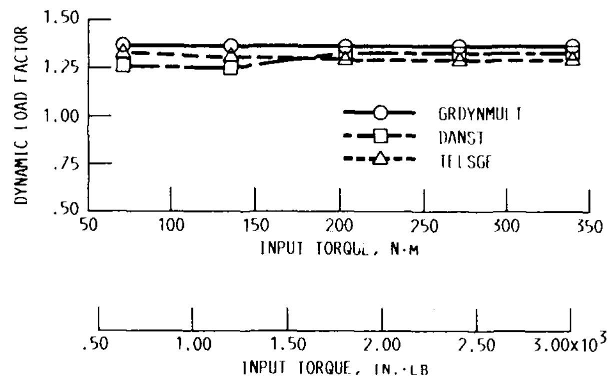


Figure 30.—Comparison of programs GRDYNMULT, DANST, and TELSGE. Maximum dynamic load factor as function of input torque at 2000-rpm input speed (Table VIII, runs 5, 17-20).

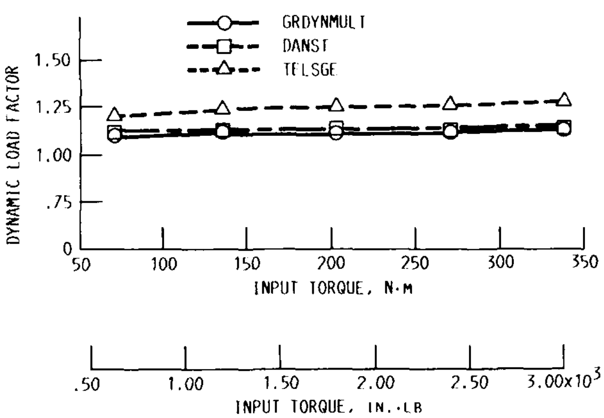


Figure 31.—Comparison of programs GRDYNMULT, DANST, and TELSGE. Maximum dynamic load factor as function of input torque at 6000-rpm input speed (Table VIII, runs 12-16).

comparison of the actual dynamic load plots from each program for a variety of speeds can be seen in figures 26 to 29. As illustrated in these figures, the dynamic load factor plots are very similar in both magnitude and form. All three programs show a decrease in the frequency of dynamic load fluctuations as the input speed increases, and a condition close to tooth separation at the 8000 rpm input speed (fig. 29). Figures 30 and 31 are plots of the maximum dynamic load factor as a function of input torque for input speeds of 2000 and 6000 rpm, respectively. As seen in these figures, the programs predict a fairly constant dynamic load factor regardless of the input torque value. This is as expected since the dynamic and static load are both linear functions of the input torque.

Tooth root stress.—Tooth root stress was another variable compared using a variety of input loads and torques. As illustrated in figure 32, the maximum root stress predicted by DANST and GRDYNMULT correlate reasonably well through the speed range, showing similar form and magnitudes that disagree only slightly (average difference within 16 percent).

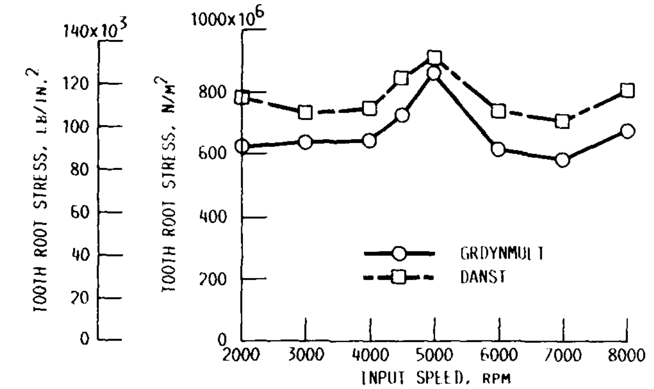


Figure 32.—Comparison of programs GRDYNMULT and DANST. Maximum tooth root stress as function of input speed. Input torque = 203.4 N•m (Table VIII, runs 5-11).

