Automated Component Select

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ABSTRACT

The goal of the automated component select project is to reduce, to under one hour, the time for component select on the Dynamically Tuned Gyro (DTG). Currently, the process takes from 4-7 hours. This paper reports the status of the project and lays the theoretical foundation for the automation of the component select process.

A three dimensional geometric model of pickoff circuitry response is presented which, for the first time, provides an algorithm to predict the correct components to null the gyro. The method was tested manually on two gyros in the engineering environment and was found to be successful in both axes of both gyros in one iteration. Component selection was performed in two hours.

Automation of the component select process presented in this paper could save Smiths Industries millions of dollars in DTG build time of the next decade.

OUTLINE

Introduction:

In the introduction, an overview of the component select project, aspects of the gyro circuitry which are critical to the understanding of the current problems, and the history of the component select process will be presented. Finally, the goals of this paper will be outlined.

Goal of the Component Select Improvement Project:

The goal of the automated component select project is to reduce, to under one hour, the time it takes to select components for the dynamically tuned gyro (DTG). Currently it takes operators from four to seven hours to select components on a gyro. Moreover, because the component select process requires in depth operator knowledge, excessive and costly operator training time is required. The impact of the cost savings to Smiths Industries would be enormous if the one hour automated component select procedure were developed. Not only would less time be required in the component select phase of DTG build, but cockpit type operator errors would be virtually eliminated. Component select automation will fit in well with the production effort to automate the entire gyro calibration process.

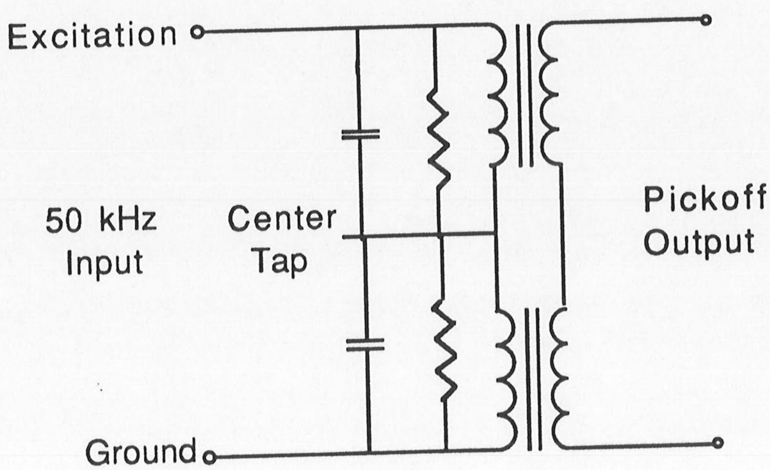
Goal of Component Select Process:

The goal of component select is to bring the electrical null of the pickoff circuit to be coincident with the mechanical null of the rotor. To more clearly explain the component select process, both electrical and mechanical null will be defined.

First, the pickoff circuit is said to be at electrical null when its output is zero. As will be shown later, the pickoff circuit output is a function of both the resistor and capacitor in the pickoff circuit and the position of the rotor. Second, the mechanical null of the rotor is defined as the position of the rotor where it spins freely with no extraneous torques, the rotor's "happy" state. For a given gyro there is only one mechanical null position, but the mechanical null position can vary form gyro to gyro due to variations in the mountings between the suspension, shaft, and rotor.

The Pickoff Circuit:

Figure 1 shows a simplified version of one axis of the pickoff circuit.



The resistor can be either to excitation or to ground.
The capacitor can be either to excitation or to ground.

Figure 1
The Pickoff Circuit

The transformers in this circuit are the rotor pickoffs. When the rotor changes position, the transformers change their coupling because of a change in the air gap above the transformers. Thus, a change in rotor position results in a pickoff circuit output.

The component select process yields resistors and capacitors for the pickoff circuit which force the output of the circuit to be zero when the rotor is in its mechanical null position.

How is it known if the rotor is in its mechanical null position? If there are no extraneous torques on the rotor, the spin speed of the rotor could be changed from the resonant speed to a different speed without causing a change in rotor position. In the lab, this means that a 120 Hz reduction in the motor excitation frequency will not result in a change in the torquer voltage. If the rotor is not running in the mechanical null position, it can be brought back into mechanical null by injecting a potentiometer-controlled voltage into the torquers. Automation of the voltage injection is described in the auto-null portion of this report.

The Difficulty with Component Select:

Several factors make component select a difficult process to characterize. The fact that every gyro's rotor has a different mechanical null position means that each gyro has a pickoff circuit that reacts differently when the rotor is in its mechanical null position. Thus, different values of resistor and capacitor are needed for each gyro. In addition, gyro to gyro variation in the impedance of the pickoff coils makes it impossible to specify components which will correctly null all gyros.

Moreover, the nature of the pickoff/torquer loop makes it difficult to analyze and predict which components will bring the electrical null to mechanical null. When a new component is added to the circuit, the pickoffs send different signals to the torquers because the primary side characteristics change. When the torquers receive the new signal, they cause the rotor to change position causing a change in the pickoff coil coupling. Thus, the introduction of a new component affects a change in both the impedance of the primary side of the coils and the coupling of the pickoff transformers.

The History of Component Select:

In the past, the aforementioned difficulties with component select have led to what Bill Berendsen calls the "Component Select Fog". We have been unable to lift the fog because current component select techniques have been inherited from the company which sold us the DTG technology, Incosym. Their understanding of the component select process was not passed on to us in a clear understandable form. Currently, an operator controlled iterative process steps through a number of resistors and capacitors on a trial and error basis to select components. Using this process we can do component select, but we can't explain why our method works.

Goal of this Paper:

The goal of this paper is to lift the component select process out of the fog by doing four things. First, I want to lay the theoretical foundation for a component prediction scheme that will work for every gyro. Second, I want to present a procedure for data collection that has been successful in engineering testing. Third, I will present the requirements for an auto-null system which will speed up gyro characterization data collection. After each of the above three sections, I will attempt to show how it impacts our ultimate goal of automating the component select process. Finally, I will present a vision for the automated component select system using process flow charts.

