LOW SPEED PROPELLERS – IMPACT OF ADVANCED TECHNOLOGIES

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ABSTRACT

Studies have indicated that the application of advanced technologies to General Aviation propellers can reduce fuel consumption in future aircraft an average of 10 percent, meeting current FAR Part 36 noise limits. Through the use of composite blade construction, up to 25 percent propeller weight reduction can be achieved. This weight reduction in addition to 7 percent propeller efficiency improvements through application of advanced technologies result in 4 percent reduction in direct operating costs, 10 percent reduction in aircraft acquisition cost, and 7 percent lower gross weight for General Aviation aircraft.

INTRODUCTION

In order to insure that USA built General Aviation aircraft remain competitive and dominant in the world market place, support energy conservation needs, and meet the more stringent environmental controls, NASA sponsored programs are necessary to improve propeller technology based for the most part on that developed during the World War II era. Attention to the area of materials used and fabrication methods is the cornerstone leading to the pursuit of advanced technology concepts and sophisticated computer analysis tools to evaluate those concepts.

Preliminary indications are that proper techniques could be developed with the utilization of composite materials in the structure of propeller assemblies. A proper blend of design and fabrication techniques will result in significant weight and cost reductions, enhanced safety through improved fatigue life, greater adaptability to a variety of design concepts and less capital requirements to produce propellers suitable to the General Aviation market.

The use of lighter weight blades will permit both the increase in blade retention hardware safety margins and the reduction in weight and complexity of such hardware.

The combination of improvements in cost and weight reduction, fatigue life increases, more consistently produced airfoil sections, and more widely varied potential design selection has a significantly broadening effect on typical installation compromises which will be apparent as the potential impact of the various advanced technologies are enumerated in later sections of this paper.

It will be shown that significant propeller weight improvements are possible for current propeller/engine/aircraft installations while achieving improvements in performance and reduced noise, both within the aircraft and in the airport environment.

The potential propeller weight reductions and efficiency improvements can directly result in reductions in aircraft fuel consumption, direct operating costs, acquisition cost, and lower gross weight.

Improvements in propeller fatigue safety margins would permit corresponding increases in overhaul life, provide greater tolerance for field maintenance or lack of same and thus increase safety, productivity, and economy.

The current research program awarded to McCauley is needed to structure a realistic and effective technology plan for General Aviation propellers, to identify the advanced technologies and their potential costs and benefits, and to determine and identify areas of key technical risks and required research programs (Figure 1). It is hoped that once the areas of greatest potential are identified, NASA research funding can then be channeled into the most appropriate areas. The team comprising the current study effort (contract number NAS3-21719) is highlighted in Figure 2.

SENSITIVITY STUDIES

Sensitivity studies were performed to evaluate the potential of each technology element on propeller performance, noise, weight, and cost for the following two categories of General Aviation aircraft:

I. Low speed (up to 250 knots)/low power (up to 350 HP), 2 - 8 place, single and twin engine, currently powered by reciprocating engines.

II. High speed (up to 400 knots)/high power (up to 650 HP), 6 - 18 place, twin engine, turboprop.

In order to evaluate the improvement potential for the various technology elements, specific aircraft satisfying the characteristics outlined above for each category were chosen. The representative aircraft, illustrated in Figure 3, chosen for each aircraft category, are as follows:

Category I	:	Cessna 172N Cessna 210M Cessna 414A
Category II	:	Cessna 441

TECHNOLOGY ELEMENTS INVESTIGATED

Technology elements were considered with the potential for improving airplane/mission characteristics such as fuel burned, direct operating cost, acquisition cost, and gross weight. The original scope of technology elements considered were screened to include any element felt to have any potential whatsoever based on McCauley experience, other's experience, and available literature. Each technology element was first evaluated in terms of its effect on propeller criteria of merit including performance, noise, weight, cost, and structural considerations. The total impact of the technology elements affecting performance and weight were then investigated to determine their impact on airplane/mission characteristics. The General Aviation propeller concept incorporating the appropriate advanced technologies is illustrated in Figure 4.

PERFORMANCE CONSIDERATIONS

The following list of technology elements show potential for performance improvements. The element is specified along with the loss to be minimized, keeping in mind the practical limitations of each of the technology elements and their impact on other important propeller criteria of merit such as noise, weight, and structure.

