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(54) **Turbo-machine temperature control**

(57) A method, system, and computer program for turbo-machine (15) temperature control is presented. The method includes: receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise (T_{rise}) parameter of the turbo-machine (15) during operation using a computing device (30) (S1); comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine (15) using the computing device (30) (S2); and creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a user (50) (S3).

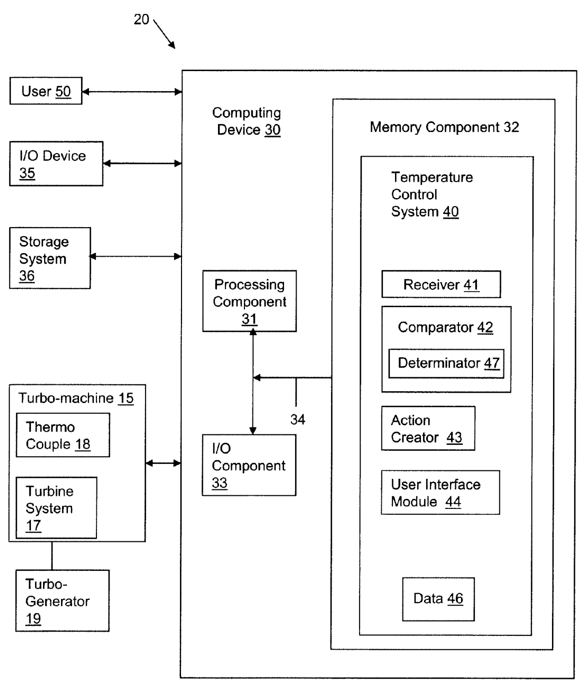

FIG. 1

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Description

[0001] The invention relates generally to monitoring operational parameters of a turbo-machine. More particularly, the invention relates to a system and a method for providing temperature control during operation of the turbo-machine.

[0002] Turbo-machine systems are complex and typically require automated control of a large number of parameters across a wide variety of operation loads. For example, for an electricity generating system including a turbine system and a turbo-generator, the temperature of a variety of structures on the turbine itself must be controlled. Typically, turbo-machine systems and articles therein are subjected to temperature stresses due to the harsh environment that exists during operation of the turbo-machine.

[0003] A first aspect of the disclosure provides a method for controlling the temperature of a turbo-machine, the method comprising: receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise ($T_{rise)}$ parameter of the turbo-machine during operation using a computing device; comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine using the computing device; and creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a user.

[0004] A second aspect of the disclosure provides a temperature control system for a turbo-machine, the system comprising: at least one device including: a receiver for receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise ($T_{rise)}$ parameter of the turbo-machine during operation; a comparator for comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine; and an action creator for creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary.

[0005] A third aspect of the disclosure provides a computer program comprising program code embodied in at least one computer-readable medium, which when executed, enables a computer system to implement a method for controlling the temperature of a turbo-machine, the method comprising: receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise ($T_{rise)}$ parameter of the turbo-machine during operation using a computing device; comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine using the computing device; and creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{flre} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a user.

[0006] Various other aspects of the invention provide methods, systems, program products, and methods of using and generating each, which include and/or implement some or all of the actions described herein. The illustrative aspects of the invention are designed to solve one or more of the problems herein described and/or one or more other problems not discussed.

[0007] Various features of this invention will be more readily understood from the following detailed description of the various aspects of the invention taken in conjunction with the accompanying drawings that depict various embodiments of the invention, in which:

FIG. 1 shows a block diagram of an illustrative environment and for implementing a temperature control system for a turbo-machine, in accordance with an embodiment of the present invention;

FIG. 2 shows a flow diagram of a method for controlling the temperature of a turbo-machine, in accordance with an embodiment of the present invention;

FIG. 3 shows a plot of a turbo-machine operating space for a method for controlling the temperature of a turbo-machine, in accordance with an embodiment of the present invention;

FIG. 4 shows another plot of a turbo-machine operating space for a method for controlling the temperature of a turbo-machine, in accordance with an embodiment of the present invention;

FIG. 5 shows another plot of a turbo-machine operating space for a method for controlling the temperature of a turbo-machine, in accordance with an embodiment of the present invention;

FIG. 6 shows a schematic depiction of a turbine having a control system, in accordance with an embodiment of the present invention;

FIG. 7 shows a high-level block diagram of a turbine, model, and Kalman filter model correction estimator, in accordance with an embodiment of the present invention; and

FIG. 8 shows a block diagram of a more detailed flow chart of the Kalman filter model correction estimator, in accordance with an embodiment of the present invention.

[0008] It is noted that the drawings may not be to scale. The drawings are intended to depict only typical aspects of the invention, and therefore should not be considered as limiting the scope of the invention. In the drawings, like numbering represents like elements between the drawings.

[0009] Turbo-machine systems are complex and typically need automated control of a large number of parameters across a wide variety of operation loads. For example, the temperature of a variety of structures of a turbine needs to be controlled. Historically, turbo-machine parameters were measured and fed back to a turbo-machine control system, which would provide any necessary automated control based on the measured parameters. The measure and feedback scheme is adequate for a number of parameters. However, due to the complexity of a turbo-machine, and how different parameters directly and indirectly impact other parameters, developing control systems that employ a larger variety of parameters in a more robust manner presents a number of challenges.

[0010] Embodiments of the present invention are described herein with reference to flow diagram illustrations and/or block diagrams of methods, apparatus (systems) and computer program products. It will be understood that each block of the flow diagram illustrations and/or block diagrams, and combinations of blocks in the flow diagram illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions may be provided to a processing component of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processing component of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flow diagram and/or block diagram block or blocks.

[0011] These computer program instructions may also be stored in a computer-readable medium that can direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the computer-readable medium produce an article of manufacture including instruction means which implement the function/act specified in the flow diagram and/or block diagram block or blocks.

[0012] The computer program instructions may also be loaded onto a computer or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer or other programmable apparatus to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flow diagram and/or block diagram block or blocks.

Illustrative Environment

[0013] Referring to FIG. 1, an illustrative environment for controlling the temperature of a turbo-machine 15 during operation is shown according to an embodiment of the present invention. To this extent, the environment includes a computer infrastructure 20 that can perform various process steps described herein relative to various control systems. For example, computer infrastructure 20 is shown including a computing device 30 that comprises, among other components, a temperature control system 40, which enables computing device 30 to carry out controlling a temperature of turbo-machine 15 during operation by performing the process steps described herein.

[0014] Computing device 30 is shown in communication with turbo-machine 15. In an embodiment, turbo-machine 15 includes a turbine system 17 coupled to a turbo-generator 19. One having ordinary skill in the art will recognize that turbine system 17 and turbo-generator 19 may include any now known or later developed structure required for turbine system 17 and turbo-generator 19 operation. For example, turbine system 17 may include a gas turbine and/or a steam turbine, etc. with any number of low, intermediate, or high pressure sections.

[0015] Turbine system 17 may also include a combustion turbine engine such as a MS9001FB engine, sometimes referred to as a 9FB engine, commercially available from General Electric Company, Schenectady, N.Y. The present invention is not limited to any one particular engine and may be used in connection with other engines including, for example, the MS7001FA (7FA) and MS9001FA (9FA), the GE 90, and the LMS100 engine models of General Electric Company. Other examples also include the F119 Pratt and Whitney military engine as well as the 8000H Siemens machine.

[0016] Further, computing device 30 is shown in communication with a user 50. User 50 may, for example, be a programmer, an operator, or another computer system. Interactions between the aforementioned and computing device 30 are discussed herein.

[0017] Computing device 30 is shown including a processing component 31 (e.g., one or more processors), a memory component 32 (e.g., a storage hierarchy), an input/output (I/O) component 33 (*e.g.*, one or more I/O interfaces and/or devices), and a communications pathway 34 such as a bus. Further, computing device 30 is shown in communication with an external I/O device/resource 35 and a storage system 36. In one embodiment, processing component 31 may execute program code, such as temperature control system 40, which may be at least partially fixed in memory component 32 and/or storage system 36.

[0018] Computer program code for carrying out operations of embodiments of temperature control system 40 may be written in any combination of one or more programming languages, including an object oriented programming language such as Java, Smalltalk, C++ or the like and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The program code may execute entirely on a user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

[0019] While executing program code, processing component 31 can process data, which can result in reading and/or writing the data, such as turbo-machine 15 exhaust temperature data, firing temperature data, combustor temperature rise data, and corresponding operational boundary data to/from memory component 32, storage system 36, and/or I/O component 33 for further processing. Communications pathway 34 provides a communications link between each of the components in computing device 30. I/O component 33 can comprise one or more human I/O devices or storage devices, which enable user 50 to interact with computing device 30 and/or one or more communications devices to enable user 50 to communicate with computing device 30 using any type of communications link. To this extent, temperature control system 40 can manage a set of interfaces *(e.g.,* graphical user interface(s), application program interface, and/or the like) that enable human and/or users 50 to interact with temperature control system 40. Further, temperature control system 40 can manage (e.g., store, retrieve, create, manipulate, organize, present, etc.) data 46, such as but not limited to turbo-machine 15 exhaust temperature data, firing temperature data, combustor temperature rise data, and corresponding operational boundaries using any solution.

[0020] I/O device 35 may comprise any device that enables user 50 to interact with computing device 30 or any device that enables computing device 30 to communicate with one or more other computing devices. I/O device 35 (includes but is not limited to a keyboard, a display, a pointing device, etc.) may be coupled to computing device 30 either directly or through intervening I/O controllers.

[0021] In any event, computing device 30 can comprise one or more general purpose computing articles of manufacture (e.g., computing devices) capable of executing program code, such as temperature control system 40, installed thereon by a user 50 (e.g., a personal computer, server, handheld device, etc.). As used herein, it is understood that program code may mean any collection of instructions, in any language, code or notation, that cause a computing device having an information processing capability to perform a particular function either directly or after any combination of the following: (a) conversion to another language, code or notation; (b) reproduction in a different material form; and/or (c) decompression. To this extent, temperature control system 40 can be embodied as any combination of system software and/or application software.

[0022] Further, one having ordinary skill in the art will recognize that temperature control system 40 and various control systems described herein can also be embodied as a method(s) or computer program product(s), e.g., as part of an overall control system for a turbo-machine. Accordingly, embodiments of the present invention may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a circuit, module, or system.