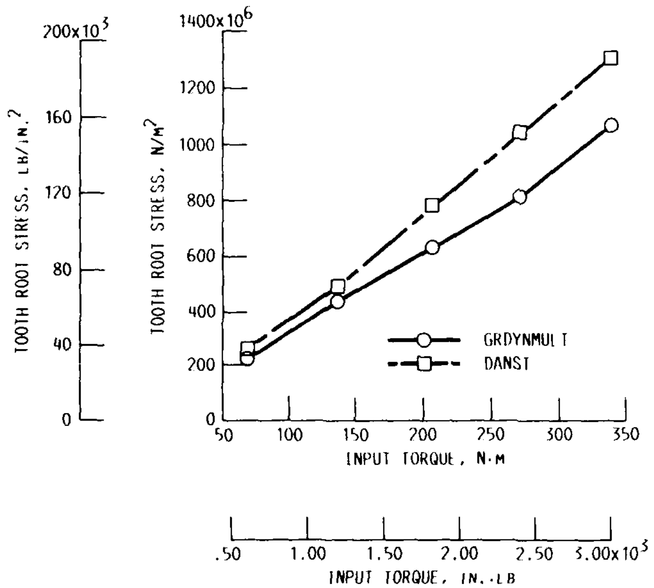


Figure 33.—Comparison of programs GRDYNMULT and DANST. Maximum tooth root stress as function of input torque at 2000-rpm input speed (Table VIII, runs 5, 17-20).

As expected, both show peak values at the 5000 rpm data point. Figures 33 and 34 plot the maximum tooth root stress as a function of input torque at input speeds of 2000 and 6000 rpm, respectively. As seen in these figures, both programs show the tooth root stress to be relatively linear with input torque. This is expected since both use a form of the modified Heywood formula which gives tooth root stress as a linear function of applied load.

Contact stress.—The local contact pressure, or hertz stress, is calculated by programs TELSGE and GRDYNMULT. As seen in figure 35, both programs show similar trends and values (average difference within 4 percent) with input speed with the exception of the TELSGE results between 5000 and 6000 rpm. Here, due to the close proximity of the half harmonic of the system, TELSGE would not converge. Both

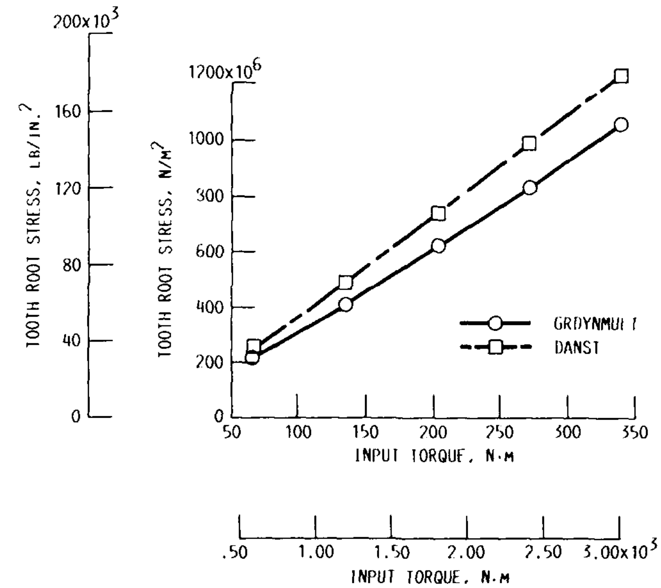


Figure 34.—Comparison of programs GRDYNMULT and DANST. Maximum tooth root stress as function of input torque at 6000-rpm input speed (Table VIII, runs 9, 12-16).

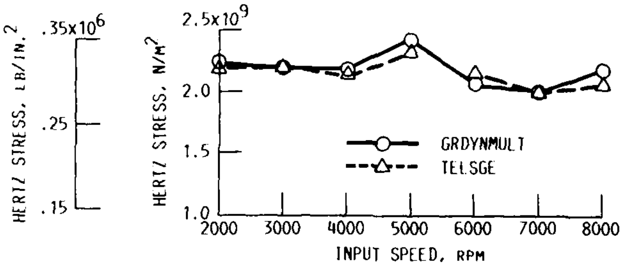


Figure 35.—Comparison of programs GRDYNMULT and TELSGE. Maximum Hertz stress as function of input speed. Input torque = 203.4 N•m (Table VIII, runs 5-11).

