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## Cross-bleed safety mechanism for a linear hydraulic actuator


### Abstract

Apparatus and associated methods relate to passively limiting a load of a stalled linear hydraulic actuator that actuates a kinematic device. Damage to a stalled linear hydraulic actuator, associated mounting structure(s), any associated linking mechanism(s), and/or a kinematic device controlled thereby can be prevented quickly and without necessarily forfeiting control of the kinematic device. Such damage prevention can be performed using a cross-bleed safety mechanism connected in parallel with the linear hydraulic actuator. The cross-bleed safety mechanism includes a bilaterally moveable spool within a hydraulic cylinder. The bilaterally moveable spool is located between hydraulic chambers that are in fluid communication with corresponding chambers of the linear hydraulic actuator. In response to being sufficiently displaced from an equilibrium position in each direction of movement by a pressure difference thereacross, the bilaterally moveable spool unblocks bypass channels thereby limiting the stalled linear actuator.



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## Background/Summary

BACKGROUND

(1) A linear hydraulic actuator can be used to position a kinematic device, sometimes via an intermediate linking mechanism. A linear hydraulic actuator typically has a bilaterally moveable piston within a hydraulic cylinder. On either side of the bilaterally moveable piston are hydraulic chambers which are typically filled with hydraulic fluid. An unbalanced pressure (i.e., a non-zero differential pressure across the bilaterally moveable piston) applied to the hydraulic fluids in the hydraulic chambers on opposite sides of the bilaterally moveable piston generates a force that can move the bilaterally moveable piston, which can then position the kinematic device coupled thereto. The displacement of the bilaterally moveable piston is in the direction of a central axis of the hydraulic piston. Because hydraulic fluids are typically incompressible (or nearly so), a hydraulic controller of the linear hydraulic actuator can provide precise linear displacement of the bilaterally moveable piston.

(2) Hydraulic systems are used to manipulate or operate various kinematic devices in aircraft, especially larger aircraft. Such kinematic devices, which can be hydraulically manipulated or operated, can include moveable airfoil surfaces, landing gear deployment and retraction mechanisms, turbofan engine control devices, etc. In some scenarios, such kinematic devices can become difficult or impossible to operate. For example, in icing conditions, various flight control surfaces can become frozen, making them inoperable. In another example, Foreign Object Debris (FOD) can be ingested into a turbofan engine, causing damage to stators, which can be rotationally

oriented by linear hydraulic actuators. When such kinematic devices are damaged or worn, they can experience binding or higher than normal friction, or they can even become inoperable. Such increased friction and binding can sometimes be overcome, but with greater than the normal load to the linear hydraulic actuator. If the load to the linear hydraulic actuator exceeds the sizing limit of the linear hydraulic actuator, operation of the stalled kinematic device can cause damage to the kinematic device, any linking mechanism, the linear hydraulic actuator, or the mounting of any of these components. When the compromised kinematic devices can be operated only by loads in excess of such a sizing limit of the linear hydraulic actuator, the linear hydraulic actuator can be referred to as a stalled actuator.

(3) A traditional system for preventing damage to the kinematic device, any linking mechanism, the linear hydraulic actuator, or the mounting of any of these components, may include methods of physically disconnecting the linear hydraulic actuator from the kinematic device if the load output is high enough to cause such damage. For example, a linking mechanism can include a shear pin sized to sheer in response to the load of the linear hydraulic actuator exceeding a predetermined threshold. Use of such a sacrificial part, such as, for example, the sheer pin, can result in the kinematic device becoming inoperable following such a sheering event, though. Such inoperability of the kinematic device can result in impaired operation or control of the aircraft.

SUMMARY

(4) Some embodiments relate to a cross-bleed safety mechanism for protecting a hydraulic system. The cross-bleed safety mechanism includes a hydraulic cylinder and a bilaterally moveable spool. The hydraulic cylinder has first and second hydraulic ports configured to provide fluid communication with extend and retract chambers, respectively, of a linear hydraulic actuator when hydraulically coupled thereto. The bilaterally moveable spool is within and provides a hydraulic seal with an interior surface of the hydraulic cylinder. The bilaterally moveable spool is located between a first chamber in fluid communication with the first port and a second chamber in fluid communication with the second port. The bilaterally moveable spool blocks first and second hydraulic bypass channels in response to the bilaterally moveable spool being at an equilibrium position. The first and second hydraulic bypass channels selectively provide fluid communication between first and second chambers. The bilaterally moveable spool blocks the second hydraulic bypass channel and begins to unblock the first hydraulic bypass channel in response to a first differential pressure between the first and second chambers exceeding a first differential cracking pressure. The bilaterally moveable spool blocks the first hydraulic bypass channel and begins to unblock the second hydraulic bypass channel in response to a second differential pressure between the extend and retract chambers exceeding a second differential cracking pressure.

(5) Some embodiments relate to a load-protected linear hydraulic actuator that includes a linear hydraulic actuator and a cross-bleed safety mechanism. The linear hydraulic actuator has an extend chamber and a retract chamber on either side of a bilaterally moveable piston within a first hydraulic cylinder. The extend chamber provides hydraulic fluid via an extend supply/return line. The retract chamber provides hydraulic fluid via a retract supply/return line. The cross-bleed safety mechanism that includes a second hydraulic cylinder. A bilaterally moveable spool is within and provides a hydraulic seal with an interior surface of the hydraulic cylinder. The bilaterally moveable spool is located between a first chamber in fluid communication with the extend chamber of the linear hydraulic actuator and a second chamber in fluid communication with the retract chamber of the linear hydraulic actuator. The bilaterally moveable spool blocks first and second hydraulic bypass channels in response to the bilaterally moveable spool being at an equilibrium position, the first and second hydraulic bypass channels selectively provide fluid communication between first and second chambers. The bilaterally moveable spool blocks the second hydraulic bypass channel and begins to unblock the first hydraulic bypass channel in response to a first differential pressure between the first and second chambers exceeding a first differential cracking pressure. The bilaterally moveable spool blocks the first hydraulic bypass channel and begins to

unblock the second hydraulic bypass channel in response to a second differential pressure between the second and first chambers exceeding a second differential cracking pressure.

