MAGNETORHEOLOGICAL BREAKING SYSTEM

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Abstract: **A Magneto-Rheological (MR) fluid disc brake is a device that transmits a torque by the shear force of MR fluid. The fluid is inserted between the rotating and fixed discs and a magnetic field is imposed on the fluid. In this paper, a complete test rig for an MR fluid disc brake is introduced. Experiments are conducted to measure the braking torque and speed of shaft during braking process and the results are presented at different voltage input to the brake. Also theoretical analysis for both MR brake and the mechanical system is developed and is solved numerically using finite difference method and Matlab software. Effect of current input to the MR brake, viscosity of fluid and design parameters is taken into consideration. A validation of the theoretical results with CFD model is introduced. The experimental results are performed and both angular velocity and the braking torque are obtained as responses during the braking process. A comparison between braking torques obtained from theoretical and experimental work shows agreement when voltage is 2 V at speed of 150 rpm and also agreement when voltage is 2 and 3 V at speed of 250 rpm.**
Keywords: leaf spring; composite; analysis, ANSYS, Finite element, Spring rate.

I. INTRODUCTION

With the boundaries of physical science expanding rapidly, present day engineers must necessarily assimilate information and knowledge of subjects that continue to become more and more complex.In the study of the nature and mechanical behavior of engineering materials, however, their knowledge seldom progresses beyond the level of elementary theory of elasticity and viscous fluids and the basic concepts of the theory of plasticity and viscoelasticity. More esoteric theories of material behavior and the interaction with various fields are generally left out of consideration or soon abolished as being mathematically intractable or economically unjustifiable.

When current is applied to the electromagnet coil, the MR fluid solidifies as its yield stress varies as a function of the magnetic field applied by the electromagnet. This controllable yield stress produces shear friction on the rotating disks, generating the braking torque.As the ATVs are designed mainly for off roads and transportation through inaccessible areas, much higher significances given to the designing of proper brake system.As of now the ATV is associated with conventional brakes.The important characteristics of MR fluids are of response time and stiffness, latter which is directly proportional to the applied magnetic field.Response time of MR fluid is less than a millisecond whereas in the case of conventional hydraulic brakes response time is around 200 – 300 milliseconds.

PURPOSE-
Faster response.Easy implementation of control system.
Less maintenance.Reduce no. of components and wiring.

OBJECTIVES:
Elimination of hazardous brake fluid.Simple software base parameters adjustment depending on driving condition.Less maintenance.Reduce no. of components and wiring.

II. LITERATURE REVIEW

Dennis William George ByattThis invention relates to electro-rheological fluid materials, that is to say, fluid materials which exhibit an apparent change of viscosity when subject to the influence of an electric field, and arrangements utilising such materials. Conventional electro-rheological fluid materials essentially comprise a fluid carrier medium in which is suspended particles of solid electrically insulating material. In operation, the viscosity of the fluid material may be quite low, so that it flows readily, until subjected to the influence of a relatively high voltage electric field whereupon the apparent viscosity increases considerably so as to increase the resistance of the material to shear stress.

Kang Tae JinThe invention magnetorheological fluid is impregnated with a polyurethane / aramid composites, and as it relates to a process for the preparation, and more particularly to polyurethane used for the material of the individual rooms and doors or lightweight fighting vehicles, armored vehicles such as, banggeom dragon for bulletproof the present invention relates to a magnetorheological fluid is impregnated coating aramid composite material and a method of manufacturing the same.The present invention includes the steps of compressing the intermediate composition wherein themagnetorheological fluid is impregnated is formed on the step.

Todd M. York,Curt D. Gilmore,Thomas G. Libertiny this fluid coupling device for coupling torque between two members and utilizing a magnetorheological fluid having a controllable yield strength in shear in response to a magnetic field and having a determinable viscosity in the absence of a magnetic field and with the coupling device having a rotor, rotatably supported in a cavity in a housing with the cavity filled with the magnetorheological fluid and with the cavity and rotor having similarly shaped contours and constructed to concentrate the magnetic coupling effect through the fluid at the radially outer end of the rotor and a torque load simulator system utilizing the fluid coupling for determining the performance of a torque tool or other torque related apparatus relative to a predetermined standard of performance.