[0023] In any event, the technical effect of computing device 30 is to provide processing instructions for controlling the temperature of turbo-machine 15 during operation. In another embodiment of computing device 30, it may monitor, record, and track operating parameters related to turbo-machine 15 via temperature control system 40, including but not limited to exhaust temperature, firing temperature, and combustor temperature rise data.

[0024] Further, temperature control system 40 can be implemented using a set of modules such as a receiver 41, a comparator 42, and an action creator 43. In this case, a module can enable computing device 40 to perform a set of tasks used by temperature control system 40, and can be separately developed and/or implemented apart from other portions of temperature control system 40. Temperature control system 40 may include modules that comprise a specific use machine/hardware and/or software. Regardless, it is understood that two or more modules, and/or systems may share some/all of their respective hardware and/or software.

[0025] As used herein, the term "component" means any configuration of hardware, with or without software, which implements the functionality described in conjunction therewith using any solution, while the term module means program code that enables computing device 40 to implement the functionality described in conjunction therewith using any solution. When fixed in memory component 32 of computing device 30 that includes the processing component 31, a module is a substantial portion of a component that implements the functionality. Regardless, it is understood that two or more components, modules, and/or systems may share some/all of their respective hardware and/or software. Further, it is understood that some of the functionality discussed herein may not be implemented or additional functionality may be included as part of computing device 30. When computing device 30 comprises multiple computing devices, each computing device may have only a portion of temperature control system 40 embodied thereon (e.g., one or more modules).

[0026] However, it is understood that computing device 30 and temperature control system 40 are only representative of various possible equivalent computing devices that may perform the various process steps of the present invention. To this extent, in other embodiments, computing device 30 can comprise any specific purpose computing article of manufacture comprising hardware and/or computer program code for performing specific functions, any computing article of manufacture that comprises a combination of specific purpose and general purpose hardware/software, or the like. In each case, the program code and hardware can be created using standard programming and engineering techniques, respectively.

[0027] Similarly, computer infrastructure 20 is only illustrative of various types of computer infrastructures for implementing the invention(s) described herein. For example, in one embodiment, computer infrastructure 20 may comprise two or more computing devices (e.g., a server cluster) that communicate over any type of wired and/or wireless communications link, such as a network, a shared memory, or the like, to perform the various process steps described herein. When the communications link comprises a network, the network may comprise any combination of one or more types of networks (e.g., the Internet, a wide area network, a local area network, a virtual private network, etc.).

[0028] Network adapters may also be coupled to the system to enable the data processing system to become coupled to other data processing systems or remote printers or storage devices through intervening private or public networks. Modems, cable modem and Ethernet cards may be just a few of the currently available types of network adapters. Regardless, communications between the computing devices may utilize any combination of various types of transmission techniques.

[0029] Temperature control system 40 enables computing device 30 to provide processing instructions for controlling the temperature of turbo-machine 15. Temperature control system 40 is provided to protect turbo-machine 15, and in particular, a gas turbine of a turbine system 17 against exceeding temperature limits that may damage turbo-machine 15. Receiver 41 receives temperature parameters of turbo-machine 15 during operation. For example, receiver 41 may receive an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise (T_{rise}) parameter.

[0030] In embodiments of the present invention, T_{exh} may represent the direct temperature of exhaust gas exiting turbo-machine 15. T_{fire} may represent the firing temperature of a combustor (not shown) of turbo-machine 15. T_{rise} may represent the temperature rise across the combustor of turbo-machine 15. In an embodiment, receiver 41 may also receive any number of additional temperature parameters and corresponding operational boundaries of the turbo-machine15 during operation that may be used to control the temperature of turbo-machine 15 during operation.

[0031] Receiver 41 receives temperature parameters and corresponding operational boundaries of turbo-machine 15. In an embodiment, receiver 41 may receive T_{exh}, $T_{fire,}$ and T_{rise} parameters and corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries. Receiver 41 may also receive any now known or later discovered temperature parameter data and/or operational boundary data of turbo-machine 15 that may be related to the operation and in particular, temperature control, of turbo-machine 15.

[0032] Receiver 41 may receive the temperature parameters and corresponding operational boundaries from user 50. For example, user 50 may be an operator or programmer inputting the T_{exh}, T_{fire}, and T_{rise} operational boundaries into computing device 30 or from another computing article of manufacture. Alternatively, user 50 may be an external computing device(s) of another computer system providing the T_{exh}, T_{fire}, and T_{rise} parameters and corresponding operational boundaries to computing device 30 via I/O component 33. Further, user 50 may be linked to computing device 30 as described herein, and may also provide any now known or later discovered temperature parameter data and/or operational boundary data of turbo-machine 15 that may be related to the operation and in particular, temperature control, of turbo-machine 15 in any conventional manner. Subsequently, receiver 41 may receive any of the aforementioned.

[0033] Comparator 42 compares T_{exh}, T_{fire}, and T_{rise} parameters to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of turbo-machine 15. In an embodiment, comparator 42 may additionally comprise determinator 47, which determines if the T_{exh}, T_{fire}, and T_{rise} parameters exceed the T_{exh}, T_{fire}, and T_{rise} operational boundaries of turbo-machine 15 during operation. In another embodiment, determinator 47 may determine if any temperature parameter exceeds its corresponding operational boundary of turbo-machine 15. In a further embodiment, determinator 47 may determine if any temperature parameter exceeds its corresponding operational boundary of turbo-machine 15 by a predetermine temperature value. The temperature value may be a value of, for example, 5° C, 10° C, 15° C, and etc.

[0034] Comparator 42 may also compare any now known or later discovered temperature parameter data and/or operational boundary data of turbo-machine 15 that may be related to the operation and in particular, temperature control, of turbo-machine 15. Subsequently, determinator 47 may also determine if any now known or later discovered temperature parameter data exceeds its corresponding operational boundary and/or exceeds its corresponding operational boundary by a predetermined temperature value.

[0035] Action creator 43 creates an action, such as an alarm or trip, in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for user 50. In an embodiment, an alarm or a trip may be created if one of the parameters exceeds an operational boundary for a period of time, for example, 0.5 seconds. One having ordinary skill in the art will recognize that any period of time may be selected to trigger the alarm or the trip such that temperature control of turbo-machine 15 may be maintained. Further, action creator 43 may create an alarm or trip in response to at least one of: any now known or later discovered temperature parameter data exceeding its corresponding operational boundary.

[0036] Temperature control system 40 may provide the created alarm and trip for user 50, for example, via a user interface module 44. In an embodiment, user interface module 44 may provide a graphical user interface in a turbo-machine 15 control room.

Temperature Control Methodology

[0037] Referring to FIG. 2, an embodiment of a method for controlling the temperature of a turbo-machine 15 during operation is shown. Step S1 includes a receiver 41 receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise (T_{rise}) parameter of turbo-machine 15 during operation using computing device 30, see FIG. 1.

[0038] In an embodiment of step S1 of FIG. 2, receiver 41 receiving the temperature parameters comprises: a step S1A, receiving an exhaust temperature (T_{exh}) of turbo-machine 15; a step S1B, receiving a firing temperature (T_{fire}) of turbo-machine 15; and a step S1C, receiving a combustor temperature rise (T_{rise}) of turbo-machine 15. In an embodiment, receiver 41 may independently receive the T_{exh}, T_{fire}, and T_{rise} parameter from a computing article of manufacture or an external computing device(s) of another computer system (not shown) (that independently calculates the T_{exh}, T_{fire}, and T_{rise} parameter) via I/O component 33 as described herein. One having ordinary skill in the art will recognize that the T_{exh} parameter may be calculated, for example, by taking the average of a plurality of T_{exh} measurements at any given point in time during operation of turbo-machine 15. The T_{exh} measurements may be taken by thermocouples 18 that comprise turbo-machine 15, see FIG. 1.

[0039] In an embodiment, receiver 41 may receive T_{exh}, T_{fire}, and T_{rise} parameters from computing article (s) of manufacture, from an external computing device (s) of another computer system(s), and etc. that may determine the T_{exh}, T_{fire}, and T_{rise} parameters by taking one or more direct measurements of the aforementioned parameters during various operating states of turbo-machine 15. Alternatively, the T_{exh}, T_{fire}, and T_{rise} parameters may be estimated by an external computer modeling system that uses various operational inputs and outputs such as fuel flow, turbine speed, inlet temperature, power output, compressor discharge temperature, compressor discharge pressure, of turbo-machine 15 during various operational states to determine one or more of the aforementioned temperature parameters.

[0040] Examples of computing modeling systems and methods that may be used to determine the T_{exh}, T_{fire}, and T_{rise} parameters as well as others may be model-based control systems described in U.S. 7,742,904 ('904), which is hereby incorporated by reference in its entirety. For the sake of clarity and convenience, certain passages from '904 are described in Computing Modeling Systems section of this application.

[0041] An additional embodiment, method step S 1 may further comprise receiver 41 receiving one or more additional temperature parameters of turbo-machine 15 during operation. One or more of the additional temperature parameters may be any temperature parameter that may directly or indirectly represent a temperature parameter of turbo-machine 15 in operation that may be actively controlled.

[0042] In an embodiment, one or more of the additional temperature parameters may be received by receiver 41 from computing article(s) of manufacture, from an external computing device(s) of another computer system(s), and etc. that may determine one or more of the additional temperature parameters by taking one or more direct measurements of the aforementioned parameters during various operating states of turbo-machine 15. Alternatively, one or more of the additional temperature parameters may be estimated by an external computer modeling system (see passages of '904 described in Computing Modeling Systems section of this application) that uses various operational inputs and outputs of turbo-machine 15 during various operational states to determine one or more of the aforementioned temperature parameters.

[0043] Referring to FIG. 2, step S2 includes comparator 42 comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of turbo-machine 15 using computing device 30, see FIG. 1. In an embodiment of method step S2 of FIG. 2, comparator 42 comparing the temperature parameters to the corresponding operational comprises a step S2A, which includes receiver 41 receiving T_{exh}, T_{fire}, and T_{rise} operational boundaries of turbo-machine 15 during operation, see FIG 1.

[0044] Receiver 41 may receive the operational boundaries from user 50, such as but not limited to, an operator or programmer inputting the operational boundaries, from another computing article(s) of manufacture, or from an external computing device(s) of another computer system (not shown) that calculates the operational boundaries via I/O component 33 as described herein, see FIG. 1. In an embodiment, T_{exh}, T_{fire}, and T_{rise} operational boundaries independently may encompass multiple operational boundaries, for example, the T_{fire} operational boundary may encompass a T_{fire} alarm boundary and/or a T_{fire} trip boundary described herein.