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## Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) The material described herein is illustrated by way of example and not by way of limitation in the accompanying figures. For simplicity and clarity of illustration, elements illustrated in the figures are not necessarily drawn to scale. For example, the dimensions of some elements may be exaggerated relative to other elements for clarity. Further, where considered appropriate, reference labels have been repeated among the figures to indicate corresponding or analogous elements. In the figures:

(2) FIG. **1** is a perspective view of an aircraft equipped with a fast-acting system for protecting a linear hydraulic actuator by limiting load output.

(3) FIG. **2** is a schematic diagram of an embodiment of a hydraulic control equipped with a cross bleed safety mechanism.

(4) FIG. **3** is a graph of a pressure vs. flow through a hydraulic pressure cross-bleed safety mechanism.

(5) FIG. **4** is a perspective view of an embodiment of a linear hydraulic actuator equipped with an integrated cross bleed safety mechanism.

(6) FIG. **5** is a cross sectional diagram of another example of a cross-bleed safety mechanism.

DETAILED DESCRIPTION

(7) Apparatus and associated methods relate to passively limiting a load of a stalled actuator that actuates a kinematic device. Damage to a linear hydraulic actuator, associated mounting structure(s), any associated linking mechanism(s), and/or a kinematic device controlled thereby can be prevented quickly and without necessarily forfeiting control of the kinematic device. Such damage prevention can be performed using a cross-bleed safety mechanism connected in parallel with the linear hydraulic actuator. The cross-bleed safety mechanism includes a bilaterally moveable spool within a hydraulic cylinder. The bilaterally moveable spool is located between hydraulic chambers that are in fluid communication with corresponding chambers of the linear hydraulic actuator. In response to being sufficiently displaced from an equilibrium position in each direction of movement by a pressure difference thereacross, the bilaterally moveable spool unblocks bypass channels thereby limiting the stalled actuator.

(8) FIG. **1** is a perspective view of an aircraft equipped with a fast-acting system for protecting a linear hydraulic actuator by limiting load output. In FIG. **1**, aircraft **10** has wing **12** equipped with various flight control surfaces, such as aileron **14**, flaps **16**, spoilers **18**, and leading-edge slats **20**A-**20**C. Leading-edge slat **20**A is controlled by slat control system **22**. slat control system **22** includes hydraulic reservoir **24**, hydraulic pump **26**, hydraulic-fluid supply and return lines **28**S and **28**R, actuator controller **30**, extend and retract supply/return lines **32**E and **32**R, linear hydraulic actuator **34**, and cross-bleed safety mechanism **36**. Hydraulic reservoir **24** stores hydraulic fluid that can be used in various hydraulic systems, including slat control system **22**. Hydraulic pump **26** provides hydraulic fluid to actuator controller **30** via hydraulic-fluid supply line **28**S. The hydraulic fluid provided by hydraulic pump **26** is pressurized so as to be usable for positioning various kinematic devices, such as leading-edge slat **20**A. Actuator controller **30** directs hydraulic fluid received via hydraulic-fluid supply line **28**S to linear hydraulic actuator **34** in a controlled fashion so as to control position of leading-edge slat **20**A. Actuator controller **30** returns hydraulic fluid to hydraulic reservoir **24** via hydraulic-fluid return line **28**R.

(9) For example, to extend leading-edge slat **20**, actuator controller **30** provides pressurized hydraulic fluid to an extend chamber of linear hydraulic actuator **34** via extend supply/return line