Theoretical Foundation for the Automated Component Select:

The heart of the automated component select process must be a time saving method of predicting the components required to null the gyro. To do this, each gyro's pickoff electronics must be characterized.

The pickoff output can be thought of as a function of both rotor position and the components in the circuit. Or, in mathematical terms,

$$\text{P.O. output} = f(\text{ circuit components, rotor position })$$

The pickoff output is an electrical signal which has an in-phase and an out-of-phase component to it (**i** and **j**, respectively).

It is the above relationship which must be characterized, for if the circuit response to a given set of components and a given rotor position is known, we can choose the set of components which will give us the pickoff output and rotor position which we desire.

To simplify the process, characterization of the gyro electronics must be performed with the rotor always in the mechanical null position. If the circuit is characterized in this way, the pickoff coils always have the same coupling from test to test, and they act the way we want them to when the gyro has its components properly selected. Holding the rotor always in mechanical null makes the rotor position a constant, and the pickoff output is a function only of circuit components or,

$$\text{P.O. output} = f(\text{ circuit components })$$

With the above relationship, characterization of the pickoff circuit is relatively simple.

Gyro Characterization:

Characterization of a gyro's electronics can be accomplished if the following steps are followed. Each gyro can be tested with a number of different combinations of components in the circuit. For each set of components, the pickoff output signal is recorded in terms of its in-phase, **i**, and out-of-phase, **j**, components. Before each response is recorded, the rotor must be in its mechanical null position.

To look for patterns in the data, it may be plotted in three space. First, the conductance values are plotted on the x-axis (conductance is 1/resistance) where a resistor to ground is plotted as negative conductance and a resistor to excitation is plotted as positive conductance. Then the capacitance values are plotted on the y-axis where a capacitor to ground is plotted as negative capacitance and a capacitor to excitation is positive capacitance. Finally, the in-phase, **i**, and out-of-phase, **j**, components of the pickoff output signal can be plotted as two surfaces above the conductance-capacitance plane. So, for a single gyro, four surfaces can be plotted. The x-axis of the gyro has both an **i** and a **j** plane, and the y-axis of the gyro has both an **i** and a **j** plane. For mathematical details concerning gyro characterization see the appendix.

Component Prediction:

To predict which components must be used to null the gyro, the relationship between pickoff output and circuit components must be turned around. That is, the correct components must be a function of the pickoff output, or

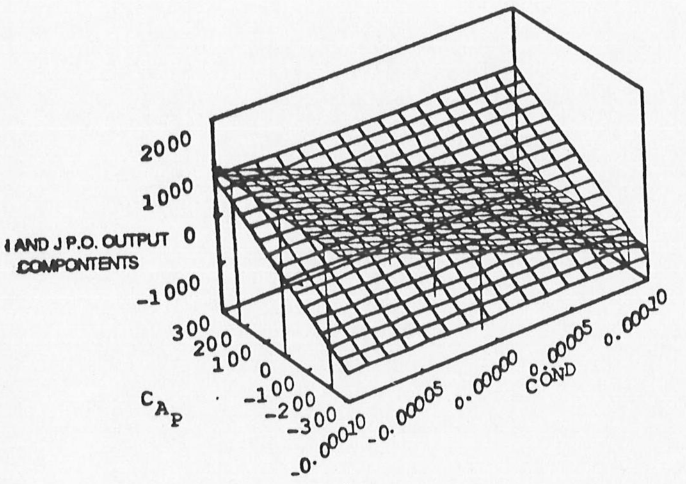
$$\text{circuit components} = f(\text{ P.O. output })$$

Experimentally it was found that when conductance is plotted instead of resistance, both the **i** and the **j** plane are simple planes. Prediction of the resistor and capacitor is then simple. In terms of the surface model for pickoff response, we want the conductance-capacitance pair where both the **i** and **j** plane are zero. Thus, the correct value of resistor and capacitor to null the gyro is the one point where the **i** plane, the **j** plane, and the z = 0 plane all intersect. Because three planes intersect at only one point, there is a single resistor/capacitor combination that will work for each axis of the gyro. See figure 2 for examples of the surfaces involved. See the appendix for details about component prediction.

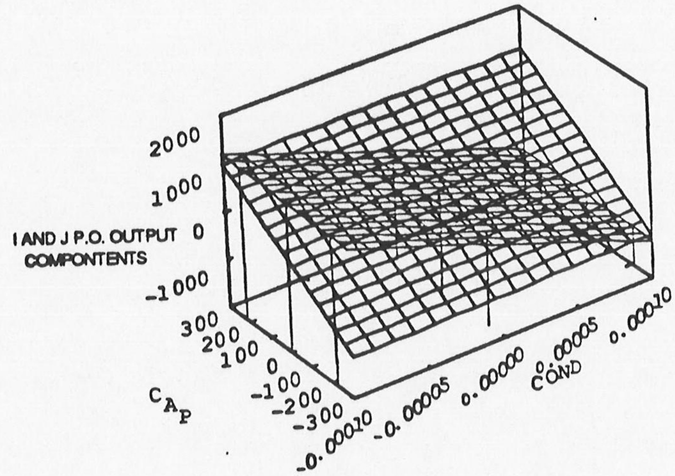
Automated Component Select and the Theoretical Foundation:

This theoretical foundation will work nicely in the automated component select scheme. A number of resistor-capacitor combinations could be inserted into the pickoff circuit by a computer controlled switching circuit. After each new set of components is inserted, the computer could automatically bring the rotor to its mechanical null position, and record the pickoff response. This data will be analyzed with multivariable regression matrix techniques to find the best fit **i** and **j** planes through the data. Moreover, the computer could be used to solve the plane equations for the point where the **i**, **j**, and z = 0 plane intersect. The corresponding resistor and capacitor values (and whether or not they should be attached to excitation or ground) could be reported to the operator who would be responsible for soldering them on the gyro and re-installing the gyro for a verification test. This process has been experimentally tested in the engineering environment, and it correctly predicted components which nulled the gyro in one iteration.