[0045] In an additional embodiment of method step S2A, receiver 41 may further receive one or more additional operational boundaries of turbo-machine 15 during operation that correspond respectively to one or more temperature parameters received in step S1. One having ordinary skill in the art will recognize, that one or more of the additional operational boundaries may be for any operating space of turbo-machine 15 that may be defined, for example, by temperature vs. power as discussed herein. One or more of the additional operational boundaries may include an operational base load curve, an alarm boundary, a trip boundary, an absolute boundary, etc (see passages of '904 described in Computing Modeling Systems section of this application).

[0046] In an embodiment of the operational temperature boundaries, FIGS. 3-5 show curves that represent T_{exh}, T_{fire}, and T_{rise} operational boundaries. In each figure, the y-axis represents temperature in incremental units of degrees C for a particular operating space and the units increase from bottom to top. The x-axis represents incremental compressor pressure ratio and the increments increase from left to right.

[0047] Referring to FIG. 3, a plot is shown representative of the T_{fire} operating space for turbo-machine 15. Curve B1 may represent an operational base load curve for T_{fire}. The T_{fire} base load curve may represent a space where normal operating conditions for turbo-machine 15 exist. Curve A1 may represent a T_{fire} alarm boundary. The T_{fire} alarm boundary may represent a space where operating conditions for turbo-machine 15 are above normal and may need attention, but may not warrant a trip (shutdown) of turbo-machine 15. One having ordinary skill in the art will recognize that curve A1 may be selected to be at any particular temperature range above curve B 1 that allows curve A1 to be representative of an alarm boundary as described herein.

[0048] Curve T1 may represent a T_{fire} trip boundary. The T_{fire} trip boundary may represent a space where operating conditions for turbo-machine 15 are above normal and may be potentially damaging to turbo-machine 15, and may warrant a trip of turbo-machine 15. One having ordinary skill in the art will recognize that curve T1 may be selected to be at any particular temperature range above curve B 1 that allows curve T1 to be representative of a trip boundary as described herein.

[0049] Referring to FIG. 4, a plot is shown representative of the T_{exh} operating space for turbo-machine 15. In an embodiment, the T_{exh} operating space may be in a temperature range from approximately 260° C to approximately 820° C. Curve B2 may represent an operational base load curve for T_{exh}. The T_{exh} base load curve may represent a space where normal operating conditions for turbo-machine 15 exist. Curve A2 may represent a T_{exh} alarm boundary. The T_{exh} alarm boundary may represent a space where operating conditions for turbo-machine 15 may be above normal and may need attention, but may not warrant a trip of turbo-machine 15. One having ordinary skill in the art will recognize that curve A2 may be selected to be at any particular temperature range above curve B2 that allows curve A2 to be representative of an alarm boundary as described herein. In an embodiment, curve A2 may be approximately 3° C higher at each point along curve B2.

[0050] Curve T2 may represent a T_{exh} trip boundary. The T_{exh} trip boundary may represent a space where operating conditions for turbo-machine 15 may be above normal and may be potentially damaging to turbo-machine 15, and may warrant a trip of turbo-machine 15. One having ordinary skill in the art will recognize that curve T2 may be selected to be at any particular temperature range above curve B2 that allows curve T2 to be representative of a trip boundary as described herein. In an embodiment, curve T2 may be approximately 6° C higher at each point along curve B2.

[0051] Curve F2 may represent a T_{exh} absolute boundary. The T_{exh} absolute boundary represents a space where operating conditions for turbo-machine 15 may be dangerous and may ultimately result in damage to turbo-machine 15 if a trip is not initiated. One having ordinary skill in the art will recognize that curve F2 may be selected to be at any particular temperature range above curve B2 that allows curve F2 to be representative of an absolute boundary as described herein. In an embodiment, curve F2 may be a boundary at a single temperature for each power unit, *i.e.,* a straight line across the entire operating space.

[0052] Referring to FIG. 5, a plot is shown representative of the T_{rise} operating space for turbo-machine 15. Curve B3 may represent an operational base load curve for T_{rise}. The T_{rise} base load curve may represent a space where normal operating conditions for turbo-machine 15 exist. Curve A3 may represent a T_{rise} alarm boundary. The T_{rise} alarm boundary may represent a space where operating conditions for turbo-machine 15 are above normal and may need attention, but may not warrant a trip (shutdown) of turbo-machine 15. One having ordinary skill in the art will recognize that curve A3 may be selected to be at any particular temperature range above curve B3 that allows curve A3 to be representative of an alarm boundary as described herein. In an embodiment, curve A3 may be approximately 3° C higher at each point along curve B3.

[0053] Curve T3 may represent a T_{rise} trip boundary. The T_{rise} trip boundary may represent a space where operating conditions for turbo-machine 15 are above normal and may be potentially damaging to turbo-machine 15, and may warrant a trip of turbo-machine 15. One having ordinary skill in the art will recognize that curve T3 may be selected to be at any particular temperature range above curve B3 that allows curve T3 to be representative of a trip boundary as described herein. In an embodiment, curve T3 may be approximately 6° C higher at each point along curve B3.

[0054] In the foregoing embodiments, the operational boundaries A1, T1, A2, T2, F2, A3, and T3 were each defined as a function of one input variable, *i.e.,* compressor pressure ratio. One having ordinary skill in the art will recognize that the aforementioned operational boundaries may be defined by additional input variables or by different input variables that are representative of an operating space of turbo-machine 15 during operation, see FIG. 1. The additional input variables may be directly measured, calculated, or estimated as described herein.

[0055] One having ordinary skill in the art will recognize that the temperature range for the operating space, *i.e.,* temperature vs. compressor pressure ratio, represented in FIGS. 3-5 does not have to be the same, and may be unique, similar, or overlapping for each operating space shown. It has been discovered that an advantage that may be realized in the practice of some embodiments of a method for controlling the temperature of a turbo-machine described herein is that when multiple operating spaces of a turbomachine are defined, greater temperature control of turbo-machine 15 during operation may be achieved as the multiple operating spaces are more representative of allowable operating temperatures at corresponding operating loads of turbo-machine 15.

[0056] In an embodiment of method step S2 of FIG. 2, comparator 42 comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of turbo-machine 15 using computing device 30, step S2 comprises a step S2B, a determinator 47 determining if at least one of: the T_{exh} parameter exceeds the T_{exh} operational boundary, the T_{fire} parameter exceeds the T_{fire} operational boundary, and the T_{rise} parameter exceeds the T_{rise} operational boundary, see FIG. 1.

[0057] In an embodiment of step S2B, the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter may be compared to the corresponding operational boundaries to determine if the T_{exh}, T_{fire}, and T_{rise} parameters have exceeded their corresponding operational boundaries. For example, the T_{exh}, T_{fire}, and T_{rise} parameters from step S 1 may be plotted against the corresponding T_{exh}, T_{fire}, and T_{rise} boundaries shown in FIGS. 6-8 respectively. If the T_{exh}. T_{fire}, and T_{rise} parameters are located above the corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries, the T_{exh}, $T_{fire,}$ and T_{rise} parameters are considered to have exceeded their corresponding operational boundaries.

[0058] As described herein, determinator 47 may determine if at least one of: the T_{exh}, T_{fire}, and T_{rise} parameters have exceeded their corresponding operational boundaries. In another embodiment, determinator 47 may also determine if at least one of: the T_{exh}, T_{fire}, and T_{rise} parameters have exceeded their corresponding operational boundaries for a time period such as but not limited to 0.5 seconds. In another embodiment, determinator 47 may determine if at least one of: the T_{exh}, T_{fire}, and T_{rise} parameters have exceeded their corresponding operational boundaries by a predetermined temperature value such as but not limited to 3° C, 6° C, and 9° C.

[0059] It has been discovered that an advantage that may be realized in the practice of some embodiments of a method for controlling the temperature of a turbo-machine described herein is that when multiple operational boundaries of a turbomachine are defined, greater temperature control of turbo-machine 15 during operation may be achieved as the multiple operational temperature boundaries provide incremental warnings representative of actual operating temperatures that may have exceeded normal operating temperatures at corresponding operating loads of turbo-machine 15.

[0060] It has also been discovered that an advantage that may be realized in the practice of some embodiments of a method for controlling the temperature of a turbo-machine described herein is that when predetermined temperature values by which at least one of: the T_{exh}, T_{fire}, and T_{rise} parameters may exceed their corresponding operational boundaries are defined, greater temperature control of turbo-machine 15 during operation may be achieved as the predetermined temperature values allow a user 50 to precisely control by how much the T_{exh}, T_{fire}, and T_{rise} parameters may exceed their corresponding operational boundaries before an alarm and/or a trip is created.

[0061] In an embodiment, step S3 of FIG. 2 comprises an action creator 43 creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for user 50, see FIG. 1.

[0062] In an embodiment of step S3, the action may comprise an alarm or a trip in response, for example, to at least one of: the T_{exh}, T_{fire}, and T_{rise} parameters exceeding the corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries at any moment in time during operation of turbo-machine 15. An alarm may include an electronic notification, such as a text message to a computer or hand-held device; a visual indicator such as flashing button on a control panel and/or a flashing light in a control room; and an auditory indicator such as a klaxon or a siren. The alarm may be communicated to user 50 via user interface module 44 and/or I/O component 33. A trip may be a shut down of turbo-machine 15.

[0063] In another embodiment of step S3, the trip may include an automatic shut down of turbo-machine 15 or a manual shut down performed by user 50 after indication by an alarm or trip, see FIG. 1.

[0064] In another embodiment of step S3, an example of an action may further include unloading, e.g., reducing turbine power output, turbo-machine 15 until a temperature parameter that may have exceeded its corresponding operational boundary has returned to a level below the operational boundary.

[0065] Alternatively, action creator 43 may create an action that may comprise a trip in response to at least one of: the T_{fire}, T_{exh}, and T_{rise} parameters exceeding the corresponding T_{fire}, T_{exh}, and T_{rise} operational boundaries for a period of time, as determined by determinator 47, during operation of turbo-machine 15. The time period may be employed to account for unnecessary trips that may be created by temperature spikes or temperature parameter outliers during operation of turbo-machine 15, see FIG. 1. In an embodiment, the T_{fire} parameter may exceed the T_{fire} trip boundary for approximately 0.5 seconds before action creator 43 creates an action. In another embodiment, the T_{exh} parameter may exceed the T_{exh} trip boundary for approximately 0.5 seconds before action creator 43 creates an action. In a further embodiment, the T_{rise} parameter may exceed the T_{rise} trip boundary for approximately 0.5 seconds before action creator 43 creates an action.