Technology Element	Performance Loss To Be Minimized	Reference Utilized
Design optimization		
Decreased power loading	Axial momentum	1
Increased number of blades	Tip	1
Maintain tip speed	Axial momentum	1
Decreased activity factor	Profile	2
Use of proplets	Tip	Purdue Univ.
Use of sweep (helical tip mach number reduction)	Compressibility	2
Advanced technology airfoil type	Compressibility, profile	4
Decreased thickness ratio	Profile	2
Improved propeller/nacelle integration	Blade profile, nacelle drag	2,3
Improved surface finish	Profile	5,6,7
Maintainability of airfoil shape	Profile	7

The advanced technology concept of sweep is unique since it both improves performance and reduces noise. The predicted effect of sweep on performance and noise is shown in Figure 5. Sweep is structure limited with 25-30 degrees probably feasible for future General Aviation applications. The effect of sweep in addition to the effect of other significant advanced technology elements on cruise performance gains are shown in Figure 6. Power loading, number of blades, tip speed, activity factor, and proplets are grouped together and classified as design optimization parameters. Maintainability of airfoil shape is not included since it is a parameter to prevent degradation through the use of composites and not to improve current technology.

ACOUSTIC CONSIDERATIONS

The primary technology elements affecting acoustics are number of blades, tip speed, thickness ratio, activity factor, sweep, blade loading, advanced technology airfoils, and proplets.

The following is a list of these primary technology elements:

Technology Element	References Utilized
Design Optimization	
Increased number of blades	8
Decreased tip speed	
Decreased activity factor	
Use of proplets	Purdue University
Peak blade loading moved inboard	8
Use of sweep (helical tip mach number reduction)	8
Advanced technology airfoil types	
Decreased thickness ratio	

As with performance considerations, several elements are grouped together under design optimization. From the acoustic standpoint, all items other than advanced airfoils, sweep, and reduced thickness ratio are considered design optimization variables. The main technology elements affecting acoustics, including sweep whose effects were isolated earlier, are shown in Figure 7. These gains can be realized without any noticeable loss in performance. The delta dB(A) improvements possible are in many cases more than that required to meet noise regulations. During design tradeoff studies, the relative importance of each design parameter must be evaluated. Greater noise reductions could be obtained if one were willing to sacrifice performance.

MATERIAL CONSIDERATIONS

In order to reliably meet the future performance and acoustic requirements of General Aviation propellers with weight reduction and approaching price competitiveness with aluminum, consideration of composite materials requires appropriate attention as a viable solution. Advanced filamentary composite materials combine low densities and low notch sensitivity with high strengths and stiffnesses. Adequate safety margins of current propellers can be further enhanced. Figure 8 outlines the advantages of composites and their associated propeller benefits. Because filamentary materials are only strong in the filament direction, careful consideration must be given to ply orientation to match the design requirements.

Through variations in the composite matrix, blade sections can be tailored to meet the specific radial stiffness distribution required. The shape of primary bending and torsional modes can be altered effectively through the use of composites. Reductions in blade section size permissible with composites will result in higher blade deflections than are customary with aluminum. Blade aeroelastic instabilities can result from large out of plane deflections and must be given careful consideration.

Appropriate blade materials, type of hub retention system, methods of construction for composite materials, and material consideration for blade leading edge erosion resistant strips are all areas which must be addressed in detail.

STRUCTURAL CONSIDERATIONS

In evaluating the structural integrity of advanced technology propellers, considerable attention must be given to the steady and alternating loadings experienced in service. The steady loads consist primarily of centrifugal, bending due to thrust loading, and torsion. The alternating vibratory loads are due to blade aerodynamic excitations and alternating torsional input due to reciprocating engine cylinder firing sequence and frequency. Aerodynamic inflow angles excite 1xP alternating loads which are primarily evident on turboprop installations being overshadowed by engine alternating torsionals in reciprocating installations. In all installations one should assure that 1xP resonance does not occur in the normal operating RPM range.

It is a relatively easy job to evaluate the steady loads on a propeller blade using conventional techniques. To determine the vibratory effects, however, with incorporation of advanced technologies such as sweep and proplets, may require the use of three dimensional finite element analysis rather than two dimensional beam analysis or lumped parameter matrix manipulation techniques currently utilized. With regard to vibratory analysis, available analytical techniques applicable to General Aviation propellers determine mode frequencies with good accuracy and vibratory loads and resultant stresses within 25-30 percent on turbine installations. The effect of alternating torsionals from reciprocating engines is currently not included in existing models. Experimental testing of strain gaged propellers is still relied upon heavily. Experience and experimental data will dictate allowable alternating stress levels with composites as is the case with aluminum alloys.