**32**E. By doing so, a bilaterally moveable piston within linear hydraulic actuator **34** will move in a direction toward the lead-edge of wing **12**, thereby causing leading-edge slat **20**A to extend forward from wing **12**. In response to movement of the bilaterally moveable piston in such a direction within linear hydraulic actuator **34**, hydraulic fluid will be forced out of a retract chamber of linear hydraulic actuator **34** will return to actuator controller **30** via retract supply/return line **32**R. Conversely, to retract leading-edge slat **20**, actuator controller **30** provides pressurized hydraulic fluid to the retract chamber of linear hydraulic actuator **34** via retract supply/return line **32**R. By doing so, the bilaterally moveable piston within linear hydraulic actuator **34** will move in a direction toward the aft of wing **12**, thereby causing leading-edge slat **20**A to retract backward to wing **12**. In response to movement of the bilaterally moveable piston in such a direction within linear hydraulic actuator **34**, hydraulic fluid will be forced out of the extend chamber of linear hydraulic actuator **34** will return to actuator controller **30** via extend supply/return line **32**E.
(10) In some embodiments, actuator controller **30** is a closed-loop feedback controller. In such embodiments, actuator controller **30** receives a signal indicative of a position of leading-edge slat **20**A. Actuator controller **30** typically compares the position of leading-edge slat **20**A, as indicated by the signal received, with a desired position of leading-edge slat **20**A. In many embodiments, an error signal is generated, the error signal being a difference between the actual position, as indicated in the signal received, and the desired position commanded by actuator controller **30**. This error signal can be used alone, or in combination with a time integral of the error signal, and/or in combination with a time derivative of the error signal (e.g., a proportional (P), proportional-integral (PI), a Proportional-Integral-Derivative (PID) controller, etc.). Should airplane **10** encounter icing conditions during flight, ice can build up on wing **12**, especially upon the leading edge of wing **12**, where leading-edge slats **20**A-**20**C are located. During such icing events, leading-edge slats **20**A-**20**C can become increasingly difficult to move, if not rendered totally inoperable. Should actuator controller **30** attempt to move leading-edge slat **20**A when such a kinematic device is inoperable, the time integral of the error would continue to increase with time, thereby resulting in actuator controller **30** to provide pressurized hydraulic fluid of ever-increasing pressure in an attempt to move leading-edge slat **20**A.
(11) To prevent damage to wing **12**, linear hydraulic actuator **34** or any mounting devices and/or linking mechanisms associated therewith, cross-bleed safety mechanism **36** is located within or proximate linear hydraulic actuator **34**. Cross-bleed safety mechanism **36** is a bilaterally moveable spool valve having two hydraulic bypass channels that provide passive pressure relief within and across linear actuator **34**. Each of these two hydraulic bypass channels provides unidirectional pressure relief in response to a pressure differential between the extend and retract chambers of linear hydraulic actuator **34** exceeding a predetermined threshold. One of the two hydraulic bypass channels provides pressure relief in response to a difference in pressures of the hydraulic fluid within the extend and retract chambers. The other of the two hydraulic bypass channels provides pressure relief in response to a difference in pressure of the hydraulic fluid within the retract and extend chambers. Such a configuration of antiparallel-aligned hydraulic bypass channels created by a bilaterally moveable spool valve can be called a cross-coupled pressure relief device.
(12) Moving leading-edge slat **20**A is but one application of linear hydraulic actuator **34** and cross-bleed safety mechanism **36**. Each of the moveable flight control surfaces depicted in FIG. **1** (i.e., aileron **14**, flaps **16**, spoilers **18**, and leading-edge slats **20**A-**20**C) can be moved by a linear hydraulic actuator, such as linear hydraulic actuator **34**. And any linear hydraulic actuator used to control such moveable flight control surfaces can be protected by a cross-bleed safety mechanism, such as cross-bleed safety mechanism **36**. Furthermore, linear hydraulic actuators can be used for many other controllable kinematic devices of an aircraft. Turbofan engines can use aircraft fuel as a hydraulic fluid to control many mechanisms in the engine. Such systems can be called fuel-draulic systems. These fuel-draulic systems control various engine mechanisms, such as attitude of stator blades, fuel delivery mechanisms, etc. Such mechanisms can be functionally impaired in response

to the engine ingesting foreign object debris (FOD), or in response to wear and tear. Cross-bleed safety mechanisms, such as cross-bleed safety mechanism **36** can be used in fuel-draulic systems as well as for the flight control surfaces described above. Operation of linear hydraulic actuator **34** and cross-bleed safety mechanism **36** will be described in more detail, with reference to FIG. **2** below.

(13) FIG. **2** is a schematic diagram of an embodiment of a hydraulic control system equipped with a cross bleed safety mechanism. In FIG. **2**, hydraulic control system **22** includes actuator controller **30**, linear hydraulic actuator **34** and cross-bleed safety mechanism **36**. Actuator controller **30** receives pressurized hydraulic fluid via hydraulic-fluid supply line **28**S and returns hydraulic fluid to a hydraulic reservoir via hydraulic-fluid return line **28**R. Actuator controller **30** then controllably provides hydraulic fluid to linear hydraulic actuator **34** via extend and retract supply/return lines **32**E and **32**R. The pressure of hydraulic fluid within extend and retract supply/return lines **32**E and **32**R varies in response to the activities of the components connected thereto (e.g., actuator controller **30**, linear hydraulic actuator **34**, and cross-bleed safety mechanism **36**) as well as in response to condition of a kinematic device controlled by actuator controller **30**.

(14) Linear hydraulic actuator **34** includes bilaterally moveable piston **38** within a hydraulic cylinder **40**. Bilaterally moveable piston **38** has a piston rod **42** which can be connected to a kinematic device, either directly or via a linking mechanism. Thus, as bilaterally moveable piston **38** moves within hydraulic cylinder **40**, so too does piston rod **42** move, either by extending out of or by retracting into hydraulic cylinder **40**. Extend chamber **44**E is located within hydraulic cylinder **40** on one side of bilaterally moveable piston **38** opposite the side of bilaterally moveable piston **38** from which piston rod **42** extends. Retract chamber **44**R is located within hydraulic cylinder **40** on the side of bilaterally moveable piston **38** from which piston rod **42** extends.

(15) Actuator controller **30** causes bilaterally moveable piston **38** to move toward or into the retract chamber **44**R by forcing hydraulic fluid into extend chamber **44**E via extend supply/return line **32**E. Such movement of bilaterally moveable piston **38** causes extend chamber **44**E to grow in volume and causes retract chamber **44**R to correspondingly shrink in volume. In response to such movement of bilaterally moveable piston **38**, hydraulic fluid is expelled from retract chamber **44**R and received by actuator controller **30** via retract supply/return line **32**R. Movement of bilaterally moveable piston **38** in such a direction causes piston rod **42** to extend from hydraulic cylinder **40**. Conversely, actuator controller **30** causes bilaterally moveable piston **38** to move toward or into the extend chamber **44**E by forcing hydraulic fluid into retract chamber **44**R via retract supply/return line **32**R. Such movement of bilaterally moveable piston **38** causes retract chamber **44**R to grow in volume and causes extend chamber **44**E to correspondingly shrink in volume. In response to such movement of bilaterally moveable piston **38**, hydraulic fluid is expelled from extend chamber **44**R and received by actuator controller **30** via extend supply/return line **32**E. Movement of bilaterally moveable piston **38** in such a direction causes piston rod **42** to retract into hydraulic cylinder **40**.