[0066] In another embodiment of step S3, action creator 43 may create an action which may comprise an alarm or a trip in response, for example, to at least one of: the T_{exh}, T_{fire}, and T_{rise} parameters exceeding their corresponding operational boundaries by a predetermined temperature value such as but not limited to a 3° C, 6° C, and 9° C increment for a period of time, as determined by determinator 47, during operation of turbomachine 15. In another embodiment, action creator 43 may create multiple actions based on different predetermined temperature values. For example, if T_{exh} exceeds its T_{exh} operational boundary by 3° C, then an alarm may be created. If T_{exh} exceeds its T_{exh} operational boundary by 6° C, then a trip may be created.

Computing Modeling Systems

[0067] A gas turbine control system that may employ an adaptive gas turbine model to estimate certain operating parameters of an operating gas turbine is presented. Operating parameters that may be modeled include, for example, an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise ($T_{rise)}$ parameter and/or corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries as well as additional parameters. The model may estimate operational parameters that are not directly sensed, e.g., measured, by sensors for use in control algorithms. The model may also estimate operational parameters that are measured so that the estimated and measured conditions can be compared. The comparison may be used to automatically tune the model while the gas turbine continues to operate.

[0068] The gas turbine model may receive measured conditions as input parameters, e.g., ambient pressure, compressor inlet guide vane position, fuel flow, inlet bleed heat flow, generator power losses, inlet and exhaust duct pressure losses, compressor inlet temperature, etc. The model may generate estimated operating parameters, e.g., exhaust gas temperature, fire temperature, combustor rise temperature, compressor discharge pressure and temperature, and power output. The estimated operating parameters may be used in conjunction with the measured operating parameters to control the gas turbine. For example, the measured and estimated operating parameters may be input to control schedules to set the gas turbine operating state, e.g., desired turbine exhaust temperature, total combustor fuel flow, fuel split schedules and inlet bleed heat flow. In addition, the measured and estimated operational parameters may be used to evaluate the accuracy of the model and to tune the model.

[0069] The gas turbine model may be regularly, automatically and in real-time tuned using a Kalman filter. The Kalman filter may receive inputs signals indicating the differences between measured gas turbine parameters from various sensors and the estimated parameters output from the model. The Kalman filter may also receive as an input the Kalman filter gain matrix (KFGM), which is an array of numbers representing the uncertainty weighted sensitivity of model estimated parameters to changes in model performance multipliers. The Kalman filter may use the supplied inputs to generate performance multipliers that may be applied to tune the model and increase the accuracy of the estimated gas turbine parameters.

[0070] The Kalman filter gain matrix (KFGM) may be calculated by an array of mathematical equations. These equations may receive as inputs a model sensitivity matrix (MSM), and estimates of the model and measurement uncertainty. The MSM may be calculated on-line in real-time by perturbation and evaluation of the control resident gas turbine model. The Kalman filter may optimize the multiplier values to minimize the differences between the estimated and measured operating parameters.

[0071] The gas turbine model may adapt to changing efficiencies, flow capacities and other parameters of the actual gas turbine. The output performance multipliers generated by the Kalman filter may adapt the model to better match the measured parameters of the gas turbine. The Kalman filter may also tune the model to, for example, account for deterioration of component efficiencies and changes in air-flow capacities of the gas turbine that occur during extended operation.

[0072] Since the MSM and KFGM may be calculated on-line and in real-time, the Kalman filter structure is able to adapt to changes in the number of available sensors and type of measured output parameters available to compare to the estimated output parameters of the model. When an operating parameter of the gas turbine is no longer being measured, such as due to a sensor failure, the Kalman filter structure may be modified to account for the loss of the measured parameter, and may continue to generate performance multipliers based on the remaining measured conditions of the gas turbine.

[0073] Referring to FIG. 6, an embodiment of a gas turbine 110 is shown. Gas turbine 110 may include a compressor 112, a combustor 114, a turbine 116 drivingly coupled to compressor 112, and a computer control system 118 (controller). An inlet duct 120 to compressor 112 may feed ambient air and possibly injected water to compressor 112. The inlet duct may have ducts, filters, screens, and sound absorbing devices that may contribute to a pressure loss of ambient air flowing through inlet duct 120 into inlet guide vanes (I.G.V.) 121 of compressor 112. An exhaust duct 122 for turbine 116 directs combustion gases from the outlet of turbine 116 through, for example, emission control and sound absorbing devices.

Exhaust duct 122 may include sound adsorbing materials and emission control devices that may apply a backpressure to turbine 116. The amount of inlet pressure loss and back pressure may vary over time due to the addition of components to ducts 120, 122, and to dust and dirt clogging the inlet and exhaust ducts. Turbine 116 may drive a generator 124 that produces electrical power. The inlet loss to compressor 112 and turbine 116 exhaust pressure loss tend to be a function of corrected flow through gas turbine 110.

[0074] The operation of gas turbine 110 may be monitored by several sensor systems 126 detecting various observable conditions of the turbine, generator and ambient environment. In many instances, two or three redundant sensors may measure the same measured condition. For example, groups of three redundant temperature sensor systems 126 may monitor ambient temperature surrounding gas turbine 110, compressor discharge temperature, turbine exhaust gas temperature, and other temperature measurements of the gas stream through gas turbine 110. Similarly, groups of three redundant pressure sensor systems 126 may monitor ambient pressure, and static and dynamic pressure levels at the compressor inlet and outlet, turbine exhaust, at other locations in the gas stream through gas turbine 110. Groups of three redundant humidity sensor systems 126, e.g., wet and dry bulb thermometers, may measure ambient humidity in the inlet duct of compressor 112. Groups of three redundant sensor systems 126 may also comprise flow sensors, speed sensors, flame detector sensors, valve position sensors, guide vane angle sensors, or the like that may sense various parameters pertinent to the operation of gas turbine 110.

[0075] As used herein, "parameters" refer to items that may be used to define the operating conditions of the turbine, such as temperatures, pressures, and gas flows at defined locations in the turbine. Some parameters may be measured, *i.e.*, may be sensed and are directly known. Other parameters may be estimated by the model and may be indirectly known. The measured and estimated parameters may be used to represent a given turbine operating state, for example, see FIGS. 3-5.

[0076] A fuel control system 128 may regulate the fuel flowing from a fuel supply to combustor 114, the split between the fuel flowing into primary and secondary fuel nozzles, and the amount of fuel mixed with secondary air flowing into a combustion chamber. The fuel controller may also select the type of fuel for combustor 114. The fuel control system 128 may be a separate unit or may be a component of a main controller 118.

[0077] Main controller 118 may be a General Electric SPEEDTRONIC™ Gas Turbine Control System, such as is described in Rowen, W. I., "SPEEDTRONIC™ Mark V Gas Turbine Control System", GE-3658D, published by GE Industrial & Power Systems of Schenectady, N.Y. Controller 118 may be a computer system having a processor(s) that executes programs to control the operation of gas turbine 110 using sensor inputs and instructions from human operators. The programs executed by main controller 118 may include scheduling algorithms for regulating fuel flow to combustor 114. The commands generated by main controller 118 may cause actuators on gas turbine 110 to, for example, adjust valves (actuator not shown) between the fuel supply and combustors that regulate the flow, fuel splits and type of fuel flowing to the combustors, adjust inlet guide vanes 121 (actuator 127) on the compressor, and activate other control settings on the gas turbine.

[0078] The scheduling algorithms may enable main controller 118 to maintain, for example, the NO_x and CO emissions in the turbine exhaust to within certain predefined emission limits, and to maintain the combustor firing temperature to within predefined temperature limits. The scheduling algorithms may have inputs for parameter variables such as: current compressor pressure ratio, ambient specific humidity, inlet pressure loss and turbine exhaust back pressure. Control system 118 may apply the algorithms to schedule gas turbine 110, e.g., setting desired turbine exhaust temperatures and combustor fuel splits, so as to satisfy performance objectives while complying with operability boundaries of gas turbine 110.

[0079] Referring to FIG. 7, an embodiment of a high-level block diagram of a gas turbine and an adaptive real time engine simulation model 130 (ARES) is shown. ARES model 130 may electronically model, in real time, several operating parameters of gas turbine 110. Gas turbine 110 may have several observable parameters that may be referred to as "fundamental inputs" ($\bar{u}$) 132. Fundamental inputs ($\bar{u}$) 132 may be directly measured by sensors and include (without limitation): ambient conditions (A), angle of the inlet guide vanes (IGV), amount of fuel (FUEL) flowing to combustor 114 and rotational speed (SPEED) of gas turbine 110. The listed fundamental inputs ($\bar{\bar{u}}$) 132 may be illustrative embodiments and are provided merely to illustrate that sensed inputs may be collected. The specific sensed inputs are not material to this disclosure and will depend on the control system and available sensors at a particular gas turbine installation.

[0080] The term "fundamental" does not imply that each and every one these measured parameters 132 must be input to the particular embodiment of model 130 disclosed herein or that any such gas turbine model must have these inputs. Fundamental inputs ($\bar{u}$) 132 to a real time model 130 of a gas turbine may include some, all and/or other inputs. The term fundamental inputs merely indicates that for an embodiment of the particular model disclosed herein these inputs are taken from measurements of actual conditions and are applied as inputs to the model.

[0081] Fundamental inputs ($\bar{u}$) 132 may be inputted to model 130 of gas turbine 110. These inputs may be applied by model 130 to generate output values ($\hat{y}$) of model 130 corresponding to operating parameters of gas turbine 110. The outputs may include primary modeled outputs ($\hat{y}$) 138 and may be compared to corresponding measured operating parameters 144 of gas turbine 110. The modeled outputs may also include extended model outputs ($\hat{y}$ ext.) 140 that may predict gas turbine parameters, e.g., desired fuel flow rate, that may not be directly measured. The extended modeled outputs 140 may be used by the control system to operate gas turbine 110, such as by applying the desired fuel flow rate to control the actual fuel flow rate to combustor 114.