Using the torsional mode results from three dimensional finite element analysis (3-D FEA), the possibilities of stall flutter can be addressed. The stall flutter parameter is based on static torsional frequency, and semichord, velocity, and mach number at the 80 percent blade radius location. Through extensive experimental programs, a stall flutter boundary has been determined for conventional blade shapes. A similar boundary must be determined for blade shapes incorporating the advanced technology concepts outlined in Figure 4.

Stall flutter occurs under conditions of blade angle of attack and inflow velocity where a major portion of the blade is stalled. Stall flutter oscillations occur at the first torsional mode when the spanwise damping integration along a blade becomes zero or less. The conditions conducive to stall flutter are during static, takeoff, and reverse thrust operation.

By using the bending and torsional mode data from 3-D FEA and customarily presented in terms of a Campbell diagram, classical flutter can be addressed. Classical flutter can occur at high aircraft velocities where the mode spacing over the operating RPM range is insuffient and a coupling of torsional and bending modes occur (reference 9).

Because of the limited composite fatigue strength data available and the lack of analytical techniques to predict vibratory loads, the evaluation of fatigue life is highly qualitative. Only through extensive test programs and field experience, can the required data base of information be compiled from which the appropriate fatigue limits can be determined. This same process occurred many years ago to establish the current baselines utilized for aluminum.

BLADE WEIGHT, COST, AND AIRCRAFT MISSION CONSIDERATIONS

Preliminary screening of candidate materials indicates configurations of E-Glass, S-Glass, Kevlar, and Graphite with medium and high density epoxy cores to meet the mean load, alternating load, fatigue, and weight requirements of General Aviation propellers. Relative blade weight and cost comparison against aluminum are shown in Figure 9. In determining the impact of weight reductions through the use of composites it must be emphasized that the blade weight savings exist only with a direct replacement of aluminum blades. This does not take into account the blade retention area. Also, in order to achieve a desired compromise of advanced technologies between performance and noise, the potential weight savings may be reduced. In other words, the trends of decreased power loading through diameter increases, increased number of blades, sweep, and proplets will tend to increase weight while being offset through lower blade activity factors and lower thickness ratios (feasible because of composites).

The performance gains indicated earlier in addition to weight reductions possible through the use of composites have a direct effect on aircraft/mission characteristics such as fuel burned, operating cost, acquisition cost, and gross weight. In addressing mission analysis, payload, range, speed and aircraft lift to drag ratio are kept constant. Potential trip fuel savings versus aircraft cruise speed are shown in Figure 10. This assumes two hours at cruise, felt to be fairly representative. Studies indicate that average trip fuel reductions of about 10 percent result in 4 percent reductions in direct operating costs. Included in DOC determination are engine and airframe periodic maintenance, fuel and oil burned, reserves for engine and propeller overhaul, reserves for avionics, systems and miscellaneous. As fuel prices raise in the future, their effect on increases in DOC will be as indicated in Figure 11.

Aircraft acquisition cost reductions average about 10 percent. Reductions as affected by aircraft cruise speed are indicated in Figure 12. A twenty-five percent increase in propeller cost has been taken into account but does not alter the results since the propeller cost is so low in relation to aircraft cost. Studies also indicate average potential aircraft gross weight reductions of seven percent.

FUTURE RECOMMENDATIONS

It is apparent from the sensitivity studies performed on the various technology elements that NASA funding directed primarily into the areas of composite materials research, and the advanced technology concepts outlined in this paper can provide the data base required to achieve the stated airplane/mission improvements.

Since many technology elements improving performance have an adverse effect on acoustics and future government regulations controlling noise limits will probably be more stringent, it is imperative that research funding be expended in this area. This should include careful evaluation of current methodology of propeller noise prediction techniques and the unification into a common, recognized procedure for utilization by the General Aviation community. Experimental verification of resulting theories through wind tunnel testing and flight substantiation is necessary.

Through the use of composites, some of the more promising technology requirements will become possible such as thickness ratio reductions, sweep, lower activity factors, reduced power loading, more blades, advanced airfoils with complex curvature, smoother airfoil surface, and maintainability of airfoil shape in service. These factors lead to optimized designs meeting appropriate strength requirements. At a certain blade load level, the composite blade will deflect more. This can lead to aeroelastic instabilities which is an important area requiring NASA support. Although considerable research has taken place in the composite materials area, the product applications have not included propellers. The aircraft propeller is one of the most critically stressed aircraft components. It operates in a severe environment and is a major structural component with complex stress distribution. It is exposed to the wide range of variables created by power plants in a most intimate manner. The successful use of composite materials in General Aviation propellers will provide information on fatigue to establish limit lines of mean stress versus alternating stress for 10^5 and 10^8 cycles as typically represented on a Goodman diagram. Such information is not readily obtainable in any other application.