Jeremy R. Edmondson,Joshua D. Coombs,Carlos F. OsorioThe invention relates generally to the field of suspension systems for vehicles. In particular, the invention relates to a magnetorheological fluid actuated damper for use in vehicular suspension systems
A magnetorheological fluid actuated damper. At least a first and a second cylinder with the first cylinder positioned axially within the second cylinder are provided. A gap is formed between the cylinders. The second cylinder is mounted to a stationary mount of the vehicle chassis and a control arm is mounted at an end of the first cylinder. The first cylinder is mounted on bearings to allow it to rotate relative to the chassis. The gap between the cylinders contains a magnetorheological fluid having an adjustable viscosity in reaction to the application of a magnetic field. A magnetic field is generated over the fluid in the gap.
HouYoufu ,Tian ZuzhiThe invention relates to a spherical magnetorheological fluid clutch, comprising a spherical steel jacket fixed with an input shaft, a steel ball which is fixed with an output shaft and is arranged in the sphericalsteel jacket, and a magnetorheological fluid working gap filled with magnetorheological fluid is left between the spherical steel jacket and the steel ball, a round hole which leads the output shaft to pass through and is connected with the steel ball is arranged on the spherical steel jacket, a sealing ring is arranged at the periphery of the round hole, a magnetic separation ringis embedded on the spherical steel jacket, a magnetic-conduction ring sheathed on the spherical steel jacket is arranged outside of the embedded magnetic separation ring, and a magnet exciting coil is arranged in the magnetic-conduction ring, corresponding to the magnetic-conduction ring; a main round ball connected with the input shaft drives an output round ball to rotate by the magnetorheological fluid, the current magnitude in the magnet exciting coil is changed, that is, the transmission torque can be changed.

III. DESIGN & ANALYSIS

we changing the magnetic field strength the viscosity of MR fluid also change. By changing the applied current in electromagnetic coil the magnetic field strength can change.

- As we increase the current inelectro magnetic coil magnetic field strength also increase which cause increasing of viscosity of MR fluid, which applied a shear strength on rotor.
- As shear strength applied on disc which cause a braking torque on rotor. Which stops the rotation of disc and break applied.
- We applied current of 9amp. And 12W to the electromagnetic coil having 300 no. of turns.which creates a magnetic field by the formula we can create magnetic field strength.

H = magnetic field strength
N = no. of turns
I = applied current
H = MR fluid gap

$$H = \frac{N \times I}{2 \times h} = \frac{300 \times 9}{2 \times 0.0175}$$
$$= 77142.85 \ kA/m$$

formula for magnetic field strength

$$\tau_{yd} = 10^{-6} H^2 + 0.085 H + 291.4$$
$$= 12722.4 \ kPa$$

formula for shear stress

Now we have shear stress, magnetic field strength. We can calculate braking torque from this formula
T = braking torque
r1= inner diameter of rotor = 0.01m
r2 = outer diameter of rotor = 0.056m
η = viscosity of silicone oil = 0.218Pas
ω = angular velocity of rotor
N = rpm of disc = 1350rpm

$$\omega = \frac{2\pi N}{60}$$
$$= \frac{2 \times \pi \times 1350}{60} = 141.37 \ rad/sec$$

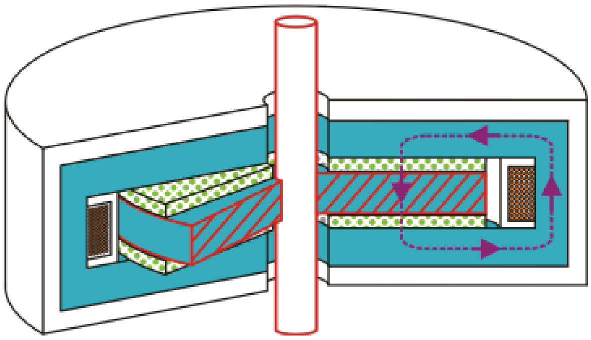
formula of angular velocity

$$T = \frac{4}{3}\left(r_2^3 - r_1^3\right)\tau_{yd} + \frac{\pi \eta \omega}{h}\left(r_2^4 - r_1^4\right)$$
$$T = 3.055 \ Nm$$

formula of braking torque

IV. COMPONENTS AND DESIGN

1.MR Disk Brake
MR brake consists out of four main parts: rotor, housingi.e. stator, coil and MR fluid, *Figure 1*. The shape of therotor is what differentiates MR brake types from eachother. One needs the quantitative parameters of MRbrake, to be able to determine its specific application suitability.