[0082] Primary outputs 138 and their corresponding measured operating parameters (tuning inputs) 144 may be applied to an error correction system 147 that may automatically and regularly tune model 130 to ensure that all of the modeled outputs ($\hat{y}$ and $\hat{y}$ ext.) accurately predict operating conditions of gas turbine 110. Modeled outputs 138, 140 may be used for controlling gas turbine 110, scheduling maintenance, and predicting the performance of gas turbine 110. The application of the modeled outputs for controlling gas turbine 110 and for functions other than tuning model 130 is well known to persons of ordinary skill in the art of controlling gas turbines.

[0083] Primary outputs ($\hat{y}$) 138 of model 130 may be, for example: modeled (M) power output (POW_M) such as to a generator 124, modeled turbine exhaust temperature (EXHTEMP_MOD), and modeled compressor conditions (C_M). The number and particular parameters corresponding to primary outputs ($\hat{y}$) 138 may vary from gas turbine model to model. Further, primary outputs ($\hat{y}$) 138 may vary during operation of gas turbine 110 if, for example, a sensor fails the corresponding measured parameter is no longer available as a comparison to one of the primary outputs.

[0084] Primary outputs 138 may each correspond to a measured, e.g., sensed operating parameter ($\bar{y}$) 144, such as actual power output (POW-A), turbine exhaust temperature (EXHTEMP_A), and compressor condition (C_A). Measured parameters 144 may be based on output signals of sensors monitoring the corresponding actual parameter of gas turbine 110. Multiple redundant sensors may also observe each of measured parameters 144. The sensed parameters may be selected based on the specific control system for a gas turbine and available sensors.

[0085] Model 130 may be a computer generated model of gas turbine 110. Model 130 may be an arrangement of mathematical representations of the primary and extended outputs. Each of these representations may rely on the input values, e.g., fundamental inputs 132, to generate an estimated value of modeled output parameters 138, 140. The mathematical representations may generate a surrogate output parameter value 138, 140 that may be used in circumstances where a measured parameter value is not available. Real-time computer models of gas turbines are well known especially when applied to control of aircraft gas turbine engines. Industrial gas turbines have also been the subject of computer models. For example, models may be used to estimate sensed operating parameters such as the primary outputs, as well as parameters that are not sensed such as combustion and turbine inlet temperatures, airflows, and compressor stall margins. The model 130 may be a physics-based aero-thermodynamic computer model, a regression-fit model, neural-net model, or other suitable computer model of a gas turbine.

[0086] Primary outputs 138 may be compared to measured parameter values 144. Measured values 144 may be referred to as tuning inputs because they may be used to tune model 130. Primary outputs 138 and measured parameter values 144 may be normalized 146 to generated normalized modeled outputs ($\bar{\hat{z}}$) and normalized measured outputs ($\bar{z}$). These normalized outputs may be compared 148, e.g., POW_MOD may be compared to POW_A, to generate a difference signal $(\Delta(\bar{\hat{z}}, \bar{z}))$ 150 such as (Δ(POW_MOD, POW_A)). The difference signal 150 may indicate an error of the modeled output parameter with respect to the measured actual parameter. There may be generally at least one difference signal 150 corresponding to each of the primary outputs 138, and there may be a difference signal corresponding to each of the redundant sensors measuring a particular parameter. At least one measured value 144, e.g., tuning input, may be generally needed for each primary output 138 to generate a difference signal. If one or more of the tuning inputs is not available, e.g., due to a failed sensor, the corresponding difference signals $(\Delta(\bar{\hat{z}}, \bar{z}))$ 150 may not be generated, but the error correction system may still operate to correct model 130.

[0087] A Kalman filter gain matrix (KFGM-K) 152 may receive as an input the difference signals 150 and may generate normalized correction factor adjustments ($\bar{\hat{x}}$) 160 which are used to tune the gas turbine model 130. As shown in FIG. 5, the KFGM may apply tuning factors 151 to adjust the difference signals 50 and generate normalized correction factors ($\bar{\hat{x}}$) 160. A relatively large number of difference signals 150, e.g., redundant sensor outputs for each of POW, EXHTEMP and C, may enable the Kalman filter gain matrix to generate normalized correction factors 160 that may be used to accurately tune the model and ensure that the model generates accurate output values ($\hat{y}$ and $\hat{y}$ ext.).

[0088] The loss of difference signals 150, may reduce (but not eliminate) the ability of the Kalman filter gain matrix to tune the model. The adaptive ability of the Kalman filter gain matrix 152 may enable it to continue to tune model 130 with a reduced set of difference signals 150. To automatically tune the model when one or more of the difference signals is not available, the Kalman filter gain matrix (K) 152 may be modified to account for the loss of a difference signal. Accordingly, the gas turbine may continue to operate and be automatically tuned even when sensors fail and tuning input data regarding observable operating conditions is not available.

[0089] Referring to FIG. 8, an embodiment of a mechanism by which the Kalman filter gain matrix (KFGM) may be created is presented. Wavy line 200 is meant to represent FIG. 7 and is connected to line 151 of FIG. 8 via K 152 of FIG. 7. Referring to FIGS. 7 and 8, the model sensitivity matrix (MSM) 166 may be determined by applying a series of inputs (fundamental inputs 132 and a series of perturbated performance multipliers, *e.g.*, perturbated corrected and normalized difference signals 164) to a gas turbine model 167 (such as model 130). The sensitivity of the primary outputs of the model 167 may be determined by a partial derivative analysis 168. The sensitivity values may be normalized 169 to form the sensitivity matrix (a, h) 166. The sensitivity matrix may be applied to the on-line filter gain calculation 165 (*e.g.*, Kalman filter equations) to determine a matrix 152 of optimal tuning values, *e.g.*, gain values, to be applied to the difference signals corresponding difference signals ($\Delta(\bar{\hat{z}}, \bar{z})$) 50 between the measured gas turbine values and the corresponding values predicted by the model.

[0090] The Kalman filter equations 165 were first published by R. F. Kalman & Bucy in the 1960s and are depicted in FIG. 5. The Kalman filter is known in the art and persons of ordinary skill in control systems will be familiar with these filters. The Kalman filter is an optimal recursive data processing algorithm.

[0091] The Kalman filter gain matrix (K) 152 may include one or more tuning factors 151 that may be applied to the difference signals ($\Delta(\bar{\hat{z}}, \bar{z})$) 150 to generate normalized correction factor adjustments 160. The normalized correction factors 160 may be summed 156 with the prior normalized correction factor (Z^{-1}) 158 to average out the differences between the current and prior correction factors. The averaged correction factor may be un-normalized 162 to produce the performance multipliers 164 (also un-normalized correction factors) that may include, for example, component efficiencies and flow capacities. The un-normalized correction factors 164 may be applied to gas turbine model 130 as, for example, multipliers, that are applied to the algorithms that model the gas turbine and generate the modeled output parameter values 138, 140. The multipliers may tune the model by adjusting the algorithms so that they generate modeled parameter values that accurately represent the actual operation of the gas turbine. The modeled output parameter values 138, 140 may be applied to determine fuel and air flow to the gas turbine and to determine other control inputs to the gas turbine.

[0092] The terms "first," "second," and the like, herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another, and the terms "a" and "an" herein do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item. The modifier "approximately" used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context, (e.g., includes the degree of error associated with measurement of the particular quantity). The suffix "(s)" as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including one or more of that term (e.g., the metal(s) includes one or more metals). Ranges disclosed herein are inclusive and independently combinable (e.g., ranges of "up to approximately 25 wt%, or, more specifically, approximately 5 wt % to approximately 20 wt %", is inclusive of the endpoints and all intermediate values of the ranges of "approximately 5 wt % to approximately 25 wt %," etc).

[0093] While shown and described herein as a method and system for controlling the temperature of a turbomachine, it is understood that aspects of the invention further provide various alternative embodiments. For example, in one embodiment, the invention provides a computer program fixed in at least one computer-readable medium, which when executed, enables a computer system to control the temperature of the turbomachine. To this extent, the computer-readable medium includes program code, such as temperature control system program 40 (FIG. 1), which implements some or all of a process described herein. It is understood that the term "computer-readable medium" comprises one or more of any type of tangible medium of expression, now known or later developed, from which a copy of the program code can be perceived, reproduced, or otherwise communicated by a computing device. For example, the computer-readable medium can comprise: one or more portable storage articles of manufacture; one or more memory/storage components of a computing device; paper; and/or the like.

[0094] In another embodiment, the invention provides a method of providing a copy of program code, such as temperature control program 40 (FIG. 1), which implements some or all of a process described herein. In this case, a computer system can process a copy of program code that implements some or all of a process described herein to generate and transmit, for reception at a second, distinct location, a set of data signals that has one or more of its characteristics set and/or changed in such a manner as to encode a copy of the program code in the set of data signals. Similarly, an embodiment of the invention provides a method of acquiring a copy of program code that implements some or all of a process described herein, which includes a computer system receiving the set of data signals described herein, and translating the set of data signals into a copy of the computer program fixed in at least one computer-readable medium. In either case, the set of data signals can be transmitted/received using any type of communications link.

[0095] In still another embodiment, the invention provides a method of generating a system for controlling the temperature of a turbo-machine. In this case, a computer system, such as computer infrastructure 20 (FIG. 1), can be obtained (e.g., created, maintained, made available, etc.) and one or more components for performing a process described herein can be obtained (e.g., created, purchased, used, modified, etc.) and deployed to the computer system. To this extent, the deployment can comprise one or more of: (1) installing program code on a computing device; (2) adding one or more computing and/or I/O devices to the computer infrastructure; (3) incorporating and/or modifying the computer infrastructure to enable it to perform a process described herein; and/or the like.

[0096] It is understood that aspects of the invention can be implemented as part of a business method that performs a process described herein on a subscription, advertising, and/or fee basis. That is, a service provider could offer to control the temperature of a turbo-machine as described herein. In this case, the service provider can manage (e.g., create, maintain, support, etc.) a computer infrastructure, such as computer structure 20 (FIG. 1), that performs a process described herein for one or more customers. In return, the service provider can receive payment from the customer(s) under a subscription and/or fee agreement; receive payment from the sale of advertising to one or more third parties, and/or the like.

[0097] The foregoing description of various aspects of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and obviously, many modifications and variations are possible. Such modifications and variations that may be apparent to an individual in the art are included within the scope of the invention as defined by the accompanying claims.