NASA sponsored research will help fill the gap in the application of composite technology (design and fabrication methods) between current applications and their potential use with propellers. Advanced composites technology has progressed to a point where reliable application as aircraft secondary structure is accepted and the application for primary structure is relatively close but the confidence level for commercial application has not been established. It is, therefore, highly desirable and appropriate to explore this General Aviation application.

Specifically, the total cost of composite blades must be nearly competitive with aluminum blades in order to experience wide use in General Aviation. Research into low cost fabrication techniques is the key to achieving cost competitiveness. Wind tunnel testing with follow-on programs for flight test verification is necessary.

In the advanced airfoil design area, NASA has continually made efforts in improving communication with the General Aviation community over the past five years through workshops, symposiums, conferences, etc., and from these have come airfoil design implementation schedules satisfying the needs of wing designers. What is needed now is an airfoil technology plan to design airfoils specifically tailored for the widely varying fluid flow conditions which prevail along a propeller blade.

The area of propeller/nacelle integration is already receiving some attention by NASA with Grant NSG1402 to Mississipi State University. The first phase involving the collection of baseline data in the NASA-Langley full scale tunnel is just getting underway. Current program calls for investigation of nacelle shapes characteristic of those used in twin reciprocating engine installations. There should be future testing including a wide variety of propeller/nacelle configurations covering the broad range of aircraft/engine combinations typical of the General Aviation fleet.

NASA has supported analytical studies to provide special purpose user oriented programs to calculate propeller inflow velocity fields, steady and unsteady aerodynamic loads and mode shapes and frequencies. The next step should be to concentrate on analytical procedures to predict the vibrational loads and stresses the propeller is subjected to in service. The model must include the coupling effects of the propeller-engine system. Accuracy of existing prediction techniques is not acceptable except for 1xP analysis. Higher order stresses prevalent with reciprocating engine installations are not predicted with adequate accuracy. A good, reliable prediction technique would eliminate much of the uncertainty which exists prior to vibration survey certification testing. Wasted time and cost associated with experimental testing of a configuration exceeding vibratory load limits could be nearly eliminated.

With the very competitive market in General Aviation which limits funds in research and development, it is very evident that NASA sponsored support is necessary to enhance the state of the art in the areas mentioned above. The key areas requiring future research enumerated above are highlighted in Figure 13.

CONCLUDING REMARKS

The study of a wide range of propeller design variables and advanced technologies has indicated that the potential exists for propeller performance improvements and weight reductions meeting consistently more stringent regulatory noise levels. Advanced technological development of propellers has a direct impact on the fuel burned, direct operating costs, acquisition cost, and gross weight of General Aviation aircraft. NASA can assure that these goals are met by allocating appropriate funds in the areas where the greatest potential exists.

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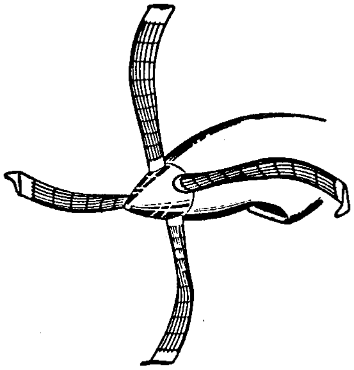
ADVANCED TECHNOLOGY PROPELLER STUDY



- IDENTIFY ADVANCED TECHNOLOGIES
- ASSESS BENEFITS, COSTS & RISKS
- DEFINE OPTIMUM CONFIG., MISSION ANALYSIS
- FORMULATE RESEARCH PROGRAM

FIG. 1

TEAM COMPRISING STUDY EFFORT

- McCAULEY
  PROGRAM MANAGEMENT, PERFORMANCE, COST, STRUCTURES
- CESSNA
  AIRPLANE MISSION ANALYSIS
- OHIO STATE
  ACOUSTICS
- MATERIALS SCIENCES & SAI
  COMPOSITES