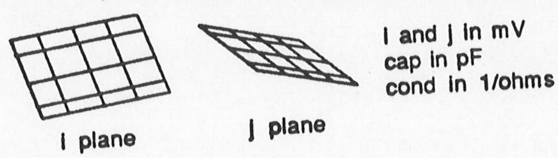
Figure 2
i and j Surfaces for 121XF and 133XF

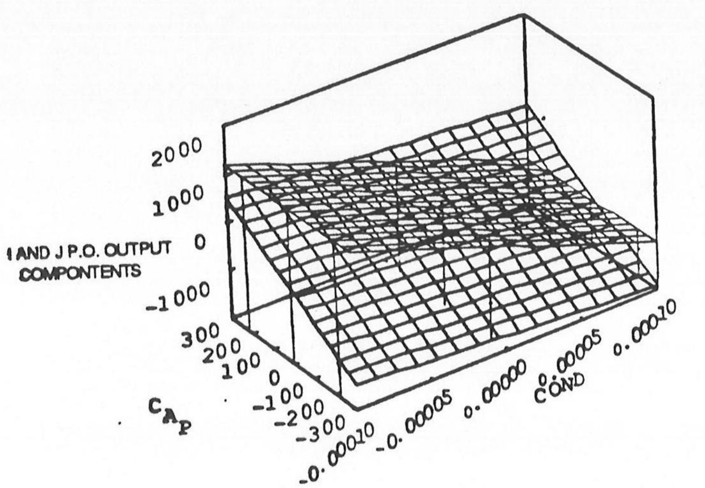


121XF - X AXIS
ROTOR IN MECH NULL POSN

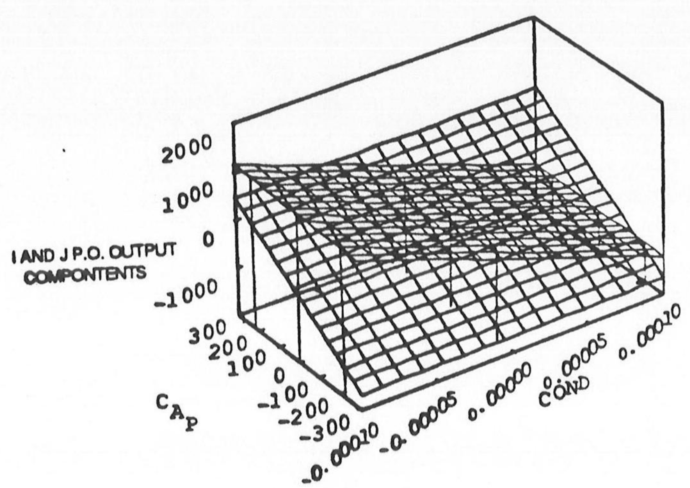


121XF - Y AXIS
ROTOR IN MECH NULL POSN





133XF - X AXIS
ROTOR IN MECH NULL POSN



133XF -Y AXIS
ROTOR IN MECH NULL POSN

Engineering Data Collection:

To analyze the effectiveness of the surface model for component selection, an operator controlled data collection scheme was developed for engineering testing purposes. It was found that manual data collection and manual data analysis reduced the time for the component select procedure to less than two hours. The following description is a formal presentation of a procedure that was developed through trial, error, and educated guesses by Kelley Brower, Bill Berendsen and myself.

Procedure:

1. Solder component sockets onto center tap, excitation, and ground tracks. (These sockets are used to allow quick removal and insertion of the components into the circuit.)
2. Put gyro on test stand.
3. Do not install any components in sockets at this time.
4. Start up the gyro - Close loops.
5. Put the gyro in the H1 position.
6. Dial the x pot until the xΔoffset voltage is 0.0003 V or less.
7. Dial the y pot until the yΔoffset voltage is 0.0001 V or less.
8. Dial the x pot until the xΔoffset voltage is 0.0001 V or less.
9. Measure the x-axis pickoff quadrature* and phase angle. Record.
10. Place the standard set of components into the x-axis sockets in the prescribed configuration.
11. Repeat steps 6 - 10 until all x-axis data has been taken (9 runs total).
12. Have computer solve for the best x-axis resistor and capacitor.

13. Put the components in the x-axis. (y-axis should be raw.)

14. Confirm that the x-axis components are in spec by repeating steps 7 and 9 - Do not dial in the x pot at this point.

15. Leave the x-axis components in the gyro.

16. Put gyro in H2 position.

17. Dial the y pot until the yΔoffset voltage is 0.0001 V or less. - Do not dial the x pot - correct x-axis components should be in the gyro.

18. Measure the y-axis pickoff quadrature* and phase angle. Record.

19. Place the standard set of components into the y-axis sockets in the prescribed configuration.

20. Repeat steps 17 - 19 until all y-axis data has been taken (9 runs total).

21. Have computer solve for the best y-axis components.

22. Confirm that all components bring the gyro in spec - do not dial pots in.

*The term quadrature which appears in steps 9 and 18 is a misnomer. Technically, quadrature is the out-of-phase component of the pickoff signal, but here it is being used as it has for years to mean the total magnitude of the pickoff signal as measured on the 50 kHz bandpass filter.

In engineering testing of this method, we collected data to fill the grid shown in figure 3. Each cell represents a different test condition, and filling a cell consisted of entering a pickoff response in terms of magnitude and phase.