(16) A kinematic device that becomes inoperable, or at least difficult to move can "stall" linear hydraulic actuator **34** (i.e., cause linear hydraulic actuator **34** be unable to move the kinematic device without producing forces that exceed a design specification). Such an event can result in damage to any elements associated with stalled linear hydraulic actuator **34** (e.g., mounting hardware, linkage, a kinematic device, and/or linear hydraulic actuator **34** itself). Cross-bleed safety mechanism **36** alleviates such risk of damage as will be shown below.

(17) Cross-bleed safety mechanism **36** is a bilaterally moveable spool valve that includes bilaterally moveable spool **46** within a hydraulic cylinder **48**. Spring **50** is attached between bilaterally moveable spool **46** within a hydraulic cylinder **48**. Spring **50** is attached to bilaterally moveable spool **46** at a first end and attached to hydraulic cylinder **48** at a second end. Spring **50** defines an equilibrium position of bilaterally moveable spool **46** within hydraulic cylinder **48**. Such an equilibrium position is one at which spring **50** provides no force upon bilaterally moveable spool **46**. Spring **50** does provide return-to-equilibrium-position bilateral forces to bilaterally moveable

spool **46** in response to bilaterally moveable spool **46** being positioned at a non-equilibrium position within hydraulic cylinder **48** (thereby either compressing or expanding spring **50**). Ports **52**A and **52**B are located in sidewalls of hydraulic cylinder **48**. Ports **52**A and **52**B function as flow windows, through which, if not blocked, hydraulic fluid can flow. Ports **52**A and **52**B are blocked by bilaterally moveable spool **46** throughout a range of positions that typically includes the equilibrium position therewithin.

(18) As bilaterally moveable spool **46** moves beyond the range of positions within which bilaterally moveable spool **46** blocks ports **52**A and **52**B, either port **52**A or port **52**B will be exposed, depending on direction of movement of bilaterally moveable spool **46**. For example, when bilaterally moveable spool **46** is moved to a location where port **52**A begins to be exposed, bypass channel **54**A will provide fluid conductivity between chambers **56**E and **56**R, which reside on opposite sides of bilaterally moveable spool **46**. Bypass channel **54**A provides fluid flow from chamber **56**E to chamber **56**R via port **52**A, hydraulic line **58**A, and retract supply/return line **32**R. Similarly, when bilaterally moveable spool **46** is moved to a location where port **52**B begins to be exposed, bypass channel **54**B will provide fluid conductivity between chambers **56**R and **56**E. Bypass channel **54**B provides fluid flow from chamber **56**R to chamber **56**E via port **52**B, hydraulic line **58**B and extend supply/return line **32**E. Thus, in response to sufficient movement of bilaterally moveable spool **46** so as to expose either one of ports **52**A and **52**B, a bypass channel, either bypass channel **54**A or **54**B, will provide fluid conductivity between chambers **56**E and **56**R, thereby limiting the pressure that can be applied to linear hydraulic actuator **34**.

(19) Chambers **56**E and **56**R are labeled thus because chambers **56**E and **56**R are in fluid conductivity with extend chamber **44**E and retract chamber **44**R of linear hydraulic actuator **34**, via extend and retract supply/return lines **32**E and **32**R, respectively. Linear hydraulic actuator **34** and cross-bleed safety mechanism **36** are depicted as being hydraulically connected in parallel between extend supply/return line **32**E and retract supply/return line **32**R. Because extend supply/return line **32**E is connected to both extend chamber **44**E of linear hydraulic actuator **34** and chamber **56**E of cross-bleed safety mechanism **36**, extend chambers **44**E is in fluid conductivity with chamber **56**E. Similarly, because retract supply/return line **32**R is connected to both retract chamber **44**R of linear hydraulic actuator **34** and chamber **56**R of cross-bleed safety mechanism **36**, retract chamber **44**R is in fluid conductivity with chamber **56**R. Because of such fluid conductivity between corresponding chambers of linear hydraulic actuator **34** and cross-bleed safety mechanism **36**, bypass channels **54**A and **54**B not only provide fluid conductivity between chambers **56**E and **56**R of cross-bleed safety mechanism **36** but they also provide fluid conductivity between extend chamber **44**E and retract chamber **44**R of linear hydraulic actuator **34** (in response to bilaterally moveable spool **46** being moved so as to expose either port **52**A or **52**B).

(20) During normal operation (i.e., when linear hydraulic actuator **34** is not stalled), bypass channels **54**A and **54**B are blocked by bilaterally moveable spool **46**, thereby preventing hydraulic fluid from flowing between extend chamber **44**E and retract chamber **44**R via bypass channels **54**A and **54**B. Even if linear hydraulic actuator **34** becomes stalled, resulting in hydraulic controller **30** increasing pressure of hydraulic fluid in one of extend chamber **44**E and retract chamber **44**R, bilaterally moveable spool **46** of cross-bleed safety mechanism **36** would still be able to move, as bilaterally moveable spool **46** of cross-bleed safety mechanism **36** is not mechanically coupled to the kinematic device causing the stall of linear hydraulic actuator **34**. Should hydraulic pressure build to a level sufficient cause bilaterally moveable spool **46** to expose one of ports **52**A and **52**B, pressure relief would be obtained by bypass channel **54**A or **54**B, respectively. In other words, by providing bypass channels **54**A and **54**B for hydraulic fluid, cross-bleed safety mechanism **36** limits a magnitude a pressure differential across bilaterally moveable piston **38** (and between extend chamber **44**E and retract chamber **44**R of bilaterally moveable piston **38**).

