NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 09/14/95

Project No. E-24-X51
Project Director BARTHOLDI J J
Center No. 10/24-6-R8126-0A0
School/Lab ISYE

Sponsor AIR FORCE/BOLLING AFB, DC
Contract/Grant No. F49620-94-1-0232
Contract Entity GTRC

Title STATIC & DYNAMIC BALANCE OF ROTOR STACKS

Effective Completion Date 950430 (Performance) 950630 (Reports)

Closeout Actions Required:

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<tr>
<th>Action</th>
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<td>Final Invoice or Copy of Final Invoice</td>
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<tr>
<td>Final Report of Inventions and/or Subcontracts</td>
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<td>Government Property Inventory &amp; Related Certificate</td>
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<td>Classified Material Certificate</td>
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<td>Release and Assignment</td>
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Comments

Subproject Under Main Project No.
Continues Project No.

Distribution Required:

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<td>Administrative Network Representative</td>
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NOTE: Final Patent Questionnaire sent to PDPI.
AMENDMENT - PROJECT

PROJECT HEADER INFORMATION

Project #: E-24-X51
Center #: 10/24-6-R8126-0A0
Contract#: F49620-94-1-0232
Prime #: 

Subprojects ?: N
Main project #: 

Cost share #: E-24-347
Center shr #: 10/22-1-F8126-0A0
Mod #: BUDGET REVISION

Rev #: 6
OCA file #: 
Work type : RES

Contract entity: GTRC

Active

Project unit: ISYE
Project director(s): BARTHOLEDI J J, VANDE VATE J H

OCA file #: 03/27/95
Rev #: 6
OCA file #: 

ISYE

Rev #: 6
OCA file #: 

Contract #: F49620-94-1-0232

Unit code: 02.010.124

Sponsor/division names: AIR FORCE
Sponsor/division codes: 104

Award period: 940501 to 950430 (performance) 950630 (reports)

Sponsor amount
Contract value New this change
Funded 0.00
Cost sharing amount

0.00
7,000.00

Total to date
40,000.00
40,000.00

Does subcontracting plan apply ?: N

Title: STATIC & DYNAMIC BALANCE OF ROTOR STACKS

PROJECT ADMINISTRATION DATA

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Sponsor issuing office
JENNIFER BELL (202)767-0623

Security class (U,C,S,TS) : U
Defense priority rating :

Equipment title vests with: Sponsor

ONR resident rep. is ACO (Y/N): N
supplemental sheet

REF. PG. 2, AUTHORIZATION TO PURCHASE PERMANENT EQUIPMENT LISTED.

Administrative comments -

PROCESSED 3/8/95 BUDGET REVISION
trudy, here is a copy of the report we sent last spring to our program manager, Dr. Neal Glassman of AFOSR.

-- john

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Dear Neal,

Our collaboration with Pratt & Whitney has been stalled a bit since the fall because they are undergoing a major reorganization. In a phone call yesterday, Bill Weiblen, Director of Assembly Engineering, reaffirmed their commitment to this project and apologized for delays in providing the data with which to test our ideas. He has invited us to come this spring to work directly with their engineers. Meanwhile, we have continued to press on in research.

Best Wishes,

John

PS I am sending some transparencies to illustrate the issues following.

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1. Research Accomplishments to date

Our main accomplishment has been to devise and analyze a heuristic algorithm that guides assembly of jet engine rotors to reduce static unbalance.

Jet engines are assembled by welding or bolting together smaller discs. As a first step in investigating methods for reducing vibration, we focused on the problem of reducing the static unbalance in each disc. One source of unbalance in a disc is differences in the weights of the fan blades sequenced around it. Consequently we began by considering the problem of sequencing the blades around the disc so that their center of gravity coincides with the center of the disc.

Unfortunately, this is NP-hard even in its simplest idealization. Nevertheless, we have devised a fast heuristic with guaranteed worst case performance. In fact, when the number of blades is even, but not a multiple of four, our heuristic provides the strongest possible worst case performance guarantee. In other words, no other procedure can provide a better performance guarantee---not even the hopelessly impractical procedure of trying all possible ways of sequencing the blades.

Theoretical analysis strongly indicates that our new procedure is superior to current industry practice. We plan to introduce this new technique on the shop floor at Pratt & Whitney during the spring.

The performance guarantee of our procedure is expressed in terms of the magnitude of the difference between successive weights of fans. This kind of bound allows us to set the manufacturing tolerances for the blades at exactly the level required to guarantee a specified quality of balance in the final
assembly. For example, the sixth stage turbine disc of the Pratt & Whitney PW 2000 jet engine must be statically balanced at a minimum of 900 rpm to within 1.0 ounce-inch without adding counterweights. Our procedure guarantees this quality of balance if the difference between successive weights is no more than 0.08 ounces. To provide the same guarantee when the blades are sequenced according to current practice, the difference between successive weights must not exceed 0.008 ounces, a manufacturing tolerance that is an order of magnitude more demanding. Thus, intelligent assembly allows the manufacturing tolerances to be relaxed significantly while guaranteeing the same performance specifications.

This illustrates the theme of our research: Intelligent assembly can reduce manufacturing costs without sacrificing performance.

Our work produced an interesting insight that may have practical implications: Our procedure has a better guarantee of performance when the turbine disc has an even number of blades---but not a multiple of four. Intuition supports this, at least in retrospect: When there are an even number of blades, we can place opposing pairs so that the resultant unbalances counteract each other...except when the number of blades is a multiple of four, when orthogonal pairs are independent of one another. Of course this effect is less pronounced with more blades; but it suggests that, where possible, turbine discs should be designed to have an even number of blades but not a multiple of four. Such discs will be easier to balance.

2. Technology Transitions

This has been delayed by continuing reorganization within Pratt & Whitney.

Our first goal is to introduce our procedure for statically balancing discs by placement of fan blades. This is planned for spring 1995.

Meanwhile, we continue to collaborate with Pratt & Whitney to develop a computer system that will use information about part geometry and mass distribution to predict the engine vibration from a given assembly and will recommend a "good" assembly that produces little vibration. This effort is aimed at reducing vibration in the engine of the F-22.

We continue to develop software tools for modelling the shape and mass distribution of the engine resulting from a given assembly and optimization tools for finding an assembly that minimizes various approximations of the vibration.

We hope to get data soon from Pratt & Whitney so that we can begin to evaluate the performance of our tools on real engines.

3. Accomplishments expected by end of 1995

- To have implemented our blade sequencing procedure at Pratt & Whitney.
- To have a prototype system running to stack rotors to reduce dynamic unbalance.
- To understand the relationships between blade sequencing and rotor stacking. In particular, can we make-up for poor rotor stack with good blade sequencing?
- To have analyzed performance of the current practice of orienting successive rotors so that their high points are diametrically opposed.

- To understand which aspects of rotor geometry are most critical for good dynamic balance. Is it eccentricity? Is it parallelism?

In addition, we have been asked by Delta Airlines to consider how their planes can be loaded to improve balance. The difficulties are similar to those faced by, for example, MAC: There are constraints on which items can be loaded where and on the total volume and weight. Also items must be loaded for easy unloading. And finally, not all information is available in advance: Some items are known exactly in advance; some are known only statistically from past experience; and some are not known at all until it is time to load them.

We have made three trips to Delta Airlines Operations to learn more about this problem; and anticipate becoming more closely involved with it during the fall.