Resistance Conductance	-10 kohms (gnd) -1e-4 (1/ohms)	∞ kohms (Open Cir) 0 (1/ohms)	+10 kohms (exc) 1e-4 (1/ohms)
Capacitance			
+220 pF (exc)			
0 pF (Open Cir)			
-220 pF (gnd)			

Figure 3
Data Collection Grid

Automated Component Select and Engineering Data Collection:

The above method of data collection will have to be automated to speed up the data collection and analysis process. I envision a connector with spring loaded contacts which engage the excitation, centertap, and ground tracks on the gyro. Computer control of component switching could quickly and efficiently cycle through all the necessary combinations of resistors and capacitors to characterize the gyro. The computer would also gather pickoff circuit responses.

For the collected data to be useful, however, it must be taken with the rotor in the mechanical null position. Thus, an auto-null capability for the test system is necessary. In the next section, requirements for an auto-null system will be presented.

Auto Null:

To bring the rotor to the mechanical null position and keep it there, I propose the introduction of a second control loop in the system. At the time of this report, no tests have been performed to assess the effectiveness of an auto-null system. However, bringing the rotor to mechanical null before taking pickoff circuit characterization data (a process termed manual-null) has proved to be an effective component prediction tool.

Auto-Null Requirements:

An auto-null system must be capable of monitoring the torquer voltage. It must be able to control the motor spin speed and the amount of voltage that is injected into the pickoff/torquer circuit integrator.

Eventually, the auto-null system will be an automation of the current mechanical nulling procedure, described in the introduction. With the gyro running closed loop at resonant speed, the torquer voltage is read by the computer. Next, the computer changes the motor speed to 120 Hz slower than resonance. Computer control of the input voltage to the pickoff circuit integrator forces the off-resonance torquer voltage to be the same as the on-resonance torquer voltage. At this point, the rotor is in mechanical null position, and the auto-null process is complete. Continuous monitoring of both gyro axes would ensure that the rotor stays at mechanical null when the pickoff circuit data is taken. After each set of components is placed in the gyro, the auto-null process must be repeated.

Automated Component Select and Auto-Null:

There are at least three benefits that can be realized from the development of an auto-null system, each of which will streamline the gyro calibration process. First, auto-null will make automated component select faster and more cost effective. Second, auto-null will speed up suspension resonant frequency determination because it introduces computer control of the rotor speed. Finally, integrator input control will help to streamline the pre-component-select 8 point tumble tests.

Vision for Automated Component Select:

The first three parts of this paper point toward revolutionizing component select as we know it. The vision which I have for the future of component select is one of complete automation where operators at the computerized component select station will need to be trained to do three things: install the gyro onto the test stand, operate the component select system (system operation would be no more than pushing function keys on a computer keyboard), and solder the components onto the gyro.

My vision of the automated component select process can be seen in the following flow charts. Chart 1 is an overall view of the component select process. In that chart, the numbered steps correspond to charts 2-9 which add detail to the process. Note that with computers and the proper fixturing, the entire process is automatable.