(21) The differential pressures required to first expose ports **52**A and **52**B are called first and second differential cracking pressures, respectively. Such differential cracking pressures

corresponding to bypass channels **54**A and **54**B can be independently tailored by the spring preload and the spring constant of spring **50** and by locations of ports **52**A and **52**B with respect to the equilibrium position of bilaterally moveable spool **46**. Furthermore, the fluid conductivity of bypass channels **54**A and **54**B can be independently tailored as well. For example, shape of ports **52**A and **52**B can be made so that a desired fluid conductivity profile is created in response to movements of bilaterally moveable spool **46** beyond first exposures of ports **52**A and **52**B. For example, ports **52**A and **52**B can be very narrow when first exposed, and then can broaden in width as more of ports **52**A and **52**B become exposed. Moreover, cross sectional areas of hydraulic lines **58**A and **58**B can be made so as to control fluid conductivity of bypass channels **54**A and **54**B. Using techniques, such as those described above, a relationship between differential pressure and fluid conductivity of bypass channels **54**A and **54**B can be designed. Such a relationship can be such that differential pressure between extend chamber **44**E and retract chamber **44**R will not exceed a design specified maximum differential pressure.

(22) In some embodiments, linear hydraulic actuator **34** and cross-bleed safety mechanism **36** are formed within a single housing. For example, in some embodiments, a unitary block can be machined with both hydraulic cylinders **40** and **48**. In other embodiments, hydraulic cylinder **48** can be formed using a stationary sleeve, having ports **52**A and **52**B formed therein. Such ports **52**A and **52**B would be formed at precise locations so as to provide flow of hydraulic fluid in response to the differential pressures thereof exceeding design pressure differentials.

(23) In some embodiments, cross-bleed safety mechanism **46** can be configured such that no fluid flows through the cavity containing spring **50**. FIG. **5** depicts such a cross sectional diagram of such a cross-bleed safety mechanism **46**. Cross-bleed-safety mechanism **46** includes bilaterally moveable spool **46** within a hydraulic cylinder **48**. Cavities in which springs **50**A and **50**B reside are in fluid communication with extend and return supply/return lines **32**E and **32**R, respectively. Springs **50**A and **50**B define an equilibrium position of bilaterally moveable spool **46** within hydraulic cylinder **48**. Such an equilibrium position is one at which the combination of springs **50**A and **50**B provides no net force upon bilaterally moveable spool **46**. Springs **50**A and **50**B do provide return-to-equilibrium-position bilateral forces to bilaterally moveable spool **46** in response to bilaterally moveable spool **46** being positioned at a non-equilibrium position within hydraulic cylinder **48**.

(24) Ports at various locations in the sidewalls of hydraulic cylinder **48** provide fluid communication between an interior of hydraulic cylinder **48** and extend supply/return lines **32**E and retract supply/return lines **32**R. In response to the differential pressure between the pressures in extend supply/return lines **32**E and retract supply/return lines **32**R increases, bilaterally moveable spool **46** moves to the right. When the differential pressure between the pressures in extend supply/return lines **32**E and retract supply/return lines **32**R exceeds a predetermined pressure differential, the extract supply/return lines **32**E on the top of the FIG. **5** embodiment will be in fluid communication with the retract supply/return lines **32**R at the bottom of the FIG. **5** embodiment. Conversely, in response to the differential pressure between the pressures in retract supply/return lines **32**R and retract supply/return lines **32**E increases, bilaterally moveable spool **46** moves to the left. When the differential pressure between the pressures in retract supply/return lines **32**R and extend supply/return lines **32**R exceeds a predetermined pressure differential, the retract supply/return lines **32**R on the top of the FIG. **5** embodiment will be in fluid communication with the extend supply/return lines **32**E at the bottom of the FIG. **5** embodiment.

(25) FIG. **3** is a graph of a pressure vs. flow through a hydraulic pressure cross-bleed safety mechanism. In FIG. **3**, graph **60** includes horizontal axis **62**, vertical axis **64**, and pressure-flow relation **66**. Horizontal axis **62** is indicative of differential pressure of a hydraulic fluid, as measured between extend chamber **44**E and retract chamber **44**R. Positive values of differential pressures are indicative pressures of hydraulic fluid in extend chamber **44**E that are greater than pressures of hydraulic fluid in retract chamber **44**R. Negative values of differential pressures are