FIG. 2

BASELINE AIRCRAFT STUDIED

FIG. 3

ADVANCED TECHNOLOGY CONCEPTS

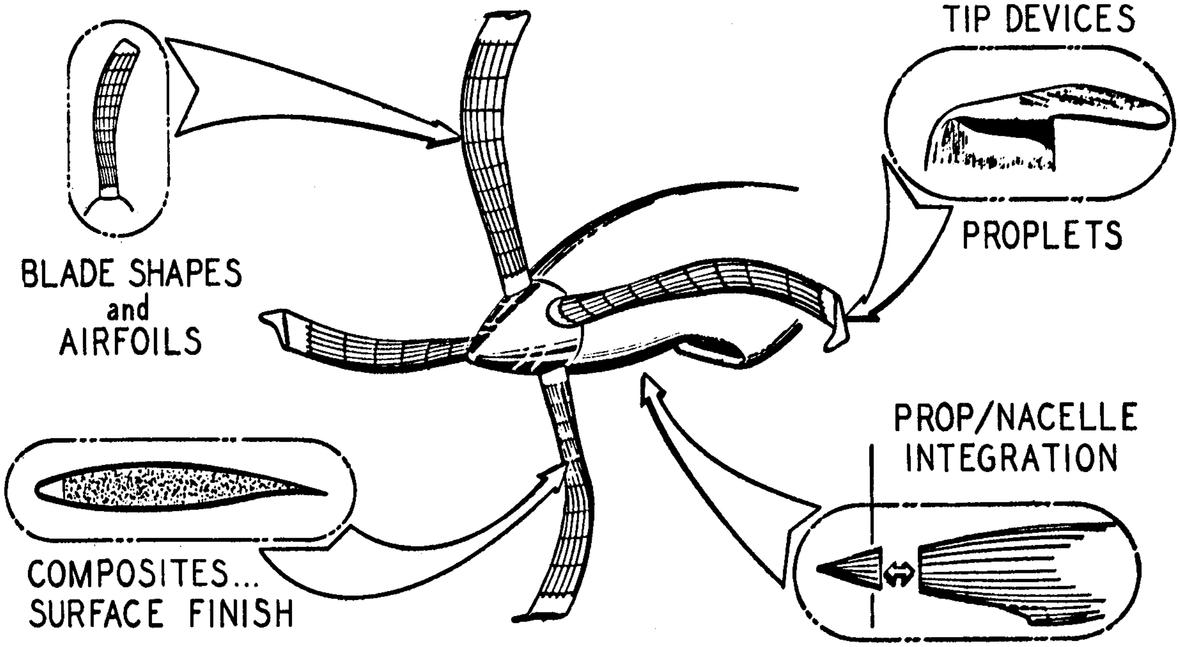


FIG. 4

PREDICTED EFFECT OF SWEEP ON PERFORMANCE AND NOISE

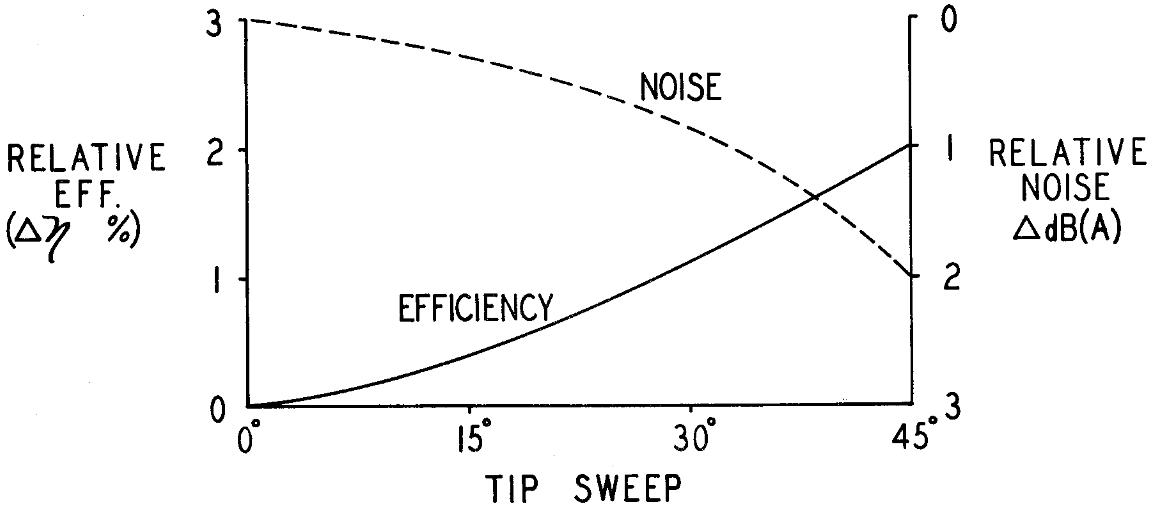


FIG. 5

POTENTIAL CRUISE PERFORMANCE GAINS

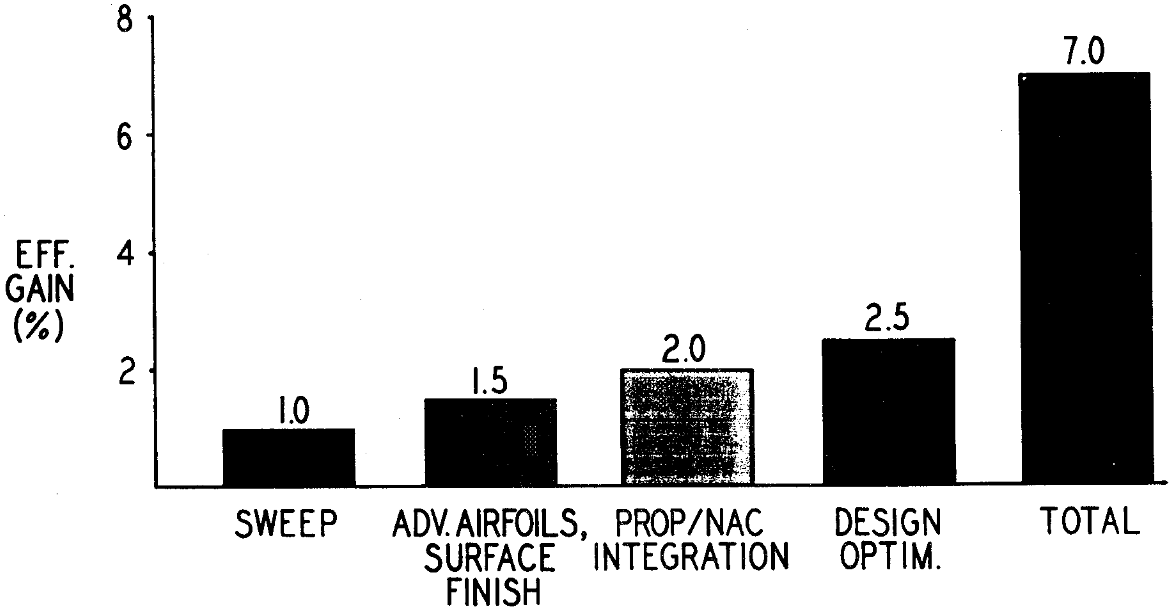