Chart 1

Overall Process Flow

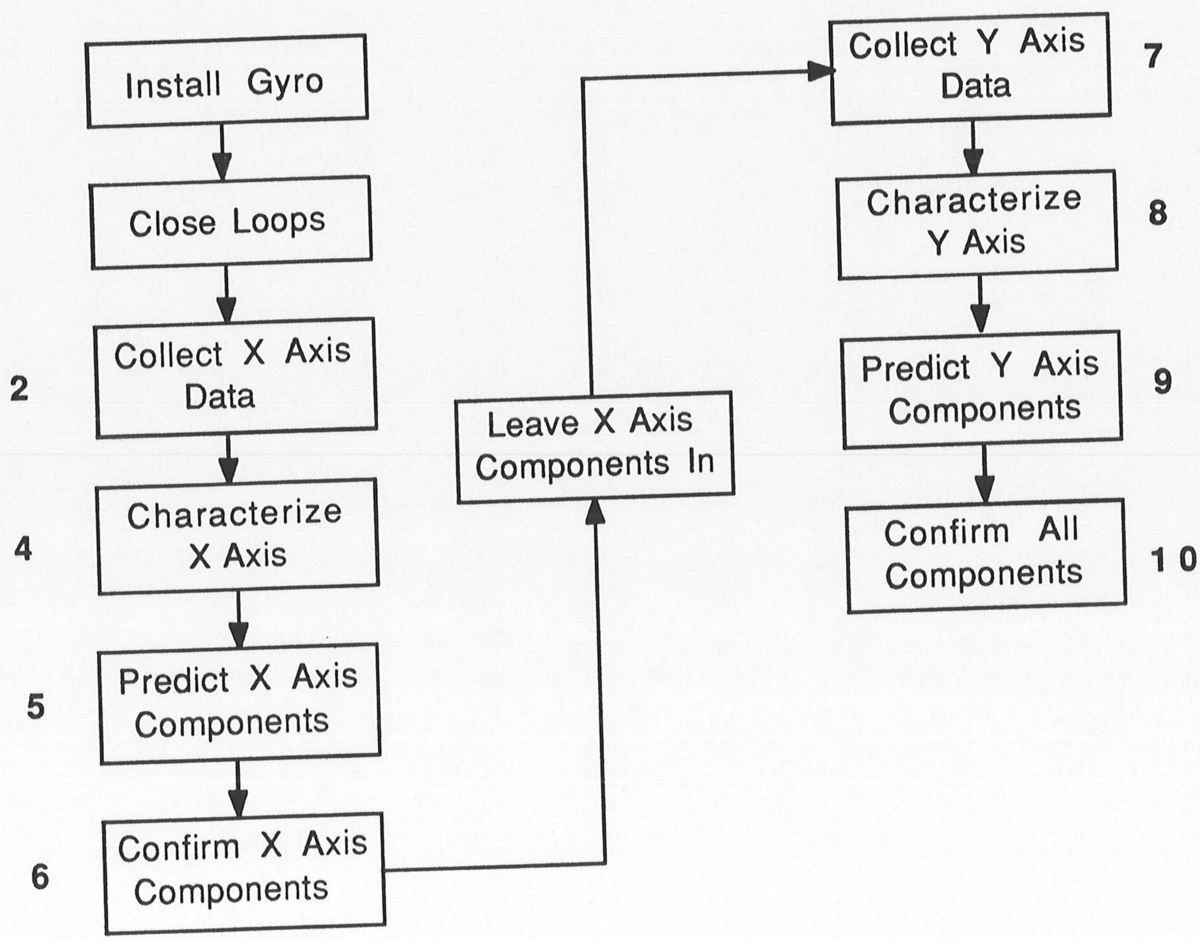


Chart 2

Collect X Axis Data

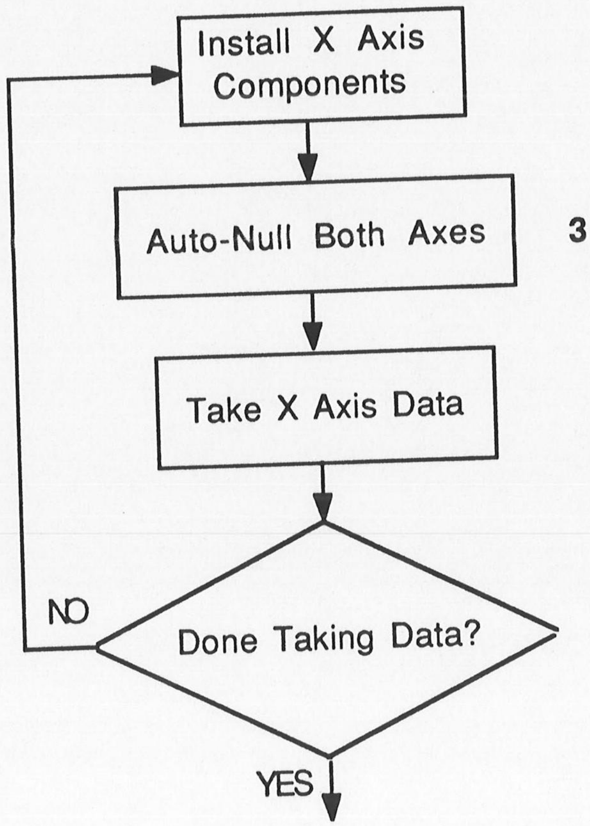


Chart 3

One Axis Auto-Null

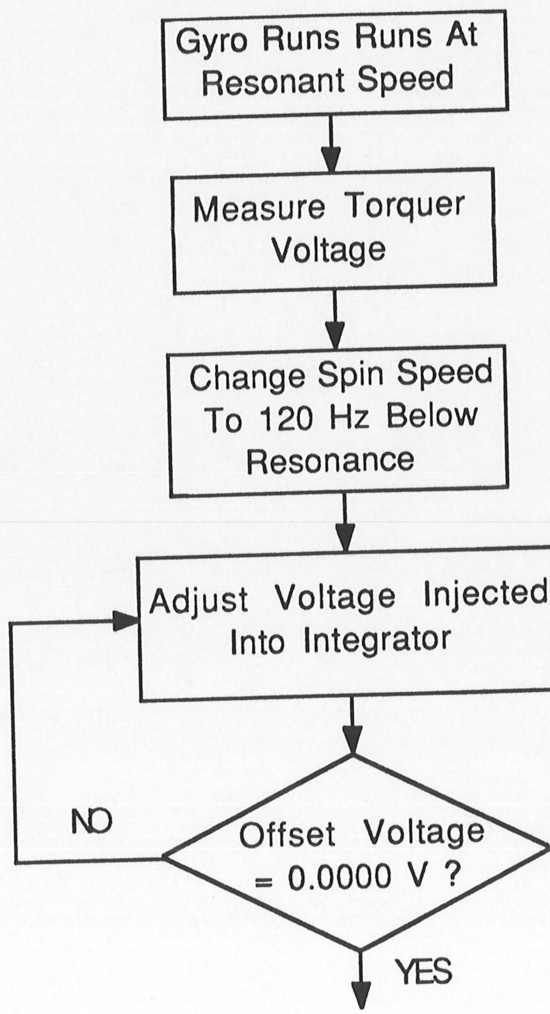


Chart 4

Characterize the X Axis

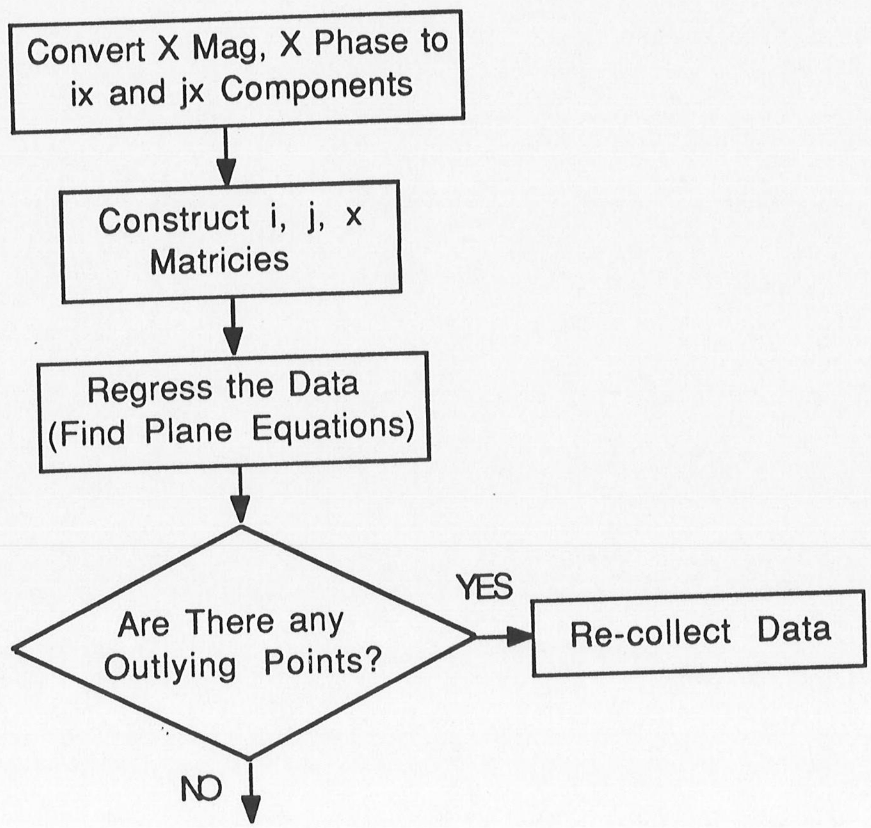


Chart 5

Predict X Axis Components

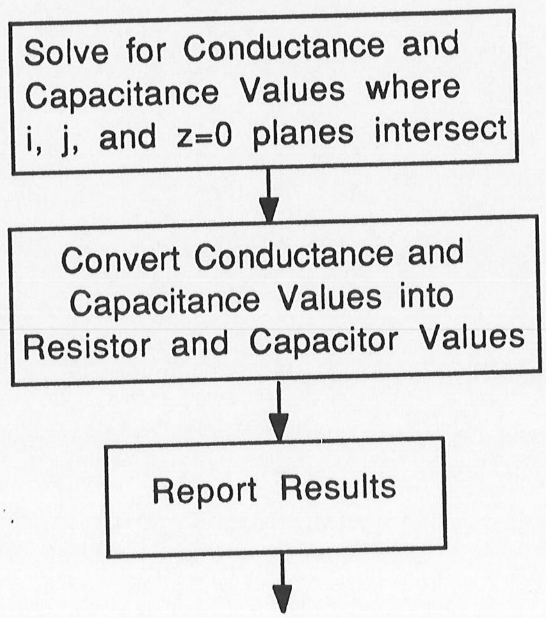


Chart 6

Confirm X Axis Components

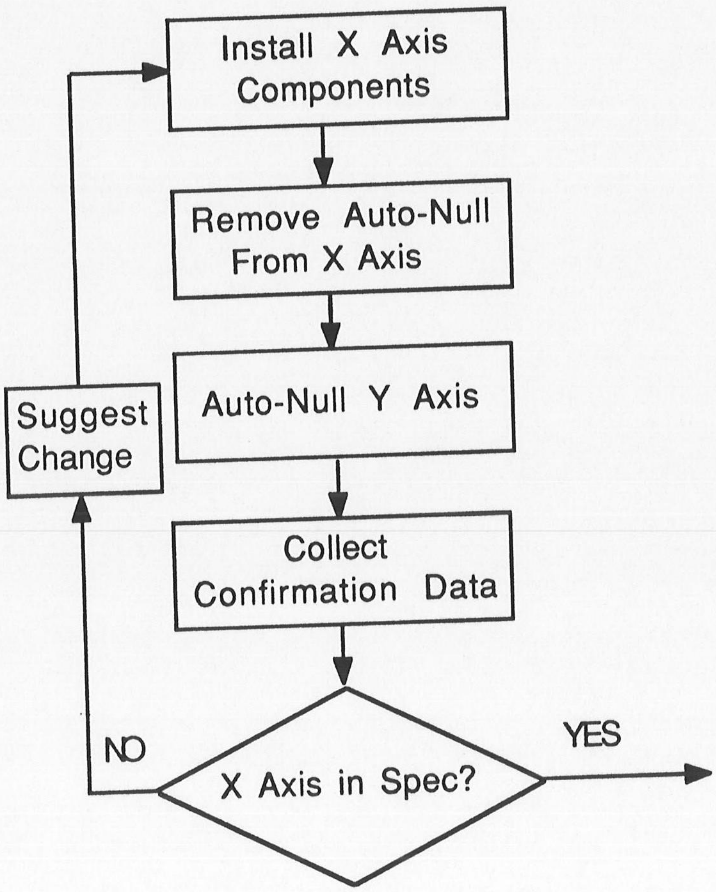


Chart 7

Collect Y Axis Data

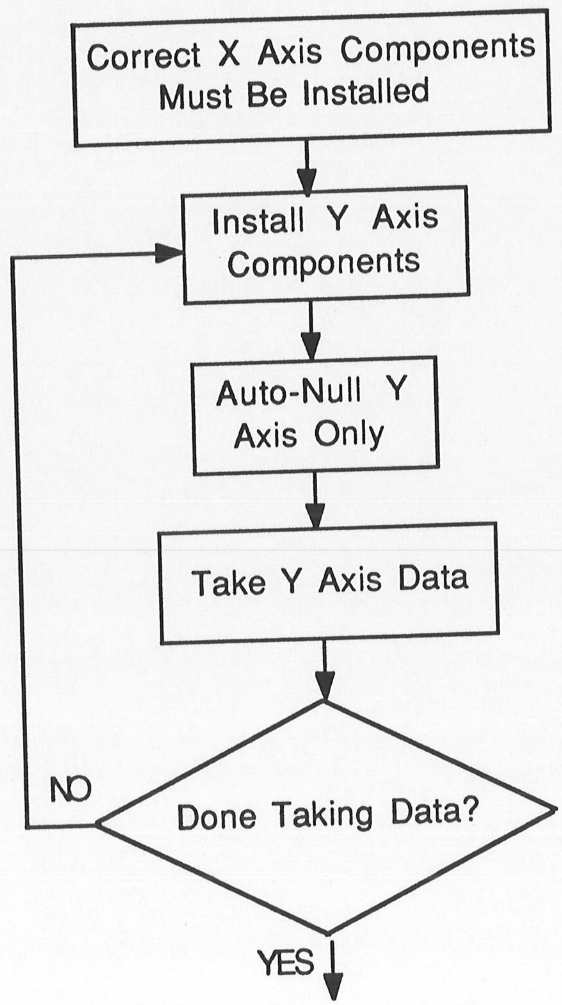