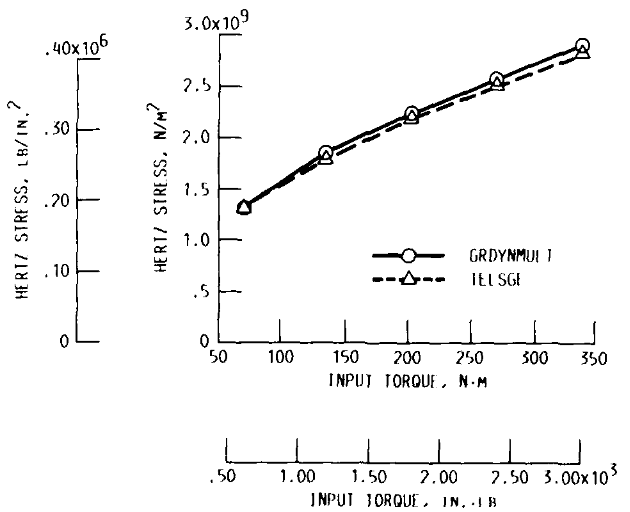


Figure 36.—Comparison of programs GRDYNMULT and TELSGE. Maximum Hertz stress function of input torque at 2000-rpm input speed (Table VIII, runs 5, 17-20).

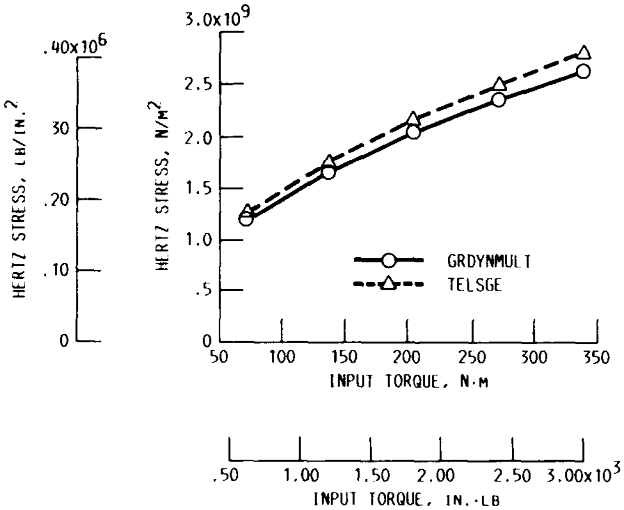


Figure 37. —Comparison of programs GRDYNMULT and TELSGE. Maximum Hertz stress as function of input torque at 6000-rpm input speed (Table VIII, runs 12-16).

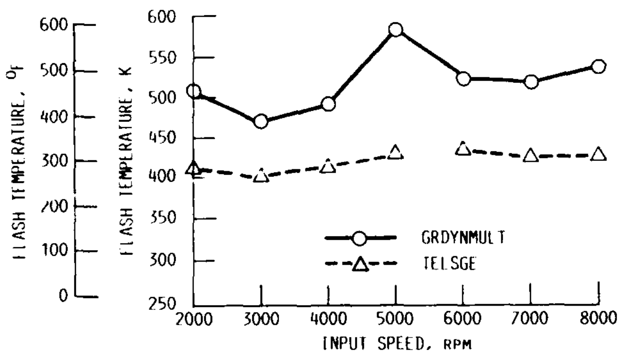


Figure 38.—Comparison of programs GRDYNMULT and TELSGE. Maximum flash temperature as function of input speed. Input torque = 203.4 N•m (Table VIII, runs, 5-11).

programs predicted nearly identical trends and values with input torque variations, as seen in figure 36 for a 2000-rpm input speed and figure 37 for a 6000-rpm input speed. The nonlinear relationship between input torque and hertz stress can be clearly seen in figures 36 and 37.

Flash temperature.—The flash temperature, as calculated by programs TELSGE and GRDYNMULT, was the last variable compared using a variety of input torques and speeds. Generally, it was found that both programs predicted similar trends with input speed and input torque; however, actual values differed by between 46 and 153 K (83 and 275 °F). Figure 38 illustrates the similar speed trends displayed by both programs. TELSGE did not converge in the input speed region between 5000 and 6000 rpm. Maximum flash temperatures are plotted as a function of input torque in figures 39 and 40 at 2000- and 6000-rpm input speeds, respectively. As seen in these figures, both programs displayed the same nonlinear increasing flash temperature trend with increasing input torque.