FIG. 6

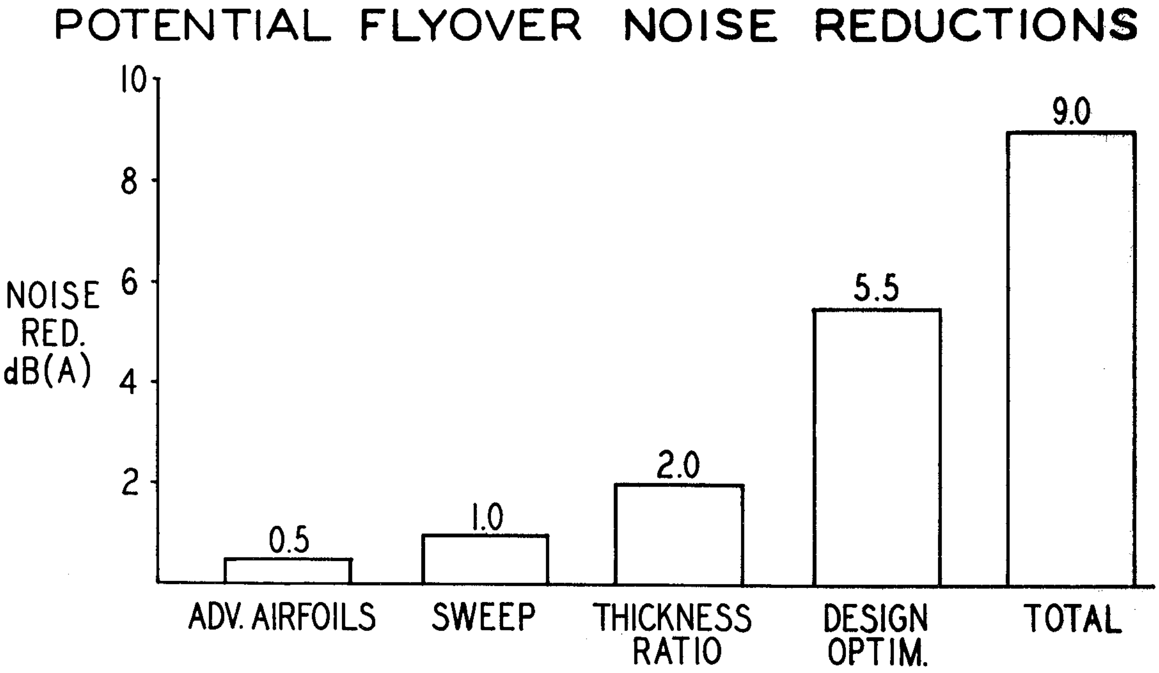


FIG. 7

BENEFITS OF COMPOSITE MATERIALS

COMPOSITE ADVANTAGES	PROPELLER BENEFITS
GREATER STRENGTH	LOWER WEIGHT
LOWER DENSITY	IMPROVED PERFORMANCE
HIGHER MODULUS	LOWER NOISE
LOWER NOTCH SENSITIVITY	ENHANCED SAFETY MARGIN