Chart 8

Characterize the Y Axis

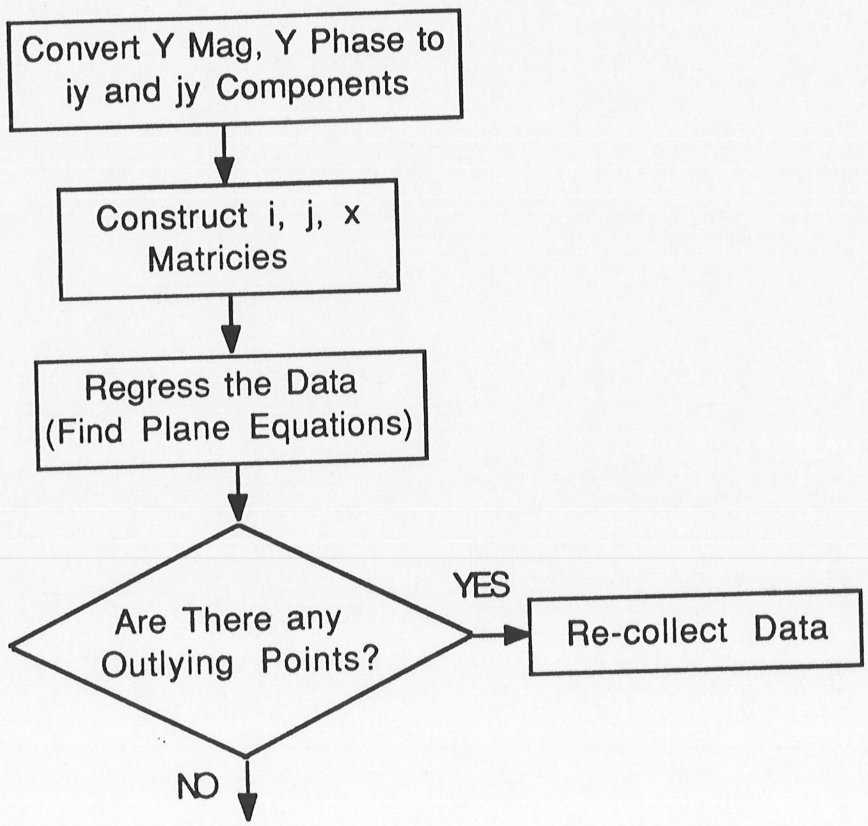


Chart 9

Predict Y Axis Components

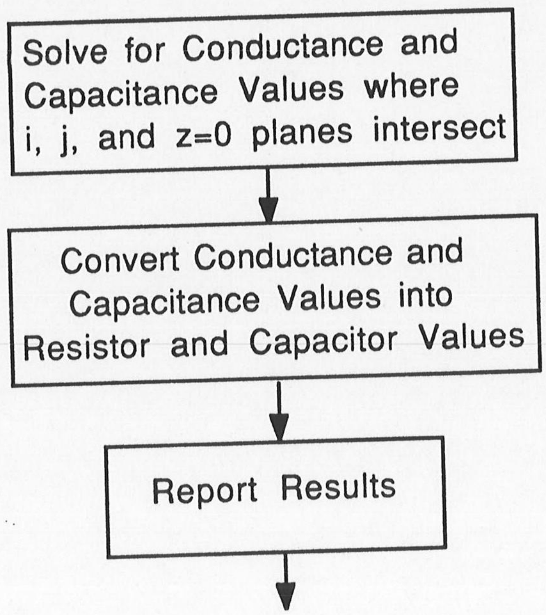
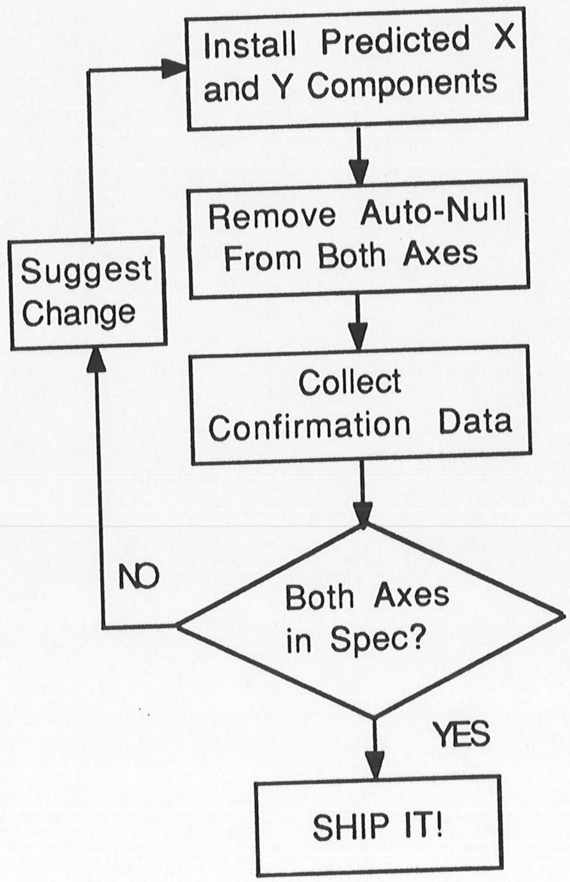


Chart 10

Confirm All Components



Conclusion:

The theoretical foundation to the automated component select process has been tested in the engineering environment.

Test Results:

Data was gathered on gyros 133XF and 121XF using the methods presented on page 9. Table 1 shows the predicted components and the resulting quadrature and offset voltages.

Table 1
Test Results

		Predicted Components	Pickoff Circuit Output
133XF	X	Res = 133 kohms exc Cap = 180 pF exc	Quad = 15 mV Δoffset = +0.0002 V
	Y	Res = 750 kohms exc Cap = 160 pF exc	Quad = 26 mV Δoffset = +0.0005 V
121XF	X	Res = 61.8 kohms exc Cap = 82 pF exc	Quad = 19.5 mV Δoffset = +0.0001 V
	Y	Res = open circuit Cap = open circuit	Quad = 29 mV Δoffset = +0.0005 V

In summary, the component select method detailed in this paper led to success in one iteration for all four axes tested.