Profile modification.—To compare the relative effects of profile modification on the dynamic load factor as calculated

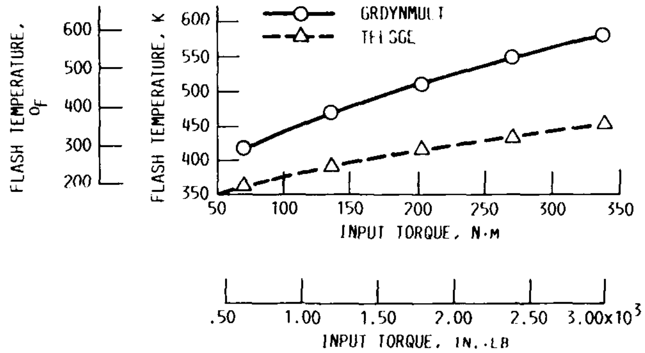


Figure 39. —Comparison of programs GRDYNMULT and TELSGE. Maximum flash temperature as function of input torque at 2000-rpm input speed (Table VIII, runs 5, 17-20).

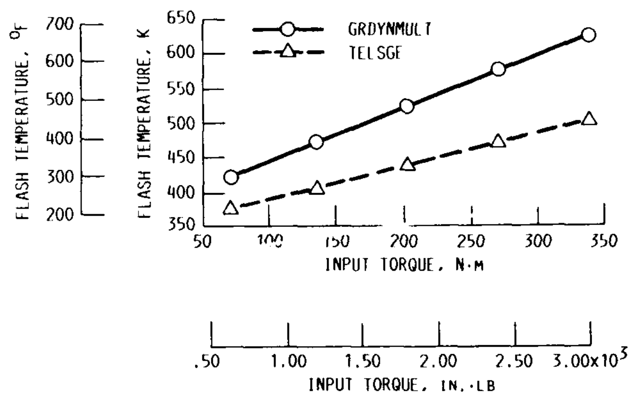


Figure 40.—Comparison of programs GRDYNMULT and TELSGE. Maximum flash temperature as function of input torque at 6000-rpm input speed (Table VIII, runs 12-16).

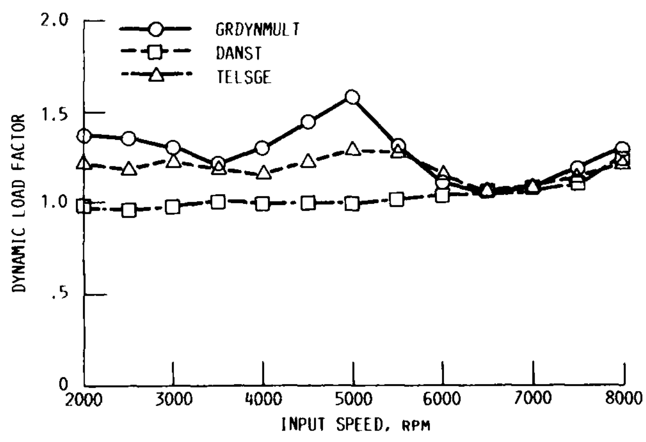


Figure 41.—Comparison of programs GRDYNMULT, DANST, and TELSGE Maximum dynamic load factor as function input speed, with tooth profile modification. Input torque = 203.4 N•m (Table VIII, run 3).

by each program, a standard tip relief was added to the single mesh system. The tip relief consisted of a parabolic shape along 50 percent of the length from the tip to the pitch point, with a maximum deviation magnitude of 0.0178 mm (0.0007 in.) at the tip. Plots of the dynamic load factor, as a function of input speed, with profile modification are given in figure 41.

Comparison of figure 41 with figure 25 (same run parameters as fig. 41 but with no profile modification) shows that the most dramatic amplitude reductions occur similarly in programs DANST and TELSGE at speeds near their predicted half harmonic speeds. DANST shows an amplitude reduction of 33 percent at the 5000-rpm data point (predicted half harmonic speed at 5191 rpm). TELSGE reduces from a divergance situation to a maximum dynamic load factor of 1.27 with profile modification at the 5500-rpm data point (predicted half harmonic speed at 5130 rpm). TELSGE and DANST also experienced similar dynamic load factor reductions at speeds below the peak amplitude speeds with profile modification added, as illustrated in figure 41. GRDYNMULT showed no appreciable difference with profile modification added. It is not known at this time why GRDYNMULT did not show any change with the addition of profile modification in this example.