FIG. 8

BLADE WEIGHT AND COST COMPARISON

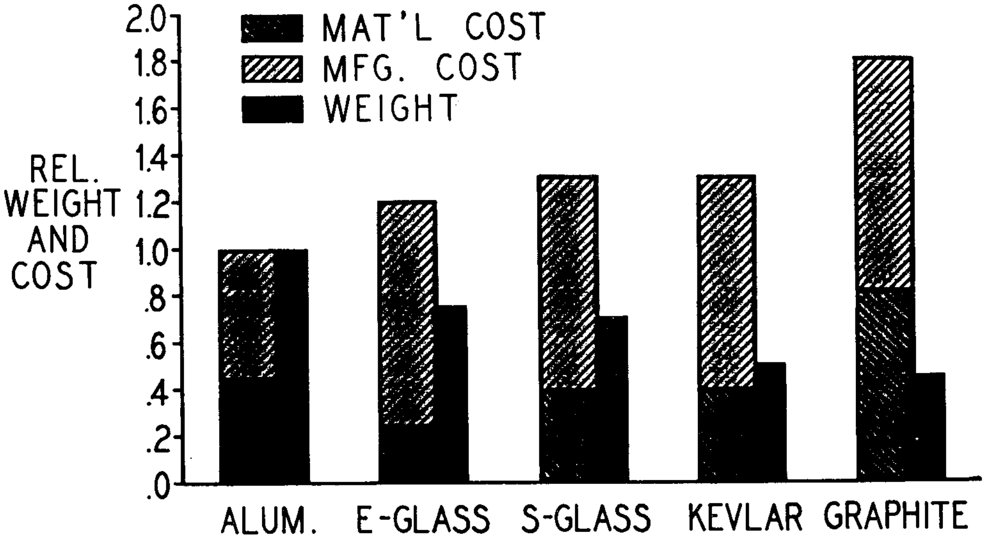


FIG. 9

POTENTIAL TRIP FUEL SAVINGS

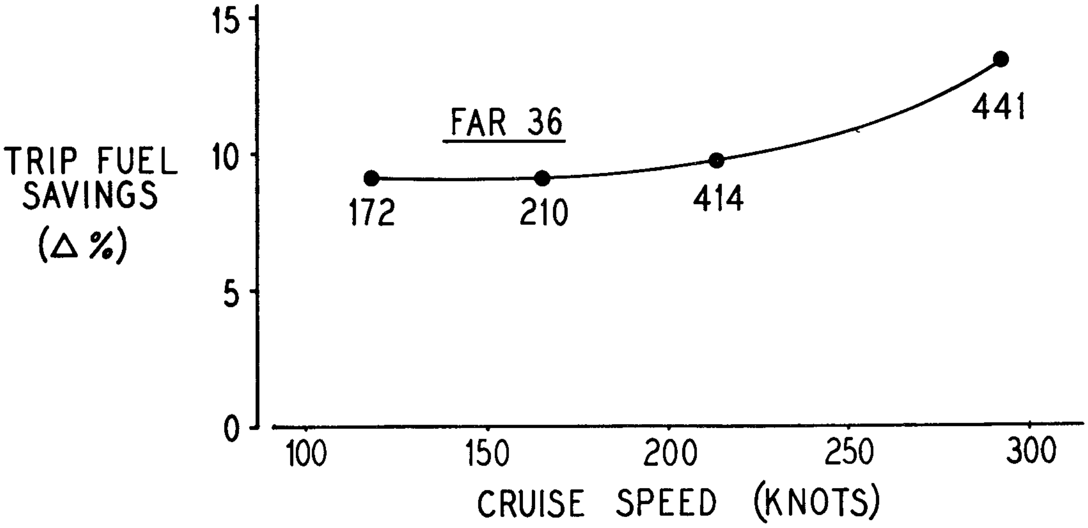


FIG. 10

FUEL PRICE EFFECTS ON DIRECT OPERATING COSTS

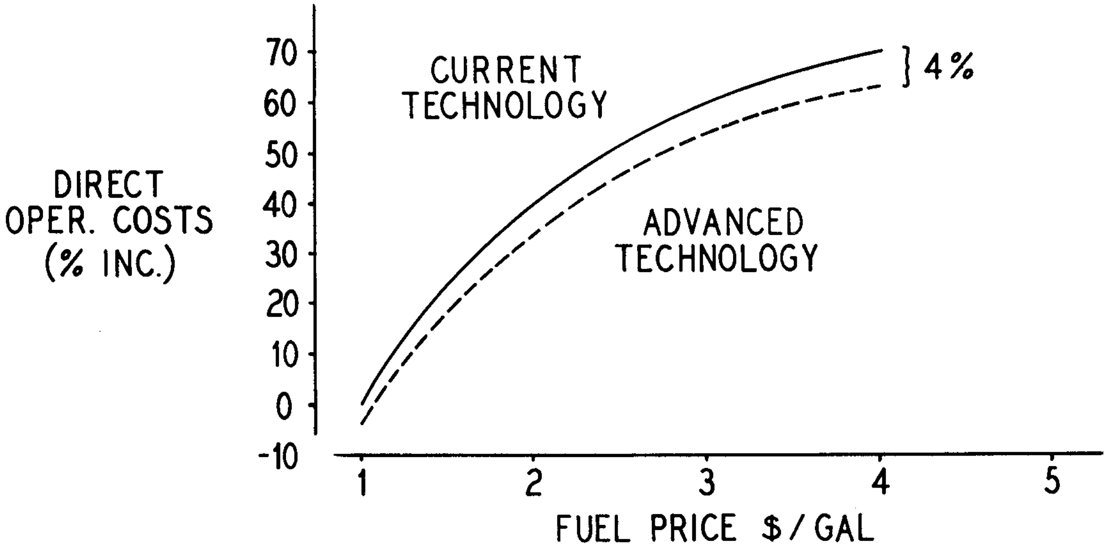