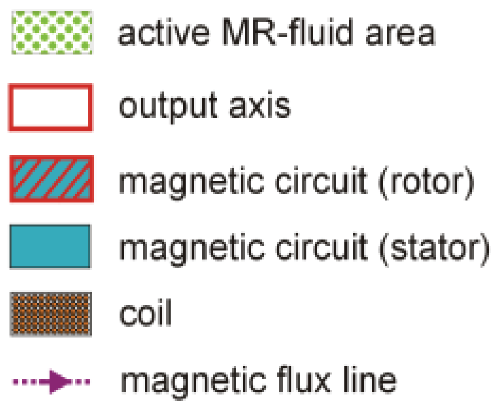


Figure 1 [MR break]

The disk brake design is the most common MR brake design found in literature today and was the first one to be investigated .It is the easiest one to manufacture and gives reasonably good results in terms
of weight and compactnessThere are some variations in MR disk brake design such as: the use of two coils instead of one in order to increase the magnetic pole area and/or relocation of the coil on top of the disk in order to reduce its external diameter but the basics remain the same.

It is also interesting to note that the MR disk brake design is currently the only one commercially available as a standard product, manufactured by Lord Corporation and that it was used in several studies

In order to increase compactness of the MR disk brake design, several disk-shape rotors can be used instead of one, with segments of stator located inbetween each rotor disk, This multiple disk design is very popular in literature and was used in several applications that required high torque in limited space and weight

2. Electromagnetic Coil

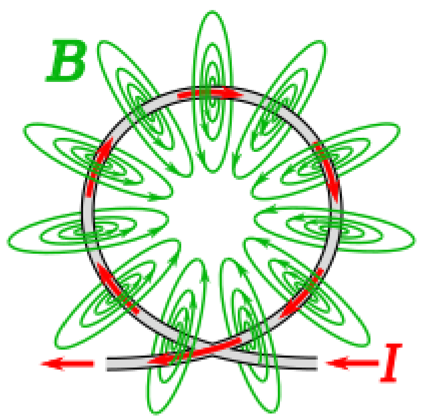


Figure 2 [MAGNETIC FIELD LINES]

The magnetic field lines (green) of a current-carrying loop of wire pass through the center of the loop, concentrating the field there An electromagnetic coil is an electrical conductor such as a wire in the shape of a coil, spiral or helix. Electromagnetic coils are used in electrical engineering, in applications where electric currents interact with magnetic fields, in devices such as electricmotors, generators, inductors, electromagnets, tran sformers, and sensor coils. Either an electric current is passed through the wire of the coil to generate a magnetic field, or conversely an external time-varying magnetic field through the interior of the coil generates an EMF (voltage) in the conductor.

A current through any conductor creates a circular magnetic field around the conductor due to Ampere's law. The advantage of using the coil shape is that it increases the strength of magnetic field produced by a given current. The magnetic fields generated by the separate turns of wire all pass through the center of the coil and add (superpose) to produce a strong field there.The more turns of wire, the stronger the field produced. Conversely, a changing external magnetic flux induces a voltage in a conductor such as a wire, due to Faraday's law of induction. The induced voltage can be increased by winding the wire into a coil, because the field lines intersect the circuit multiple times.

The direction of the magnetic field produced by a coil can be determined by the right hand grip rule. If the fingers of the right hand are wrapped around the magnetic core of a coil in the direction of conventional current through the wire, the thumb will point in the direction the magnetic field lines pass through the coil. The end of a magnetic core from which the field lines emerge is defined to be the North pole.