indicative of pressures of hydraulic fluid in extend chamber **44**E that are less than pressures of hydraulic fluid in retract chamber **44**R. Vertical axis **64** is indicative of flow through bypass channels **54**A or **54**B, which then flow to actuator controller **30** via extend and retract supply/return lines **32**A and **32**B. Positive values of fluid flow are indicative of hydraulic fluid flowing from actuator controller **30** via extend supply/return line **32**E, bypass linear hydraulic actuator **34** via bypass channel **54**A, and then return to actuator controller **30** via retract supply/return line **32**R. Negative values of fluid flow are indicative of hydraulic fluid flowing from actuator controller **30** via retract supply/return line **32**R, bypass linear hydraulic actuator **34** via bypass channel **54**B, and then return to actuator controller **30** via extend supply/return line **32**E.
(26) Pressure-flow relation **66** is inductive of the flow of hydraulic fluid through bypass channels **54**A or **54**B as a function of differential pressure of the hydraulic fluid, as measured between extend supply/return line **32**E and retract supply/return line **32**R. Pressure-flow relation **66** indicates no flow through bypass channels **54**A or **54**B between a first and second differential cracking pressures dP**1** and dP**2**. At differential pressures equal to first differential cracking pressure dP**1**, fluid flow begins via bypass channel **54**B. As differential pressures decrease below first differential cracking pressure dP**1**, the fluid flow through bypass channel **54**B increases in negative fashion. At differential pressures equal to second differential cracking pressure dP**2**, fluid flow begins via bypass channel **54**A. As differential pressures increase above second differential cracking pressure dP**2**, the fluid flow through bypass channel **54**A increases positively. The slope of pressure-flow relation **66** is indicative of fluid conductivity through bypass channel **54**A and **54**B.
(27) FIG. **4** is a perspective view of an embodiment of a linear hydraulic actuator equipped with an integrated cross bleed safety mechanism. In FIG. **4**, linear hydraulic actuator **34** and integrated cross-bleed bypass mechanism **36** are integrated in a machined block. Hydraulic cylinders **40** and **48** corresponding to linear hydraulic actuator **34** and integrated cross-bleed bypass mechanism **36**, respectively, are machined in unitary block **70**. Ends of hydraulic cylinders **40** and **48** can hydraulically sealed with endcaps **72**E and **72**R. Bilaterally moveable piston **38** and bilaterally moveable spool **46** are located in hydraulic cylinders **40** and **48**, respectively. Bilaterally moveable piston **38** is coupled to piston rod **42**, which can in turn be configured to move a kinematic device. Piston rod **42** extends from hydraulic cylinder **46**, emerging therefrom via piston rod port **74**.
(28) Spring **50**A and **50**B attached between and at opposite ends of both bilaterally moveable spool **46** and hydraulic cylinder **48** at endcaps **72**E and **72**R, respectively. Springs **50**A and **50**B define an equilibrium position of bilaterally moveable spool **46** within hydraulic cylinder **48**. Such an equilibrium position is one at which the combination of springs **50**A and **50**B provides no net force upon bilaterally moveable spool **46**. Springs **50**A and **50**B do provide return-to-equilibrium-position bilateral forces to bilaterally moveable spool **46** in response to bilaterally moveable spool **46** being positioned at a non-equilibrium position within hydraulic cylinder **48**. Bypass channels **54**A and **54**B are formed as depressions or channels formed in sidewalls of hydraulic cylinder **48**. Bypass channels **54**A and **54**B are blocked by bilaterally moveable spool **46** throughout a range of positions that typically includes the equilibrium position therewithin.
(29) Extend chamber **44**E of linear hydraulic actuator **34** and chamber **56**E of cross-bleed bypass mechanism **36** are in fluid communication with one another via port **76**E. Similarly, retract chamber **44**R of linear hydraulic actuator **34** and chamber **56**R of cross-bleed bypass mechanism **36** are in fluid communication with one another via port **76**R. bypass channels **54**A and **54**B are formed as depressions or channels in sidewalls of hydraulic cylinder **48**. Such depression or channel corresponding to bypass channel **54**A extends from an initial location, where it is blocked when bilaterally moveable spool **46** is in the equilibrium position, to a location within retract chamber **56**R. Similarly, the depression corresponding to bypass channel **54**B extends from an initial location, where it is blocked when bilaterally moveable spool **46** is in the equilibrium position, to a location within extend chamber **56**E. The cross-sectional area of such depressions can be tailored so that a desired pressure-flow relation results from such a geometry. Although in the

embodiment depicted in FIG. **4** bypass channels **54**A and **54**B are formed as depressions or channels in the sidewall of hydraulic cylinder **48**, in another embodiment, such bypass channels **54**A and **54**B can be formed using holes drilled or formed adjacent to hydraulic cylinder **48**.

Discussion of Possible Embodiments

(30) The following are non-exclusive descriptions of possible embodiments of the present invention.

(31) Some embodiments relate to a cross-bleed safety mechanism for protecting a hydraulic system. The cross-bleed safety mechanism includes a hydraulic cylinder and a bilaterally movable bilaterally moveable piston. The hydraulic cylinder has first and second hydraulic ports configured to provide fluid communication with extend and retract chambers, respectively, of a linear hydraulic actuator when hydraulically coupled thereto. The bilaterally moveable spool is within and provides a hydraulic seal with an interior surface of the hydraulic cylinder. The bilaterally moveable spool is located between a first chamber in fluid communication with the first port and a second chamber in fluid communication with the second port. The bilaterally moveable spool blocks first and second hydraulic bypass channels in response to the bilaterally moveable spool being at an equilibrium position. The first and second hydraulic bypass channels selectively provide fluid communication between first and second chambers. The bilaterally moveable spool blocks the second hydraulic bypass channel and begins to unblock the first hydraulic bypass channel in response to a first differential pressure between the first and second chambers exceeding a first differential cracking pressure. The bilaterally moveable spool blocks the first hydraulic bypass channel and begins to unblock the second hydraulic bypass channel in response to a second differential pressure between the extend and retract chambers exceeding a second differential cracking pressure.

(32) The system of the preceding paragraph can optionally include, additionally and/or alternatively, any one or more of the following features, configurations and/or additional components:

(33) A further embodiment of the foregoing system can further include a spring attached to the bilaterally moveable spool at a first end and attached to the hydraulic cylinder at a second end, the spring defining the equilibrium position of the bilaterally moveable spool within the hydraulic cylinder and providing a return-to-equilibrium-position bilateral force to the bilaterally moveable spool in response to the bilaterally moveable spool being positioned at a non-equilibrium position within the hydraulic cylinder.

(34) A further embodiment of any of the foregoing systems, wherein the spring can have a spring constant that provides a force on the bilaterally moveable spool that counterbalances the first differential cracking pressure when the bilaterally moveable spool begins to unblock the first hydraulic bypass channel.

(35) A further embodiment of any of the foregoing systems, wherein the spring can have a spring constant that provides a force on the bilaterally moveable spool that counterbalances the second differential cracking pressure when the bilaterally moveable spool begins to unblock the second hydraulic bypass channel.

(36) A further embodiment of any of the foregoing systems, wherein the first bypass channel can be a hydraulic path extending from a first port or depression in a sidewall of the hydraulic cylinder to the first chamber of the hydraulic cylinder. The first port or depression can be selectively blocked or unblocked by the bilaterally moveable spool in response to position of the bilaterally moveable piston.