FIG. 11

AIRCRAFT ACQUISITION COST REDUCTIONS

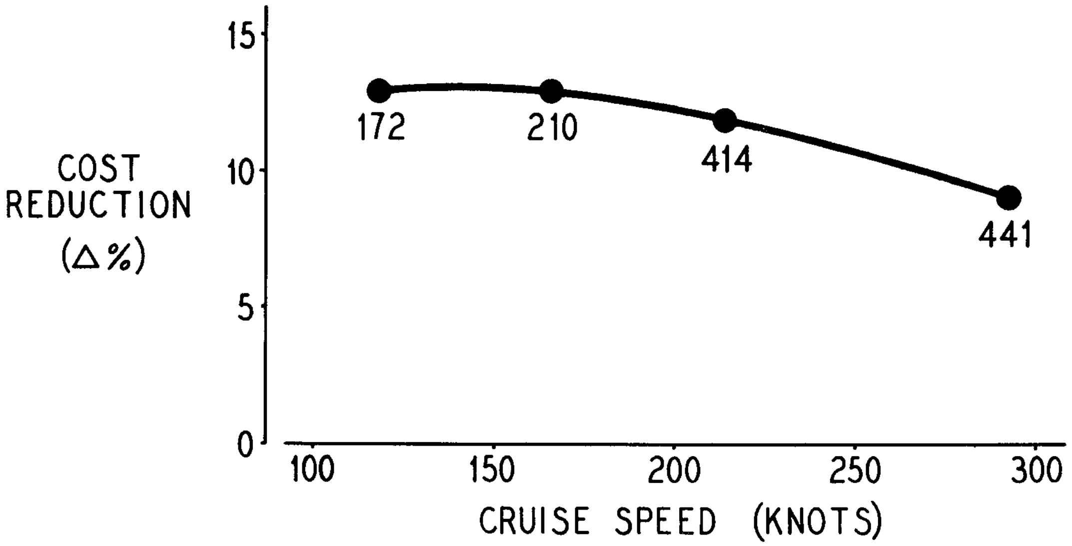


FIG. 12

PROPOSED RESEARCH PROGRAM

- PERFORMANCE
- NOISE
- AEROELASTICS
- COMPOSITES
- OPTIMIZATION
- FULL SCALE VERIFICATION

FIG. 13