Mesh damping.—To compare the relative effects of the mesh damping ratio on the dynamic load factor, a number of runs were made with mesh damping ratio input values ranging from 0.03 to 0.17. Because damping effects are more prominent at system resonance points, an input speed of 5000 rpm was chosen because of its close proximity to the half harmonic speeds predicted by each program. As illustrated in figure 42, all three programs show good correlation at damping ratios of 0.10 or greater. As seen in this figure, all of the programs predict a reduction in maximum dynamic load factor as the mesh damping ratio value is increased from 0.10 to 0.17 (12 percent reduction for TELSGE, 19 percent reduction for GRDYNMULT, and 14 percent reduction for DANST). At damping ratios lower than 10 percent, the TELSGE program diverged. The close proximity of the 5000-rpm input speed to the half harmonic of the first natural frequency predicted by TELSGE (within 3 percent of 5130 rpm) is most probably the reason TELSGE is highly sensitive to the mesh damping ratio changes at this speed. DANST and GRDYNMULT show good correlation over the whole range of damping ratios used. As seen in figure 42, as the mesh damping ratio increases from 0.03 to 0.17 both programs show a near identical decrease of the dynamic load factor in both form and magnitude (DANST: 22 percent reduction, GRDYNMULT: 23 percent reduction) from an average value of 1.64 to 1.27.

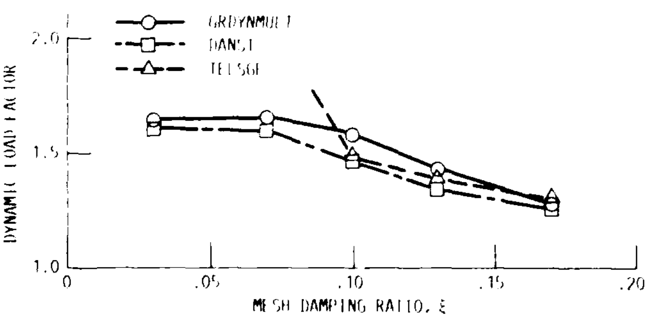


Figure 42.—Comparison of programs GRDYNMULT, DANST, and TELSGE. Maximum dynamic load factor as function of mesh damping. Input torque = 203.4 N•m, input speed = 5000 rpm (Table VII, runs 8, 21–24).

Concluding Remarks

A comparison study was performed with the gear dynamic analysis computer programs PGT, GRDYNMULT, TELSGE, and DANST at NASA Lewis Research Center. The comparison study consisted of two major parts. The first part involved a direct comparison of the capabilities, input options, and output options of the programs. Results of this study were tabulated and some general comments are as follows:

1. GRDYNMULT appears to be the most versatile in system size, type, and analysis capabilities of all the programs compared.
2. TELSGE provides the most detailed analysis on lubrication dynamics, yielding quantities such as film thickness and flash temperatures.
3. DANST incorporates the most versatile tooth profile deviation routine, allowing the user to enter standard or user defined shapes and magnitudes.
4. PGT provides a sun center movement routine which allows the user to obtain the displacement of the sun center through one or more revolutions.

The second part of the comparison study involved performing parametric comparison runs using identical input models. Some general results from this study are given below:

1. Computer programs PGT and GRDYNMULT predicted similar levels and form of the dynamic sun/planet mesh loads as the input speed was varied. Ring/planet mesh loads differed significantly between the programs.
2. Programs TELSGE, GRDYNMULT, and DANST all predicted dynamic mesh loads of similar form and magnitudes as the input speed and torque were varied. TELSGE results diverged at input speeds near its half harmonic resonant speed.
3. Root stress predictions from programs DANST and GRDYNMULT showed good trend correlation with input speed and torque variations. Magnitudes correlated reasonably well with only minor variations.
4. Programs TELSGE and GRDYNMULT predicted nearly identical hertz stress levels and trends as input torques and speeds were varied.
5. Programs TELSGE and GRDYNMULT predicted similar flash temperature trends; however, actual values were not in close agreement. GRDYNMULT consistently predicted higher than expected flash temperatures.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 19, 1988

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TABLE I.—GENERAL INFORMATION

Program name	Dynamics of planetary gear trains, PGT	Epicyclic gear dynamic analysis program, GRDYNMULT	Thermal elasto-hydrodynamic lubrication of spur gears, TELSGE	Dynamic analysis of spur gear transmissions, DANST
Documentation	NASA CR-3793	NASA CR-179563	NASA CR-3241, NASA TP-2610	NASA CR-179473
Operating system	HP 1000	IBM 370	Cray XMP	IBM 370
System types	Planetary with input/output peripheral components	Planetary system, star system, differential system, single mesh (external-external), single mesh (external-internal)	Single mesh (external-external)	Single mesh (external-external) with input and output peripheral components
System size	Single stage planetary system with three planets	Single mesh, epicyclic gear train with 20 planets maximum	Single mesh	Single mesh
Gear types	Spur gears	Spur gears, single helical, double helical	Spur gear	Spur gear
Tooth forms	Internal, external	Internal, external, buttress	External	External
Maximum contact ratio	2.0	3.0	2.0	2.0