(37) A further embodiment of any of the foregoing systems, wherein the first bypass channel can facilitate flow of hydraulic fluid from the first chamber to the second chamber in response to the first bypass channel being unblocked.

(38) A further embodiment of any of the foregoing systems, wherein the first bypass channel can be in fluid communication with the first chamber.

(39) A further embodiment of any of the foregoing systems, wherein the second bypass channel can be a hydraulic path extending from a second port or depression in a sidewall of the hydraulic cylinder to the second chamber of the hydraulic cylinder. The second port or depression can be selectively blocked or unblocked by the bilaterally moveable spool in response to position of the bilaterally moveable piston.
(40) A further embodiment of any of the foregoing systems, wherein the second bypass channel can facilitate flow of hydraulic fluid from the second chamber to the first chamber in response to the first bypass channel being unblocked.
(41) A further embodiment of any of the foregoing systems, wherein the second bypass channel can be in fluid communication with the second chamber.
(42) A further embodiment of any of the foregoing systems, wherein the first and second bypass channels can be formed as depressions in the sidewall of the of the hydraulic cylinder.
(43) A further embodiment of any of the foregoing systems, wherein the first and second bypass channels can be formed via ports in the sidewall of the of the hydraulic cylinder.
(44) Some embodiments relate to a load-protected linear hydraulic actuator that includes a linear hydraulic actuator and a cross-bleed safety mechanism. The linear hydraulic actuator has an extend chamber and a retract chamber on either side of a bilaterally moveable piston within a first hydraulic cylinder. The extend chamber provides hydraulic fluid via an extend supply/return line. The retract chamber provides hydraulic fluid via a retract supply/return line. The cross-bleed safety mechanism that includes a second hydraulic cylinder. A bilaterally moveable spool is within and provides a hydraulic seal with an interior surface of the hydraulic cylinder. The bilaterally moveable spool is located between a first chamber in fluid communication with the extend chamber of the linear hydraulic actuator and a second chamber in fluid communication with the retract chamber of the linear hydraulic actuator. The bilaterally moveable spool blocks first and second hydraulic bypass channels in response to the bilaterally moveable spool being at an equilibrium position, the first and second hydraulic bypass channels selectively provide fluid communication between first and second chambers. The bilaterally moveable spool blocks the second hydraulic bypass channel and begins to unblock the first hydraulic bypass channel in response to a first differential pressure between the first and second chambers exceeding a first differential cracking pressure. The bilaterally moveable spool blocks the first hydraulic bypass channel and begins to unblock the second hydraulic bypass channel in response to a second differential pressure between the second and first chambers exceeding a second differential cracking pressure.
(45) The system of the preceding paragraph can optionally include, additionally and/or alternatively, any one or more of the following features, configurations and/or additional components:
(46) A further embodiment of the foregoing system, wherein the first and second hydraulic cylinders can be formed within a unitary body.
(47) A further embodiment of any of the foregoing systems can further include a piston rod coupled to the bilaterally moveable piston and extending from the first cylindrical housing. The piston rod configured to link to a kinematic device.
(48) A further embodiment of any of the foregoing systems can further include a spring attached to the bilaterally moveable spool at a first end and attached to the hydraulic cylinder at a second end. The spring defines the equilibrium position of the bilaterally moveable spool within the hydraulic cylinder and providing a return-to-equilibrium-position bilateral force to the bilaterally moveable spool in response to the bilaterally moveable spool being positioned at a non-equilibrium position within the hydraulic cylinder.
(49) A further embodiment of any of the foregoing systems, wherein the spring can have a spring constant that provides a force on the bilaterally moveable spool that counterbalances the first differential cracking pressure when the bilaterally moveable spool begins to unblock the first hydraulic bypass channel.

(50) A further embodiment of any of the foregoing systems, wherein the spring can have a spring constant that provides a force on the bilaterally moveable spool that counterbalances the second differential cracking pressure when the bilaterally moveable spool begins to unblock the second hydraulic bypass channel.
(51) A further embodiment of any of the foregoing systems, wherein the first bypass channel can be a hydraulic path extending from a first port or depression in a sidewall of the hydraulic cylinder to the first chamber of the hydraulic cylinder. The first port or depression can be selectively blocked or unblocked by the bilaterally moveable spool in response to position of the bilaterally moveable spool.
(52) A further embodiment of any of the foregoing systems, wherein the actuator controller can include a Proportional Integral (PI) control algorithm that generates a control signal in response to a difference between a desired position and an actual position of the bilaterally moveable piston as indicated by the signal indicative of the position of the bilaterally moveable spool.
(53) While the invention has been described with reference to an exemplary embodiment(s), it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment(s) disclosed, but that the invention will include all embodiments falling within the scope of the appended claims.