[0098] Various aspects and embodiments of the present invention are defmed by the following numbered clauses:

1. A method for controlling the temperature of a turbo-machine, the method comprising:

   receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise ($T_{rise)}$ parameter of the turbo-machine during operation using a computing device;

   comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine using the computing device; and

   creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a user.

2. The method according to clause 1, wherein the receiving includes receiving the T_{exh}, T_{fire}, and T_{rise} parameters from an external computer system in communication with the computing device.

3. The method according to any preceding clause, further comprising: receiving the T_{exh}, T_{fire}, and T_{rise} operational boundaries using the computing device.

4. The method according to any preceding clause, wherein the receiving includes receiving the T_{exh}, T_{fire}, and T_{rise} operational boundaries from an external computer system in communication with the computing device.

5. The method according to any preceding clause, wherein the action creating includes creating an alarm or trip of the turbo-machine in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary.

6. The method according to any preceding clause, wherein the alarm or trip creating includes creating the alarm or trip in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a period of time.

7. The method according to any preceding clause, further comprising: receiving one or more additional temperature parameters of the turbo-machine during operation; comparing the one or more additional temperature parameters to corresponding one or more additional operational boundaries; and creating an action in response to at least one of: a) the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary and b) the one or more additional temperature parameters exceeding the corresponding one or more additional operational boundaries using the computing device.

8. The method according to any preceding clause, wherein the T_{rise} parameter represents the firing plane temperature of a combustor of the turbo-machine.

9. The method according to any preceding clause, wherein the T_{rise} parameter represents the temperature rise across a combustor of the turbo-machine.

10. The method according to any preceding clause, wherein the T_{exh}, T_{fire}, and T_{rise} parameters are independently measured or estimated by a computer modeling system.

11. The method according to any preceding clause, wherein the exceeding includes the temperature parameters exceeding the corresponding operational boundaries by a predetermined temperature value.

12. A temperature control system for a turbo-machine, the system comprising:

at least one device including:

a receiver for receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise (T_{rise}) parameter of the turbo-machine during operation;

a comparator for comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine; and

an action creator for creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary.

13. The temperature control system according to any preceding clause, wherein the receiver further receives the T_{exh}, T_{fire}, and T_{rise} operational boundaries from an external computer system in communication with the computing device.

14. The temperature control system according to any preceding clause, wherein the comparator comprises a determinator for determining whether the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter exceeds the corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries.

15. The temperature control system according to any preceding clause, wherein the determinator determines whether the T_{exh}, T_{fire}, and T_{rise} parameters exceeds the corresponding T_{exh}, $T_{fire,}$ and T_{rise} operational boundaries by a predetermined temperature value.

16. The temperature control system according to any preceding clause, wherein the action creator creates an alarm or trip of the turbo-machine in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary.

17. The temperature control system according to any preceding clause, wherein the action creator creates an alarm or trip of the turbo-machine in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a period of time.

18. A computer program comprising program code embodied in at least one computer-readable medium, which when executed, enables a computer system to implement a method for controlling the temperature of a turbo-machine, the method comprising:

receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise ($T_{rise)}$ parameter of the turbo-machine during operation using a computing device;

comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}. T_{fire}, and T_{rise} operational boundaries of the turbo-machine using the computing device; and

creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a user.

19. The computer program according to any preceding clause, wherein the creating an action includes creating an alarm or trip of the turbo-machine in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary using the computing device.

20. The computer program according to any preceding clause, further comprising: receiving one or more additional temperature parameters of the turbo-machine during operation; comparing the one or more additional temperature parameters to corresponding one or more additional operational boundaries; and creating an action in response to at least one of: a) the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary and b) the one or more additional parameters exceeding the corresponding one or more additional operational boundaries using the computing device.

Claims

1. A method for controlling the temperature of a turbo-machine (15), the method comprising:

   receiving an exhaust temperature (T_{exh}) parameter, a firing temperature T_{fire} parameter, and a combustor temperature rise (T_{rise}) parameter of the turbo-machine (15) during operation using a computing device (30) (S1);
   comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine (15) using the computing device (30) (S2); and
   creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a user (50) (S3).

2. The method according to claim 1, wherein the receiving includes receiving the T_{exh}, T_{fire}, and T_{rise} parameters from an external computer system in communication with the computing device (30).

3. The method according to any preceding claim, wherein the action creating includes creating an alarm or trip of the turbo-machine (15) in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary.

4. A temperature control system (40) for a turbo-machine (15), the system (40) comprising:

   at least one device including:

   a receiver (41) for receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise (T_{rise}) parameter of the turbo-machine (15) during operation;
   a comparator (42) for comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine (15); and
   an action creator (43) for creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary.

5. The temperature control system (40) according to claim 4, wherein the receiver (41) further receives the T_{exh}, T_{fire}, and T_{rise} operational boundaries from an external computer system in communication with the computing device (30).

6. The temperature control system (40) according to claim 4 or claim 5, wherein the comparator (42) comprises a determinator (47) for determining whether the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter exceeds the corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries.

7. The temperature control system (40) according to any of claims 4 to 6, wherein the action creator (43) creates an alarm or trip of the turbo-machine (15) in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary.

8. A computer program comprising program code embodied in at least one computer-readable medium, which when executed, enables a computer system to implement a method for controlling the temperature of a turbo-machine (15), the method comprising:

   receiving an exhaust temperature (T_{exh}) parameter, a firing temperature (T_{fire}) parameter, and a combustor temperature rise ($T_{rise)}$ parameter of the turbo-machine (15) during operation using a computing device (30) (S1);
   comparing the T_{exh} parameter, the T_{fire} parameter, and the T_{rise} parameter to corresponding T_{exh}, T_{fire}, and T_{rise} operational boundaries of the turbo-machine (15) using the computing device (30) (S2); and
   creating an action in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary for a user (50) (S3).

9. The computer program according to claim 8, wherein the creating an action includes creating an alarm or trip of the turbo-machine (15) in response to at least one of: the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary using the computing device (30).

10. The computer program according to claim 8 or claim 9, further comprising: receiving one or more additional temperature parameters of the turbo-machine (15) during operation; comparing the one or more

additional temperature parameters to corresponding one or more additional operational boundaries; and creating an action in response to at least one of: a) the T_{exh} parameter exceeding the T_{exh} operational boundary, the T_{fire} parameter exceeding the T_{fire} operational boundary, and the T_{rise} parameter exceeding the T_{rise} operational boundary and b) the one or more additional temperature parameters exceeding the corresponding one or more additional operational boundaries using the computing device (30).

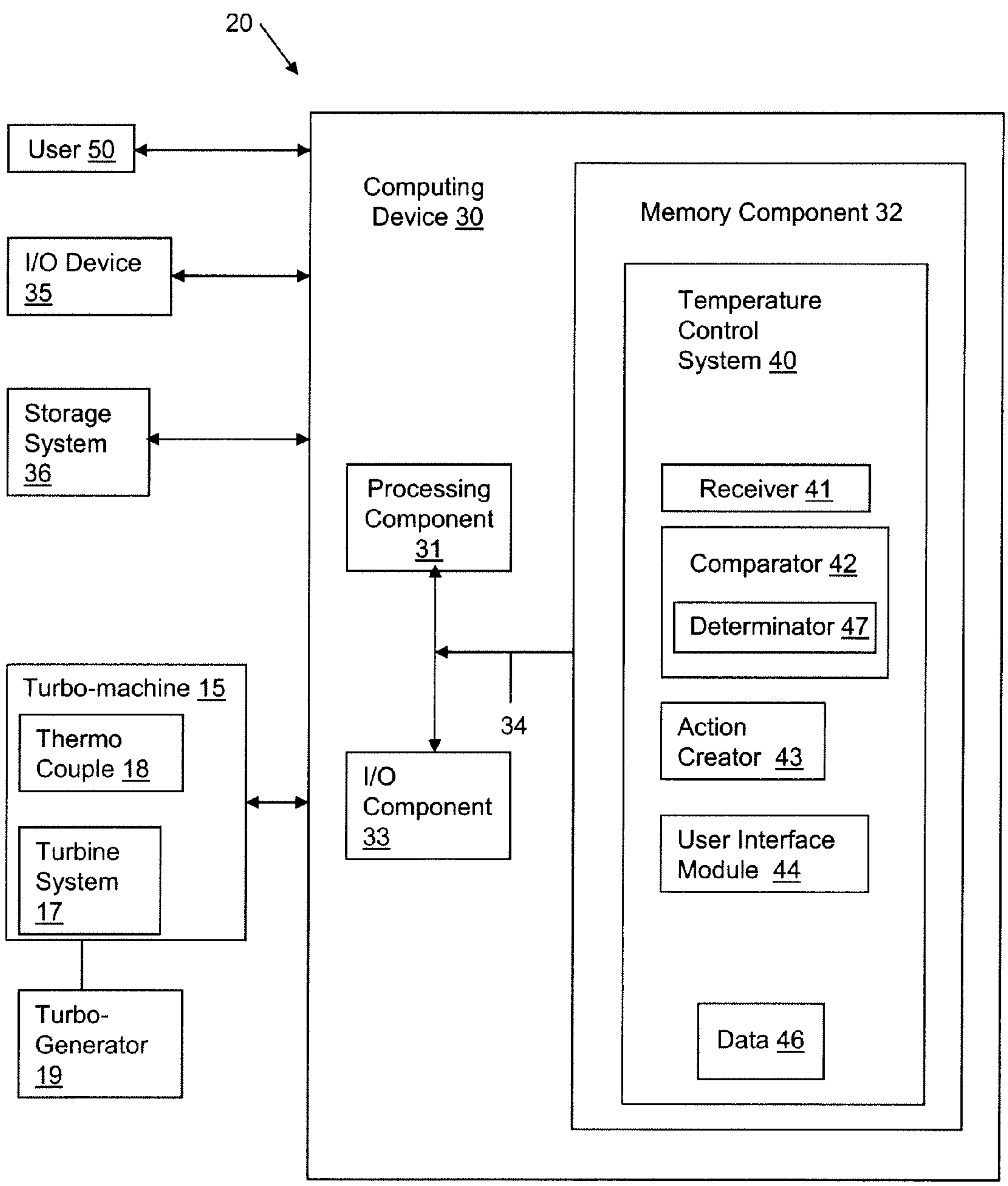
20
User 50
I/O Device 35
Storage System 36
Turbo-machine 15
Thermo Couple 18
Turbine System 17
Turbo-Generator 19
Computing Device 30
Processing Component 31
I/O Component 33
34
Memory Component 32
Temperature Control System 40
Receiver 41
Comparator 42
Determinator 47
Action Creator 43
User Interface Module 44
Data 46