TABLE II.—COMPARISON

Program	Gear life calculation	Calculates dynamic mesh load	Calculates combined stiffness	Calculates tooth root stress	Calculates tooth hertz stress	Film thickness calculations	Calculates surface temperature
PGT	No	Yes, for each mesh at each planet, as a function of roll angle	Yes, for each mesh at each planet, as a function of roll angle	No	No	No	No
GRDYNMULT	No	Yes, maximum value for each mesh at each planet, and as a function of position along line of contact	Yes, compliance function coefficients calculated	Yes, maximum value for each gear in mesh, and as a function of position along line of contact	Yes, maximum value for each mesh at each planet, and as a function of position along line of contact	No	No
TELSGE	Yes, based on dynamic mesh loads	Yes, maximum value, and as a function of position along line of contact	Yes, as a function of position along line of contact	No	Yes, as a function of position along line of contact	Yes, as a function of position along line of contact	Yes, gear and pinion surface temperature as a function of position along line of contact
DANST	No	Yes, as a function of roll angle	Yes, as a function of roll angle	Yes, for each gear as a function roll angle	No	No	No

OF CAPABILITIES

Calculations flash temperature	Parameter run survey	Calculates dynamic PV (surface damage) factor	Geometric preprocessor	Natural frequency predictions	Frequency analysis	Sun center movement calculation
No	No	No	Yes, for tooth geometry input in dynamic load calculation	No	No	Yes
Yes, maximum value for each mesh at each planet, and as a function of position along line of contact	Yes, speed run, determines maximum dynamic load at each mesh for each speed increment	Yes, maximum value for each mesh at each planet, and as a function of position along line of contact	Yes, for tooth geometry input in dynamic load calculation, and determines optimum profile modification	Yes, predicts natural frequencies and mode shapes of the system	Yes, with post-processing program "freplot" performs frequency analysis on mesh load variations	No
Yes, gear and pinion flash temperature as a function of position along line of contact	Yes, speed run, load run, face width run, outside radius run, number of teeth run, and surface convection heat transfer coefficient run	No	Yes, for tooth geometry input in dynamic load calculation	Yes, predicts system natural frequency	No	N/A
No	Yes, speed run, determines maximum dynamic load at each speed increment	No	Yes, for tooth geometry input in dynamic load calculation	Yes, predicts first three natural frequencies of the system	Yes, performs frequency analysis on dynamic mesh load, and on the static transmission error	N/A

TABLE III.—PROGRAM

Program	Lubrication	Iteration convergence tolerance	Mesh damping ratio	Planet gears phasing constant	Face width crowning parameter	Stiffness of peripheral shafts	Damping of peripheral shafts
PGT	No	No	Yes	No	No	Yes, actual stiffness value entered	Yes, damping coefficient entered
GRDYNMULT	Yes, choice of several oils in program, or user defined oil	Yes, number of iterations, and convergence tolerance can be input	Yes	Yes	Yes, length of face width crown, and edge relief are input	No	No
TELSGE	Yes, user inputs oil type and properties	No	Yes	N/A	No	No	No
DANST	Yes, user can define one of two lubrication models available	No	Yes	N/A	No	Yes, user inputs shaft diameter, length, and modulus for both input and output shafts	No

INPUT OPTIONS

Load and driver mass moment of inertia	Gear material	Errors	Profile modifications	Planet carrier flexibility	Ring gear rim flexibility	Floating sun gear
Yes	Yes, Young's modulus, Poisson's ratio, material density	Yes, planet phase angle error input, tooth profile error input	None indicated in documentation	No	?	Yes, sun center stiffness and damping coefficient can be input
No	Yes, Young's modulus, Poisson's ratio, material density	Yes, tooth spacing errors input, sun gear run-out errror, heli angle error	Yes, tooth profile modification shape, length along tooth surface, and magitude can be input	Yes, azimuthal planet carrier stiffness can be input	Yes, azimuthal ring gear rim stiffness can be input	Yes, sun center stiffness and damping coefficient can be input
No	Yes, Young's modulus, Poisson's ratio, material density, specific heat, thermal conductivity	Yes, 100 point array available for user defined tooth profile deviation	Yes, 100 point array available for user defined tooth profile deviation	N/A	N/A	N/A
Yes	Yes, Young's modulus Poisson's ratio, material density	Yes, 121 point array available for user defined tooth profile deviation	Yes, tip relief parameters can be input for a linear or parabolic shape, or, user can define shape using 121 point file deviation array	N/A	N/A	N/A