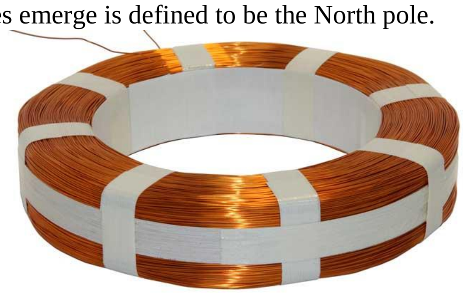


Figure 3 [COPPER COIL]

3. Stator(Casing)

Depending on the configuration of a spinning electromotive device the stator may act as the field magnet, interacting with the armature to create motion, or it may act as the armature, receiving its influence from moving field coils on the rotor. The first DC generators (known as dynamos) and DC motors put the field coils on the stator, and the power generation or motive reaction coils on the rotor. This is necessary because a continuously moving power switch known as the commutator is needed to keep the field correctly aligned across the spinning rotor. The commutator must become larger and more robust as the current increases.

The stator of these devices may be either a permanent magnet or an electromagnet. Where the stator is an electromagnet, the coil which energizes it is known as the field coil or field winding.

The coil can be either iron core or aluminum. To reduce loading losses in motors, manufacturers invariably use copper as the conducting material in windings.[1] Aluminum, because of its lower electrical conductivity, may be an alternate material in fractional horsepower motors, especially when the motors are used for very short durations.

Figure 4 [STATOR]

4. Bearing

A bearing is a machine element that constrains relative motion to only the desired motion, and reduces friction between moving parts. The design of the bearing may, for example, provide for free linear movement of the moving part or for free rotation around a fixed axis; or, it may prevent a motion by controlling the vectors of normal forces that bear on the moving parts. Most bearings facilitate the desired motion by minimizing friction. Bearings are classified broadly according to the type of operation, the motions allowed, or to the directions of the loads (forces) applied to the parts.

Rotary bearings hold rotating components such as shafts or axles within mechanical systems, and transfer axial and radial loads from the source of the load to the structure supporting it. The simplest form of bearing, the plain bearing, consists of a shaft rotating in a hole.Lubrication is often used to reduce friction. In the ball bearing and roller bearing, to prevent sliding friction, rolling elements such as rollers or balls with a circular cross-section are located between the races or journals of the bearing assembly. A wide variety of bearing designs exists to allow the demands of the application to be correctly met for maximum efficiency, reliability, durability and performance.

Figure 5 [BEARINGS]

5. Magneto-Rheological Fluid

A magnetorheological fluid (MR fluid, or MRF) is a type of smart fluid in a carrier fluid, usually a type of oil. When subjected to a magnetic field, the fluid greatly increases its apparent viscosity, to the point of becoming a viscoelastic solid. Importantly, the yield stress of the fluid when in its active ("on") state can be controlled very accurately by varying the magnetic field intensity. The upshot is that the fluid's ability to transmit force can be controlled with an electromagnet, which gives rise to its many possible control-based applications. Extensive discussions of the physics and applications of MR fluids can be found in a recent book

MR fluid is different from a ferrofluid which has smaller particles. MR fluid particles are primarily on the micrometre-scale and are too densefor Brownian motion to keep them suspended (in the lower density carrier fluid). Ferrofluid particles are primarily nanoparticles that are suspended by Brownian motion and generally will not settle under normal conditions. As a result, these two fluids have very different applications

Magneto-rheological fluid material behaviour

To understand and predict the behavior of the MR fluid it is necessary to model the fluid mathematically, a task slightly complicated by the varying material properties (such as yield stress). As mentioned above, smart fluids are such that they have a low viscosity in the absence of an applied magnetic field, but become quasi-solid with the application of such a field. In the case of MR fluids (and ER), the fluid actually assumes properties comparable to a solid when in the activated ("on") state, up until a point of yield (the shear stress above which shearing occurs). This yield stress (commonly referred to as apparent yield stress) is dependent on the magnetic field applied to the fluid, but will reach a maximum point after which increases in magnetic flux density have no further effect, as the fluid is then magnetically saturated. The behavior of a MR fluid can thus be considered similar to a Bingham plastic, a material model which has been well-investigated. However, a MR fluid does not exactly follow the characteristics of a Bingham plastic. For example, below the yield stress (in the activated or "on" state), the fluid behaves as a viscoelastic material, with a complex modulus that is also known to be dependent on the magnetic field intensity. MR fluids are also known to be subject to shear thinning, whereby the viscosity above yield decreases with increased shear rate. Furthermore, the behavior of MR fluids when in the "off" state is also non-Newtonian and temperature dependent, however it deviates little enough for the fluid to be ultimately considered as a Bingham plastic for a simple analysis.