FIG. 1

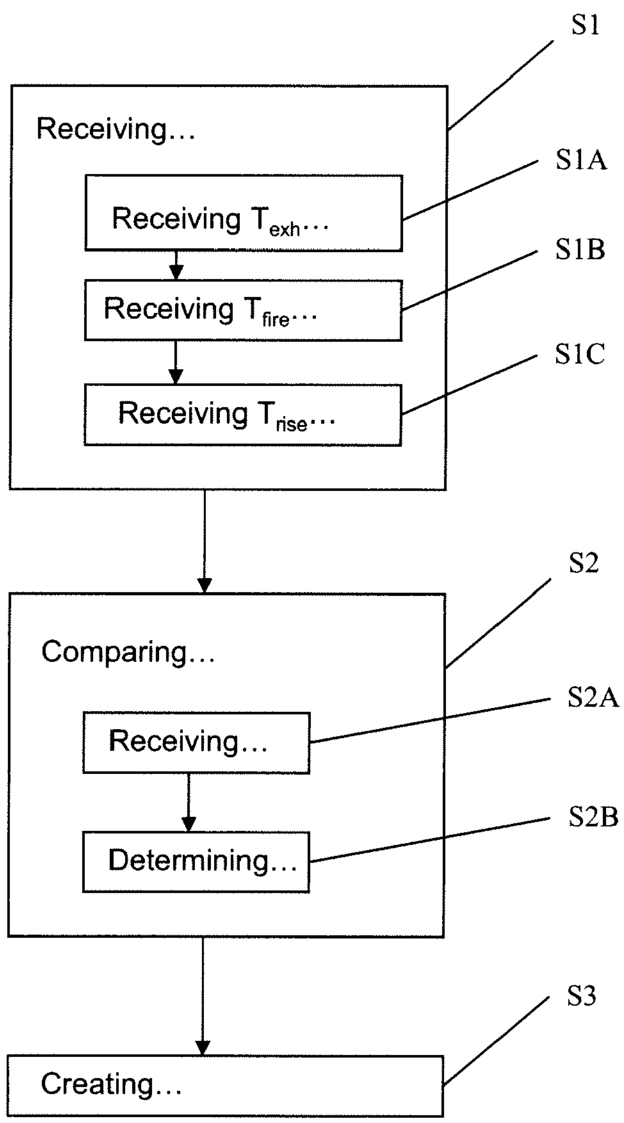
S1
Receiving…
S1A
Receiving T_{exh}…
S1B
Receiving T_{fire}…
S1C
Receiving T_{rise}…
S2
Comparing…
S2A
Receiving…
S2B
Determining…
S3
Creating…

FIG. 2

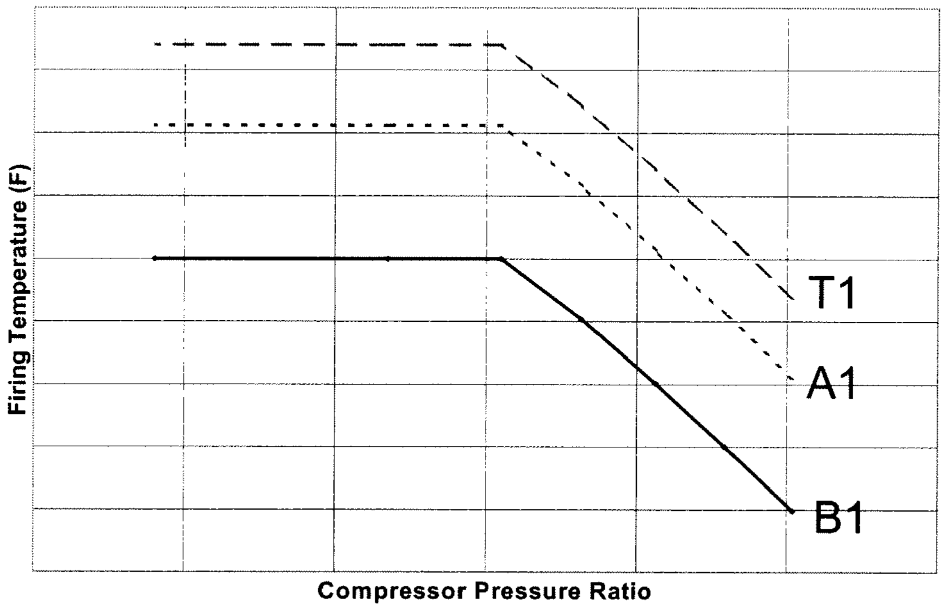
Firing Temperature (F)
T1
A1
B1
Compressor Pressure Ratio

FIG. 3

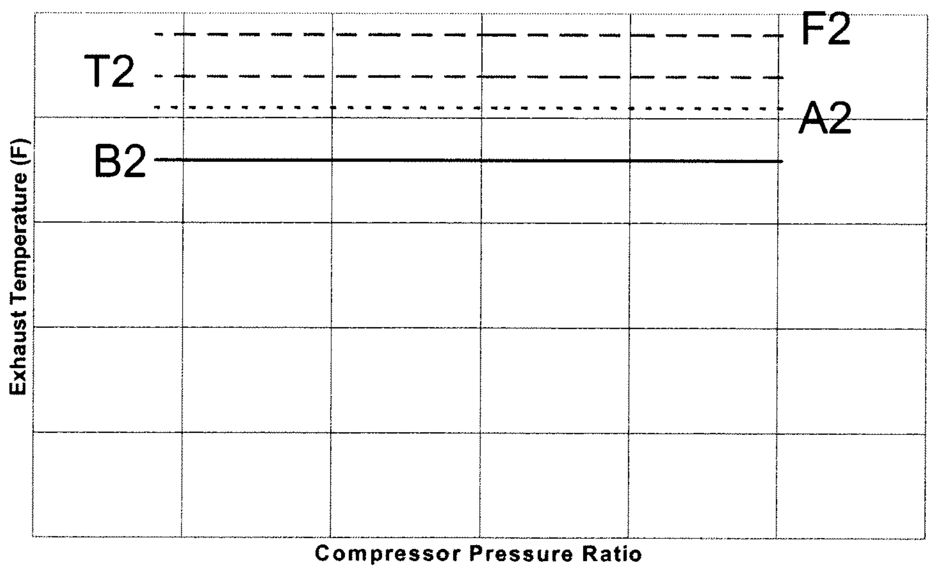
Exhaust Temperature (F)
F2
T2
A2
B2
Compressor Pressure Ratio

FIG. 4

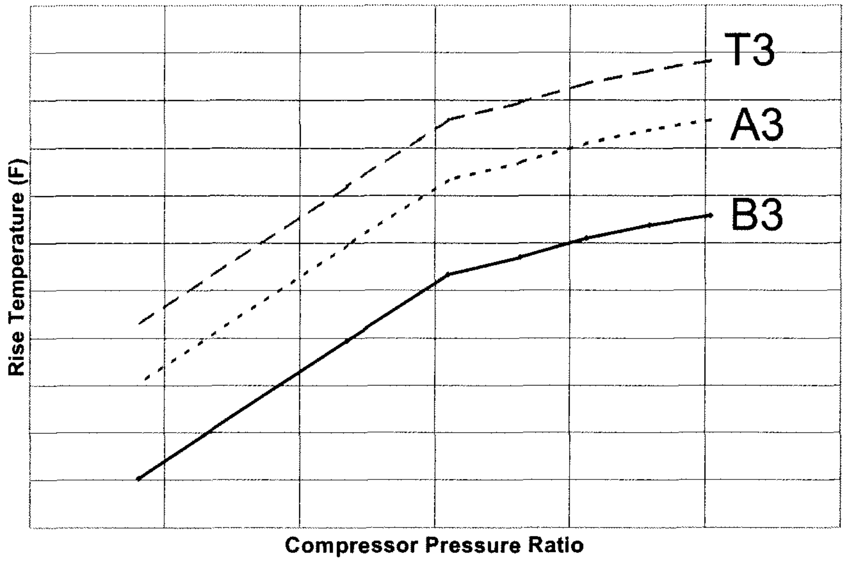

FIG. 5

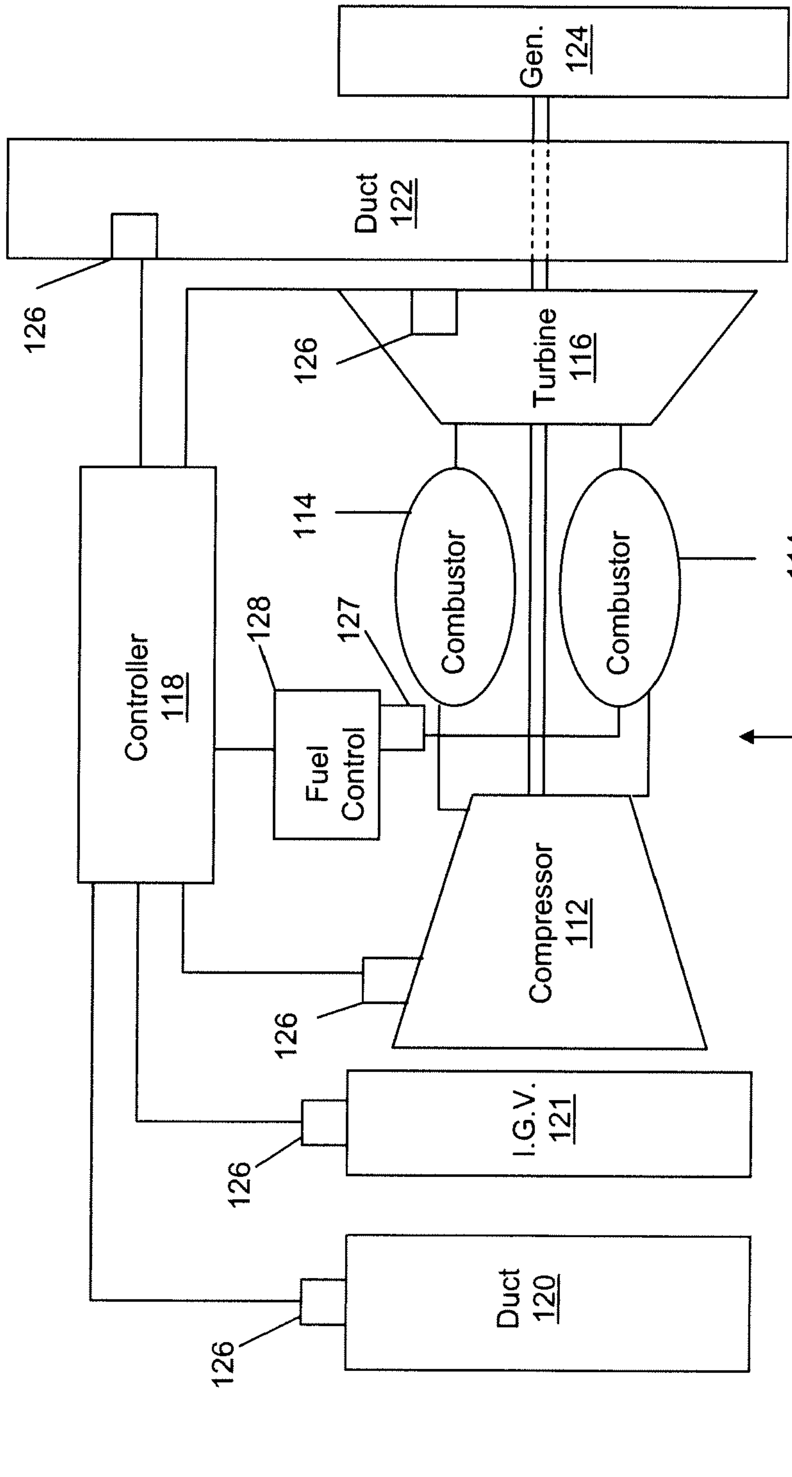
Gen.
124
Duct
122
126
126
Turbine
116
114
Combustor
Combustor
114
Controller
118
128
127
Fuel
Control
110
Compressor
112
126
I.G.V.
121
126
Duct
120
126