TABLE IV —PROGRAM OUTPUT OPTIONS

Program	PGT	GRDYNMULT	TELSGE	DANST
Printed output available	Printed as a function of gear roll angle: • Mesh stiffness • Mesh dynamic loads	Geometric preprocessor results Involute modification tables Input data Echo Constants for the fourth order compliance function Boundary conditions iteration results Maximum values for each mesh: • Hertz stress • Root stress • Dynamic load factor • Flash temperature • Dynamic PV System natural frequency results	Input data Echo Gear life calculations Printed as a function of contact position: • Combined stiffness • Dynamic load factor • Hertz stress • Film thickness • Pinion temperature • Gear temperature • Flash temperature—pinion • Flash temperature—gear Other values printed • Mesh natural frequency • Maximum dynamic load • Average mesh stiffness	Input data Echo Gear teeth deflection Static transmission error Dynamic tooth load Fourier transform of the dynamic mesh loads Fourier transform of the static transmission error
Plotted output available	Plotted as a function of gear roll angle: • Mesh stiffness • Mesh dynamic loads Sun gear center movement	Plotted as a function of position along line of action • Dynamic load factor • Pressure sliding velocity (PV) • Hertz stress • Flash temperature • Root stress—each gear Frequency analysis of mesh loads at each mesh	Plotted routine not available on Cray version	Plotted as a function of gear roll angle: • Tooth deflection • Static transmission error • Tooth stiffness • Tooth load sharing • Coefficient of friction • Torsional torque • Static and dynamic tooth loads • Tooth root stress—gear and pinion Fourier transform plot of dynamic mesh loads Fourier transform plot of the static transmission error Dynamic load factor plot for speed survey run

TABLE V —GRDYNMULT-PGT COMPARISON RUNS MATRIX DESCRIPTION

[Input torque = 33.9 N•m (300 in•lb) for all runs.]

Run number	Input speed, rpm	Sun center stiffness		Mesh damping ratio, ξ	Sun center damping	
		N/m	lb/in.		N•s/m	lb•s/in.
1	4000	1751.0×10^6	$10.\times10^6$	0.1	17.51	0.1
2	5000					
3	6000					
4	7000					
5	8000	↓	↓			
6	4000	175.1×10^6	1.0×10^6		↓	↓
7		1751.0×10^6	$10.\times10^6$	↓	3.50	.02
8		1751.0×10^6	$10.\times10^6$	.03	17.51	.1
9	↓	17.51×10^6	0.1×10^6	.1	17.51	.1

TABLE VI.—SYSTEM DESCRIPTION AND NATURAL FREQUENCY PREDICTION OF THE PLANETARY GEAR TRAIN USED IN PGT—GRDYNMULT COMPARISON RUNS

System description	
System type	Planetary
Diametral pitch	8.4667
Pressure angle, deg	22.5
Number of teeth	
Sun	14
Planets	28
Ring	70
Number of planets	3
Face width, mm (in.)	
Sun	30 (1.1811)
planets	30 (1.1811)
ring	36 (1.4184)

Natural frequency predictions (from program GRDYNMULT)

N	fn, Hz	2•fn, Hz	3•fn, Hz	4•fn, Hz
1	144	288	432	576
2	765	1530	2295	3060
3	1020	2040	3060	----
4	1416	2832	----	----
5	2378	----	----	----
6	2513	----	----	----

For PGT input only:	
J (driver), N•m•s² (in.•lb•s²)	113×10⁻⁶ (0.001)
J (load), N•m•s² (in.•lb•s²)	113×10⁻⁶ (0.001)
Input shaft stiffness, N•m (lb/in.)	1.75×10⁹ (10×10⁶)
Output shaft stiffness, N•m (lb/in.)	1.75×10⁹ (10×10⁶)
Input shaft damping, N•s/m (lb•s/in.)	0.175 (0.001)
Output shaft damping, N•s/m (lb•s/in)	0.175 (0.001)