Thus our model of MR fluid behavior in the shear mode becomes:

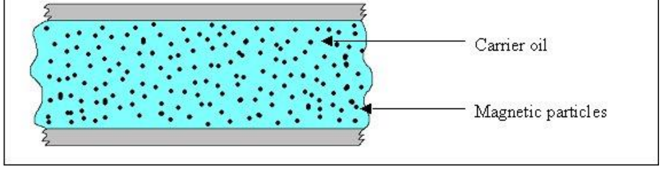


Figure 6
[IN ABSENSE OF MAGNETIC FIELD]

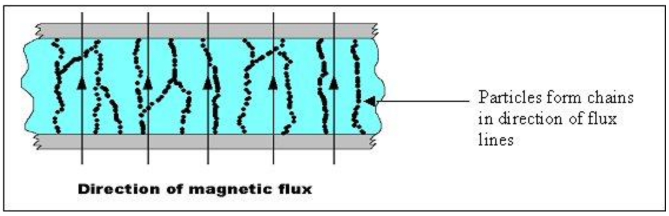


Figure 7
[IN PRESENCE OF MAGNETIC FIELD]

6. Shaft & Rotor

A shaft is a rotating machine element, usually circular in cross section, which is used to transmit power from one part to another, or from a machine which produces power to a machine which absorbs power.The various members such as pulleys and gears are mounted on it.

Figure 8 [Shaft & Rotor]

Shaft diameter & length is 20mm & 600mm and rotor Outer diameter is 121mm.

- Shear stresses due to the transmission of torque (due to torsional load).
- Bending stresses (tensile or compressive) due to the forces acting upon the machine elements like gears and pulleys as well as the self weight of the shaft.
- Stresses due to combined torsional and bending loads

The material used for ordinary shafts is mild steel. When high strength is required, an alloy steel such as nickel, nickel-chromium or chromium-vanadium steel is used.

Shafts are generally formed by hot rolling and finished to size by cold drawing or turning and grinding.

7. Casing

A casing is use to enclose the internal parts of machine and it also use to make leak proof internal parts of machine.

Figure 9 [casing]

-It is made of mild steel material

-having outer diameter 165mm & inner diameter 161mm

Wall thickness is 5mm , face thickness is 24 mm .

-its is enclosed by nuts and bolts in which rubber is fit periphery of casing which make it leak proof.

-In this casing we use oil sil which is resist a leakage in the casing. This is also take responsibility of a bearing.

-a piece of heavy steel pipe used to line a borehole or well.

8. Motor

An electric motor is an electrical machine that converts electrical energy into mechanical energy. Most electric motors operate through the interaction between the motor's magnetic field and electric current in a wire winding to generate force in the form of rotation of a shaft. Electric motors can be powered by direct current (DC) sources, such as from batteries, motor vehicles or rectifiers, or by alternating current(AC) sources, such as a power grid, inverters or electrical generators. An electric generator is mechanically identical to an electric motor, but operates in the reverse direction, converting mechanical energy into electrical energy.

Figure 10 [Motor]

We use AC motor for fast rotation like 1500-2000 rpm.

A DC motor is any of a class of rotary electrical machines that converts direct current electrical energy into mechanical energy. The most common types rely on the forces produced by magnetic fields. Nearly all types of DC motors have some internal mechanism, either electromechanical or electronic, to periodically change the direction of current flow in part of the motor.

9. Battery

A battery is a device consisting of one or more electrochemical cells with external connections provided to power electrical devices

Figure 11 [Battery]

-We use 12 volts and 9 ampere battery for making an electromagnet.

-We use standard exide battery of 4 year warrenty and continuous 5 hour working experience.

-When a battery is supplying electric power, its positive

terminal is the cathode and its negative terminal is the anode. The terminal marked negative is the source of electrons that will flow
through an external electric circuit to the positive terminal.

Advantages

- Elemenation of hazardous brake fluid
- The efficiency of break increase compare to convectional friction brake.
- Reduce no. of components and wiring
- Maintanancecost reduce.
- Braking torque increase
- Simple software base parameters adjustment depending on driving condition.

Disadvantage

- It only works on electricity.
- Leakage maybe take place from brakes.
- Not use in heavy automotive work.

Future Scope.