FIG. 6

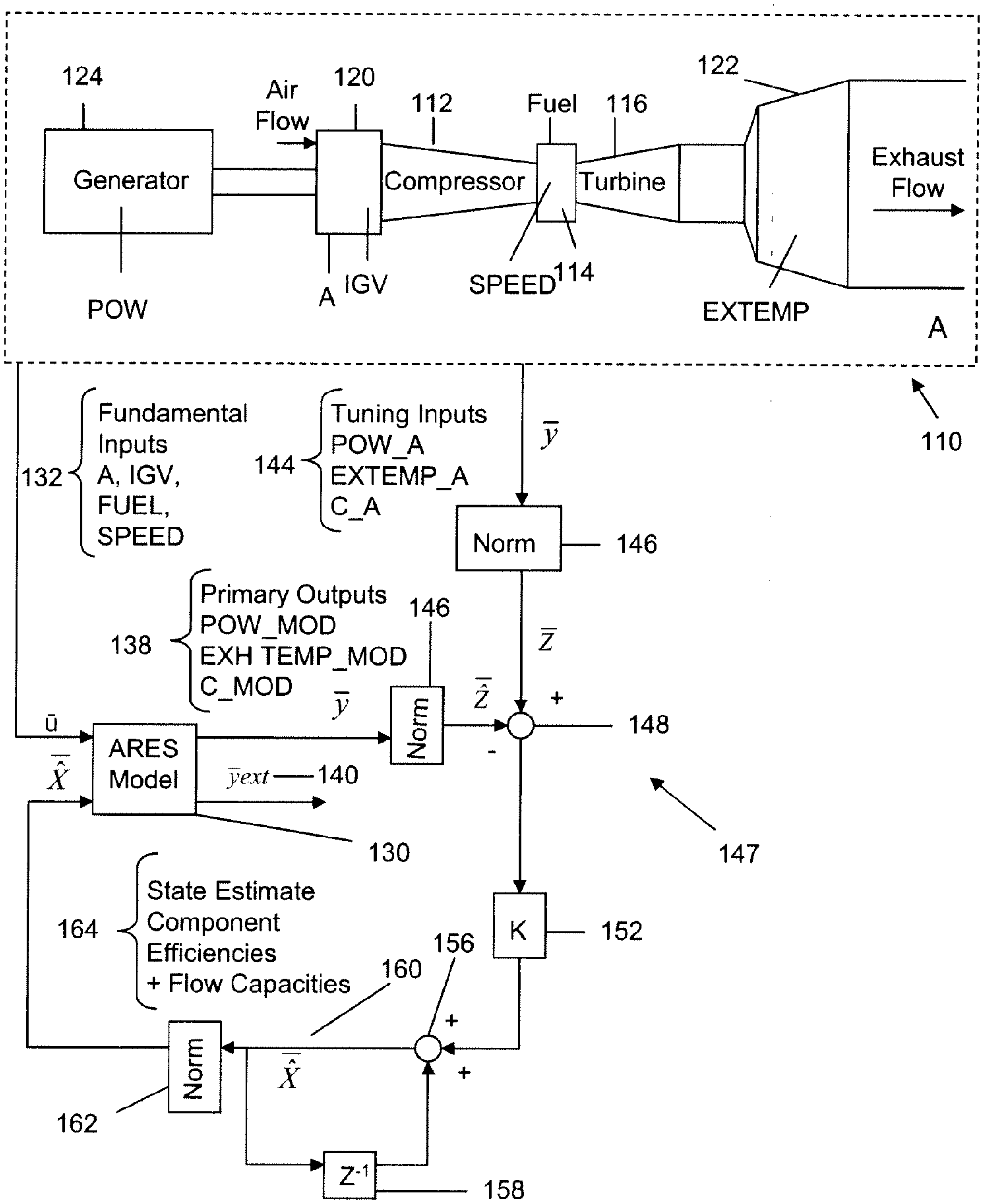
124
Generator
POW
Air Flow
120
A
IGV
112
Compressor
Fuel
116
Turbine
SPEED
114
122
Exhaust Flow
EXTEMP
A
110
Fundamental Inputs
132
A, IGV,
FUEL,
SPEED
Tuning Inputs
144
POW_A
EXTEMP_A
C_A
$\bar{y}$
Norm
146
$\bar{z}$
Primary Outputs
138
POW_MOD
EXH TEMP_MOD
C_MOD
146
$\bar{y}$
Norm
$\bar{\hat{z}}$
+
-
148
ū
$\bar{\hat{X}}$
ARES Model
$\bar{y}ext$
140
130
147
K
152
State Estimate
164
Component
Efficiencies
+ Flow Capacities
156
160
+
+
Norm
162
$\bar{\hat{X}}$
Z^{-1}
158

FIG. 7

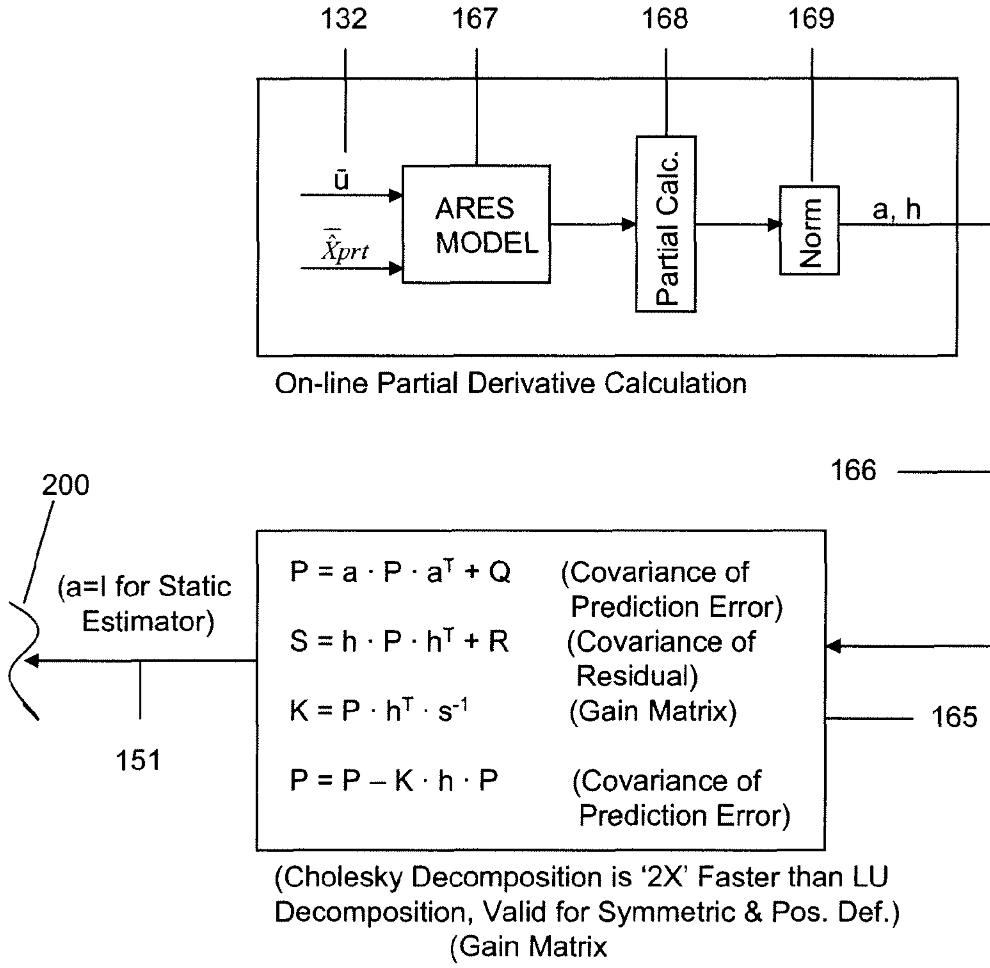
132
167
168
169
ū
$\bar{\hat{X}}prt$
ARES MODEL
Partial Calc.
Norm
a, h
On-line Partial Derivative Calculation
166
200
(a=I for Static Estimator)
151
P = a · P · a^T + Q (Covariance of Prediction Error)
S = h · P · h^T + R (Covariance of Residual)
K = P · h^T · s^{-1} (Gain Matrix)
P = P – K · h · P (Covariance of Prediction Error)
165
(Cholesky Decomposition is '2X' Faster than LU Decomposition, Valid for Symmetric & Pos. Def.) (Gain Matrix

FIG. 8

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 7742904 B **[0040]**