Unanswered Questions:

Two questions remain unanswered. First, can the gyro characterization be accomplished without always bringing the rotor to mechanical null? In other words, is auto-null necessary? I believe that if the rotor offset were somehow included in the gyro characterization formulas, component prediction could be successful. Statistician Dave Zeitler is assisting the component select team by looking for a component prediction scheme which does not require auto-null during characterization. Taguchi and other statistical methods are being employed in the search.

Second, in every test conducted the resistor affected the out-of-phase component of the pickoff signal, and the capacitor affected the in-phase component of the pickoff signal. Why is this? It seems as though the resistor should affect the in-phase component of the pickoff signal, and the capacitor should affect the out-of-phase component of the pickoff signal. Chris Grootenboer used various software-based analytical tools to investigate this phenomenon, but he had little success explaining why the circuit performs the way it does.

Hope for the Future:

This new approach to component select has been successful in predicting which components are required to null the gyro, and the process is automatable. In the future, if the possibilities for automation presented here are realized, Smiths Industries could save millions of dollars in gyro build time. The effectiveness of the automated component select system will be, of course, directly related to the time and money invested in the development of the system, but the potential is here to provide a substantial savings in DTG productions costs.

APPENDIX

MATHEMATICAL DETAILS FOR AUTOMATED COMPONENT SELECT

To characterize the gyro pickoff circuit responses, the best fit plane through the characterization data is needed. To find the best fit plane, a linear multivariable regression analysis with two independent variables and no interaction terms, can be used. The model is:

$$Z = \beta_0 + \beta_1 X + \beta_2 Y$$

This model yields the equations for the i and j planes of the gyro.

Characterization:

To characterize a gyro, two equations for each axis are constructed, one for the i plane and one for the j plane.

$$i = \beta_{0i}x_{0i} + \beta_{1i}(\text{cond}) + \beta_{2i}(\text{cap})$$
$$j = \beta_{0j}x_{0j} + \beta_{1j}(\text{cond}) + \beta_{2j}(\text{cap})$$

i and j are the in-phase and out-of-phase components of the pickoff output signal.

β_{0i} and β_{0j} are the z-intercepts for the i and j planes respectively.

β_{1i} and β_{1j} are the conductance coefficients.

β_{2i} and β_{2j} are the capacitance coefficients.

(cond) is 1/resistance where a resistor to excitation is positive conductance and a resistor to ground is negative conductance.

(cap) is capacitance where a capacitor to excitation is positive capacitance and a capacitor to ground is negative capacitance.

X_{0i} and X_{0j} are dummy variables which are always unity to facilitate computer solution.

If characterization data is gathered to fill the grid shown on page 11, three matrices can be constructed from the data. The **X** matrix contains the test parameters. Note that the resistances are logged as conductance, and the dummy variables are included.

$$\mathbf{X} = \begin{bmatrix} 1 & 1/R_1 & C_1 \\ 1 & 1/R_2 & C_2 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ 1 & 1/R_9 & C_9 \end{bmatrix}$$

The **i** matrix contains the in-phase components of the pickoff signal. The subscripts correspond to each of the nine test conditions.

$$\mathbf{i} = \begin{bmatrix} i_1 \\ i_2 \\ \cdot \\ \cdot \\ i_9 \end{bmatrix}$$

The **j** matrix contains the out-of-phase components of the pickoff signal. The subscripts correspond to each of the nine test conditions.

$$\mathbf{j} = \begin{bmatrix} j_1 \\ j_2 \\ \cdot \\ \cdot \\ j_9 \end{bmatrix}$$

The least squares estimate for the coefficients of the i plane equation is given by

$$\mathbf{bi} = \begin{bmatrix} \beta_{0i} \\ \beta_{1i} \\ \beta_{2i} \end{bmatrix} = (\mathbf{X'X})^{-1}\mathbf{X'i}$$

For the j plane,

$$\mathbf{bj} = \begin{bmatrix} \beta_{0j} \\ \beta_{1j} \\ \beta_{2j} \end{bmatrix} = (\mathbf{X'X})^{-1}\mathbf{X'j}$$

Prediction:

To predict which components are needed to null the gyro, the point where the i, j, and z=0 plane intersect must be found. To do this, both plane equations must be set to zero.

$$0 = \beta_{0i} + \beta_{1i}(\text{cond}) + \beta_{2i}(\text{cap})$$
$$0 = \beta_{0j} + \beta_{1j}(\text{cond}) + \beta_{2j}(\text{cap})$$

Solving the two equations for two unknowns, (cond) and (cap), is simple using matrices. First, rewrite the equation in matrix form.

$$\begin{bmatrix} -\beta_{0i} \\ -\beta_{0j} \end{bmatrix} = \begin{bmatrix} \beta_{1i} & \beta_{2i} \\ \beta_{1j} & \beta_{2j} \end{bmatrix} \begin{bmatrix} \text{cond} \\ \text{cap} \end{bmatrix}$$

Finally, premultiply the equation by the inverse of the ß matrix.

$$\begin{bmatrix} \text{cond} \\ \text{cap} \end{bmatrix} = \begin{bmatrix} \beta_{1i} & \beta_{2i} \\ \beta_{1j} & \beta_{2j} \end{bmatrix}^{-1} \begin{bmatrix} -\beta_{0i} \\ -\beta_{0j} \end{bmatrix}$$

The resistor which will null the gyro is given by R = 1/(cond) where a negative resistance means the resistor should be connected from center tap to ground, and a positive resistance means that the resistor should be connected from center tap to excitation. The capacitor which will null the gyro is given by (cap) where a negative capacitance means the capacitor should be connected from center tap to ground, and a positive capacitance means that the capacitor should be connected from center tap to excitation.

The preceding mathematics is basic matrix manipulation. During engineering testing of this component select method, the data reduction was accomplished using MATLAB software on the Macintosh computer.