- MR fluid have many application like damping, clutch, body armor
- a smart fluid have magnetic & electric response which can have various properties
- It can replace the suspension & breaking system in vehicales which makes it less cost & less maintainance.
- MR fluid have also used in plastic technology which made a composition of strong fibers
- Nanotechnology & MR OR ER fluid make a smart fluid in chemistry which make large development in future

V. CONCLUSION

As a disc is connected with shaft are rotating with rotary motion.As we apply elctricity to electro magnet which induce magnetic field.As magnetic field induce viscocity of MR fluid change.As change in viscosity, rotary motion of a disc gradually decrease untill come to rest. And its change in future braking system of automobile as well as mechanical industries vehicle and machines braking system. With the help of MR fluid its easy to maintain and reducing its cost.

REFERENCES

[1] Pinkos et al., "An Actively Damped Passenger Car Suspension System with Low Voltage Electro-Rheological Magnetic Fluid", SAE Technical Paper Series, International Congress and Exposition, Mar. 1-5, 1993, pp. 86-93.

[2] A.M. Homola et al., Novel Magnetic Dispersions Using Silica Stabilized Particles , IEEE Transactions on Magnetics , Sep. 1986, pp. 716 719, vol. Mag. 22, No. 5. no month.

[3] Lawniczak, A., Milecki, A. (1999). Cieczeelektro-imagnetoreologiczneorazichzastosowania w technice. Poznan, Poland: Wydawnictwo Politechniki Poznanskiej.

[4] Carlson, J. D. (1994). Magnetorheological Fluid Devices. U.S. Patent No. 5,284,330.LORDCorporation (2006). MRF-140CG MagnetoRheological Fluid. Retrieved from http://www.lordfulfillment.com/upload/DS7012.pdf

[5] LORD Corporation (2006). RD-1005-03 Damper. Retrieved from http://www.lordfulfillment.com/upload/ DS7017.pdf

[6] Olszowski, A. (2004). Doswiadczeniafizykochemiczne. Wroclaw, Poland: OficynaWydawniczaPWr.

[7] Press W, Teukolsky S, Vetterling W et al (1992) Numerical recipes in C. Cambridge University Press, CambridgeGoogle Scholar

[8] Malek AM, Alper SL, Izumo S (1999) Hemodynamic shear stress and its role in atherosclerosis. JAMA 282:2035–2042CrossRefPubMedGoogle Scholar

[9] He X, Ku DN (1996) Pulsatile flow in the human left coronary artery bifurcation: average conditions. J BiomechEng 118:74–82CrossRefPubMedGoogle Scholar

[10] Hollnagel DI, Summers PE, Kollias SS, Poulikakos D (2007) Laser Doppler velocimetry (LDV) and 3D phase-contrast magnetic resonanceangiography (PC-MRA) velocity measurements: validation in an anatomicallyaccurate cerebral artery aneurysm model with steady flow. J MagnReson Imaging 26:1493–1505CrossRefPubMedGoogle Scholar

[11] Tateshima S, Tanishita K, Omura H, Villablanca JP, Vinuela F (2007) Intra-aneurysmal hemodynamics during the growth of an unruptured aneurysm: in vitro study using longitudinal CT angiogram database. AJNR Am J Neuroradiol 28:622–627PubMedGoogle Scholar

[12] Markl M, Chan FP, Alley MT et al (2003) Time-resolved three-dimensional phase-contrast MRI. J MagnReson Imaging 17:499–506CrossRefPubMedGoogle Scholar

[13] Yamashita S, Isoda H, Hirano M et al (2007) Visualization of hemodynamics in intracranial arteries using time-resolved three-dimensional phase-contrast MRI. J MagnReson Imaging 25:473–478CrossRefPubMedGoogle Scholar

[14] Bammer R, Hope TA, Aksoy M et al (2007) Time-resolved 3D quantitative flow MRI of the major intracranial vessels: initial experience and comparative evaluation at 1.5 T and 3.0 T in combination with parallel imaging. MagnReson Med 57:127–140CrossRefPubMedGoogle Scholar

[15] Wetzel S, Meckel S, Frydrychowicz A et al (2007) In vivo assessment and visualization of intracranial arterial hemodynamics with flow-sensitized 4D MR imaging at 3 T. AJNR Am J Neuroradiol 28:433–438PubMedGoogle Scholar