TABLE VII.—SYSTEM DESCRIPTION AND NATURAL FREQUENCY PREDICTIONS OF THE SINGLE MESH SYSTEM USED IN GRDYNMULT—TELSGE—DANST COMPARISON RUNS

System description	
System type	Single mesh
Diametral pitch	8.000
Pressure angle, deg	20
Number of teeth (pinion)	28
Number of teeth (gear)	28
Face width, mm (in.)	6.35 (0.25)
Lubrication	MIL-L-23699

Natural frequency predictions

N	DANST		GRDYNMULT		TELSGE	
	fn, Hz	w, rpm	fn, Hz	w, rpm	fn, Hz	w, rpm
1	33	71	3963	8492	4788	10 260
2	40	86	----	----	----	----
3	4845	10 382	----	-----	----	----

For DANST input only:	
J (driver)	1•J (pinion)
J (load)	1•J (gear)
Input shaft diameter, mm (in.)	5.08 (0.20)
Output shaft diameter, mm (in.)	5.08 (0.20)
Input shaft length, mm (in.)	381 (15.0)
Output shaft length, mm (in.)	381 (15.0)

TABLE VIII—DANST-GRDYNMULT-TELSGE COMPARISON RUNS MATRIX DESCRIPTION

[A = GRDYNMULT, B = DANST, and C = TELSGE.]

Run number	Input torque		Input speed, rpm	Program used in run			Special run notes
	N•m	in•lb		A	B	C	
1	203.4	1800	Varied	X	X	X	(a, c)
2	71.8	635	↓	X		X	(a, c)
3	203.4	1800	↓	X	X	X	(b, c)
4	71.8	635	↓	X			(b, c)
5	203.4	1800	2000	X	X	X	(c)
6	↓	↓	3000	X	X	X	↓
7	↓	↓	4000	X	X	X	↓
8	↓	↓	5000	X	X	X	↓
9	↓	↓	6000	X	X	X	↓
10	↓	↓	7000	X	X	X	↓
11	↓	↓	8000	X	X	X	↓
12	71.8	635	6000	X	X	X	↓
13	135.6	1200	↓	X	X	X	↓
14	271.2	2400	↓	X	X	X	↓
15	339.0	3000	↓	X	X	X	↓
16	203.4	1800	↓	X	X	X	$\xi = 0.03$
17	71.8	635	2000	X	X	X	(c)
18	135.6	1200	↓	X	X	X	↓
19	271.2	2400	↓	X	X	X	↓
20	339.0	3000	↓	X	X	X	↓
21	203.4	1800	5000	X	X	X	$\xi = 0.03$
22	↓	↓	↓	X	X	X	$\xi = 0.07$
23	↓	↓	↓	X	X	X	$\xi = 0.13$
24	↓	↓	↓	X	X	X	$\xi = 0.17$

[a] Maximum dynamic load speed run: 2000 to 8000 rpm, step = 500 rpm.

[b] Maximum dynamic load speed run with tip relief: 2000 to 8000 rpm, step = 500 rpm, tip relief magnitude = 0.0178 mm (0.0007 in.), parabolic form, applied at 50 percent of length from tip to pitch point.

[c] Unless otherwise noted, runs used a mesh damping ratio of 10 percent ($\xi = 0.10$)

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16. Abstract

A comparison study was performed on four gear dynamic analysis computer programs developed under NASA/Army sponsorship. These programs are GRDYNMULT (a multimesh program applicable to a number of epicyclic systems), TELSGE (a single mesh program), PGT (a multimesh program applicable to a planetary system with three planets), and DANST (a single mesh program). The capabilities and features, input and output options, and technical aspects of the programs were reviewed and compared. Results are presented in a concise tabular form. Parametric studies of the program models were performed to investigate the predicted results of the programs as input parameters such as speed, torque, and mesh damping were varied. In general, the program models predicted similar dynamic load and stress levels as operating conditions were varied. Flash temperature predictions from programs GRDYNMULT and TELSGE indicated similar trends; however, actual values were not in close agreement. The program GRDYNMULT was found to be the most versatile in system size, type, and analysis capabilities. The programs DANST, TELSGE, and PGT are more specialized for specific systems; however, in specific areas they provide a more detailed treatment than GRDYNMULT.

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