## Claims

1. A cross-bleed safety mechanism for protecting a hydraulic system, the cross-bleed safety mechanism including: a hydraulic cylinder having first and second hydraulic ports configured to provide fluid communication with extend and retract chambers, respectively, of a linear hydraulic actuator when hydraulically coupled thereto; and a bilaterally moveable spool within and providing a hydraulic seal with an interior surface of the hydraulic cylinder, the bilaterally moveable spool located between a first chamber in fluid communication with the first port and a second chamber in fluid communication with the second port, wherein the bilaterally moveable spool: blocks first and second hydraulic bypass channels in response to the bilaterally moveable spool being at an equilibrium position, the first and second hydraulic bypass channels selectively provide fluid communication between first and second chambers, blocks the second hydraulic bypass channel and begins to unblock the first hydraulic bypass channel in response to a first differential pressure between the first and second chambers exceeding a first differential cracking pressure, and blocks the first hydraulic bypass channel and begins to unblock the second hydraulic bypass channel in response to a second differential pressure between the second and first chambers exceeding a second differential cracking pressure.
2. The cross-bleed safety mechanism of claim 1, further comprising: a spring attached to the bilaterally moveable spool at a first end and attached to the hydraulic cylinder at a second end, the spring defining the equilibrium position of the bilaterally moveable spool within the hydraulic cylinder and providing a return-to-equilibrium-position bilateral force to the bilaterally moveable spool in response to the bilaterally moveable spool being positioned at a non-equilibrium position within the hydraulic cylinder.
3. The cross-bleed safety mechanism of claim 2, wherein the spring has a spring constant that provides a force on the bilaterally moveable spool that counterbalances the first differential cracking pressure when the bilaterally moveable spool begins to unblock the first hydraulic bypass channel.
4. The cross-bleed safety mechanism of claim 2, wherein the spring has a spring constant that provides a force on the bilaterally moveable spool that counterbalances the second differential

cracking pressure when the bilaterally moveable spool begins to unblock the second hydraulic bypass channel.

5. The cross-bleed safety mechanism of claim 1, wherein the first bypass channel is a hydraulic path extending from a first port or depression in a sidewall of the hydraulic cylinder to the first chamber of the hydraulic cylinder, the first port or depression being selectively blocked or unblocked by the bilaterally moveable spool in response to position of the bilaterally moveable piston.

6. The cross-bleed safety mechanism of claim 5, wherein the first bypass channel facilitates flow of hydraulic fluid from the first chamber to the second chamber in response to the first bypass channel being unblocked.

7. The cross-bleed safety mechanism of claim 6, wherein the first bypass channel is in fluid communication with the first chamber.

8. The cross-bleed safety mechanism of claim 5, wherein the first and second bypass channels are formed as depressions in the sidewall of the of the hydraulic cylinder.

9. The cross-bleed safety mechanism of claim 5, wherein the first and second bypass channels are formed via ports in the sidewall of the of the hydraulic cylinder.

10. The cross-bleed safety mechanism of claim 1, wherein the second bypass channel is a hydraulic path extending from a second port or depression in a sidewall of the hydraulic cylinder to the second chamber of the hydraulic cylinder, the second port or depression being selectively blocked or unblocked by the bilaterally moveable spool in response to position of the bilaterally moveable piston.

11. The cross-bleed safety mechanism of claim 10, wherein the second bypass channel facilitates flow of hydraulic fluid from the second chamber to the first chamber in response to the first bypass channel being unblocked.

12. The cross-bleed safety mechanism of claim 11, wherein the second bypass channel is in fluid communication with the second chamber.

13. A load-protected linear hydraulic actuator comprising: a linear hydraulic actuator having an extend chamber and a retract chamber on either side of a bilaterally moveable piston within a first hydraulic cylinder, the extend chamber provided hydraulic fluid via an extend supply/return line, the retract chamber provided hydraulic fluid via a retract supply/return line; and a cross-bleed safety mechanism that includes: a second hydraulic cylinder; and a bilaterally moveable spool within and providing a hydraulic seal with an interior surface of the hydraulic cylinder, the bilaterally moveable spool located between a first chamber in fluid communication with the extend chamber of the linear hydraulic actuator and a second chamber in fluid communication with the retract chamber of the linear hydraulic actuator, wherein the bilaterally moveable spool: blocks first and second hydraulic bypass channels in response to the bilaterally moveable spool being at an equilibrium position, the first and second hydraulic bypass channels selectively provide fluid communication between first and second chambers, blocks the second hydraulic bypass channel and begins to unblock the first hydraulic bypass channel in response to a first differential pressure between the first and second chambers exceeding a first differential cracking pressure, and blocks the first hydraulic bypass channel and begins to unblock the second hydraulic bypass channel in response to a second differential pressure between the second and first chambers exceeding a second differential cracking pressure.

14. The load-protected linear hydraulic actuator of claim 13, wherein the first and second hydraulic cylinders are formed within a unitary body.

15. The load-protected linear hydraulic actuator of claim 13, further comprising: a piston rod coupled to the bilaterally moveable piston and extending from the first cylindrical housing; the piston rod configured to link to a kinematic device.

16. The load-protected linear hydraulic actuator of claim 13, further comprising: a spring attached to the bilaterally moveable spool at a first end and attached to the hydraulic cylinder at a second

end, the spring defining the equilibrium position of the bilaterally moveable spool within the hydraulic cylinder and providing a return-to-equilibrium-position bilateral force to the bilaterally moveable spool in response to the bilaterally moveable spool being positioned at a non-equilibrium position within the hydraulic cylinder.

17. The load-protected linear hydraulic actuator of claim 16, wherein the spring has a spring constant that provides a force on the bilaterally moveable spool that counterbalances the first differential cracking pressure when the bilaterally moveable spool begins to unblock the first hydraulic bypass channel.

18. The load-protected linear hydraulic actuator of claim 16, wherein the spring has a spring constant that provides a force on the bilaterally moveable spool that counterbalances the second differential cracking pressure when the bilaterally moveable spool begins to unblock the second hydraulic bypass channel.

19. The load-protected linear hydraulic actuator of claim 13, wherein the first bypass channel is a hydraulic path extending from a first port or depression in a sidewall of the hydraulic cylinder to the first chamber of the hydraulic cylinder, the first port or depression being selectively blocked or unblocked by the bilaterally moveable spool in response to position of the bilaterally moveable piston.

20. The load-protected linear hydraulic actuator of claim 13, wherein the actuator controller includes: a Proportional Integral (PI) control algorithm that generates a control signal in response to a difference between a desired position and an actual position of the bilaterally moveable piston as indicated by the signal indicative of the position of the bilaterally moveable piston.