[16] Mantha A, Karmonik C, Benndorf G et al (2006) Hemodynamics in a cerebral artery before and after

the formation of an aneurysm. AJNR Am J Neuroradiol 27:1113–1118PubMedGoogle Scholar

[17] Shojima M, Oshima M, Takagi K et al (2004) Magnitude and role of wall shear stress on cerebral aneurysm: computational fluid dynamic study of 20 middle cerebral artery aneurysms. Stroke 35:2500–2505CrossRefPubMedGoogle Scholar

[18] Meng H, Wang Z, Hoi Y et al (2007) Complex hemodynamics at the apex of an arterial bifurcation induces vascular remodeling resembling cerebral aneurysm initiation. Stroke 38:1924–1931CrossRefPubMedGoogle Scholar

[19] Hassan T, Timofeev EV, Saito T (2004) Computational replicas: anatomic reconstructions of cerebral vessels as volume numerical grids at three-dimensional angiography. AJNR Am J Neuroradiol 25:1356–1365PubMedGoogle Scholar

[20] Jou LD, Wong G, Dispensa B et al (2005) Correlation between lumenal geometry changes and hemodynamics in fusiform intracranial aneurysms. AJNR Am J Neuroradiol 26:2357–2363PubMedGoogle Scholar

[21] Jou LD, Lee DH, Morsi H et al (2008) Wall shear stress on ruptured and unruptured intracranial aneurysms at the internal carotid artery. AJNR Am J Neuroradiol 29:1761–1767CrossRefPubMedGoogle Scholar

[22] Boussel L, Rayz V, McCulloch C et al (2008) Aneurysm growth occurs at region of low wall shear stress: patient-specific correlation of hemodynamics and growth in a longitudinal study. Stroke 39:2997–3002CrossRefPubMedGoogle Scholar

[23] Valencia A, Morales H, Rivera R et al (2008) Blood flow dynamics in patient-specific cerebral aneurysm models: the relationship between wall shear stress and aneurysm area index. Med Eng Phys 30:329–340CrossRefPubMedGoogle Scholar

[24] Cebral JR, Castro MA, Burgess JE, Pergolizzi RS, Sheridan MJ, Putman CM (2005) Characterization of cerebral aneurysms for assessing risk of rupture by using patient-specific computational hemodynamics models. AJNR Am J Neuroradiol 26:2550–2559PubMedGoogle Scholar

[25] Szikora I, Paal G, Ugron A et al (2008) Impact of aneurysmal geometry on intraaneurysmal flow: a computerized flow simulation study. Neuroradiology 50:411–421CrossRefPubMedGoogle Scholar

[26] Ohshima T, Miyachi S, Hattori K et al (2008) Risk of aneurysmal rupture: the importance of neck orifice positioning-assessment using computational flow simulation. Neurosurgery 62:767–773CrossRefPubMedGoogle Scholar

[27] Shimai H, Yokota H, Nakamura S et al (2005) Extraction from biological volume data of a region of interest with non-uniform intensity. Optomechatronic Machine Vision, edited by Kazuhiko Sumi, Proceedings of SPIE Vol. 6051, 605115Google Scholar

[28] Lorensen WE, Cline HE (1987) Marching cubes: a high resolution 3D surface construction algorithm. Comput Graph 21:163–169CrossRefGoogle Scholar

[29] Masaryk AM, Frayne R, Unal O et al (1999) In vitro and in vivo comparison of three MR measurement methods for calculating vascular shear stress in the internal carotid artery. AJNR Am J Neuroradiol 20:237–245PubMedGoogle Scholar

[30] Cheng CP, Parker D, Taylor CA (2002) Quantification of wall shear stress in large blood vessels using Lagrangian interpolation functions with cine phase-contrast magnetic resonance imaging. Ann Biomed Eng 30:1020–1032CrossRefPubMedGoogle Scholar

[31] Zhao SZ, Papathanasopoulou P, Long Q, Marshall I, Xu XY (2003) Comparative study of magnetic resonance imaging and image-based computational fluid dynamics for quantification of pulsatile flow in a carotid bifurcation phantom. Ann Biomed Eng 31:962–971CrossRefPubMedGoogle Scholar

